Time history of upper-limb muscle activity during isolated piano keystrokes.

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Introduction

Up to 93% of professional pianists might develop playing-related musculoskeletal disorders (PRMDs) during their career, the most concerned structures being the back and the upper limb (Bragge et al., 2006; Moñino et al., 2017). PRMDs in pianists can lead to the modification, reduction or even cessation of performance-related activities (Moñino et al., 2017). Indeed, the first treatment of PRMDs is to decrease the magnitude and frequency of the stress on the affected structures (Hertling and Kessler, 2006) by a reduction of the practice time at the instrument. For professional musicians, this may entail risks of job loss and of financial and psychological distress (Zaza et al., 1998). It has been shown that specific warm-up routines (*i.e.* a set of piano exercises involving similar muscular structures than those used during actual practice or performance) might have a positive effect on the prevention of muscle injuries (Shellock and Prentice, 1985; Woods et al., 2007). In that context, a better understanding of the impact of performance parameters on muscle activity, so far limited, could improve the recommendations for pianists to adapt their warm-up and performance strategies and help prevent PRMDs.

Different studies have documented the biomechanical features of two types of touch: struck touch (*i.e.* striking the key from a certain height) and pressed touch (*i.e.* depressing the key with the fingertip initially in contact with the key). These studies suggest that struck touch is physiologically more efficient because *i*) it requires less forceful key action than pressed touch to produce equivalent loud piano tones (Kinoshita et al., 2007), and *ii)* it facilitates an effective use of gravity (Furuya et al., 2009) to reduce the muscular activity at the elbow during the attack of the keys. The experimental task of these studies (isolated keystrokes) included however only a short finger-key interaction (*i.e. staccato* articulation), which requires a rapid motion to remove the finger from the key immediately after the end of the key descent. Therefore, other types of articulation, for instance a sustained finger-key interaction after the end of the key descent (*i.e. tenuto* articulation), have never been included in the analysis of muscle activity related to pressed and struck touch.

Verdugo et al. (2020) showed that shoulder-girdle joints have a central role to produce the key-release upper-limb motion of isolated *staccato* keystrokes. As shown by a literature review on electromyography (EMG) and music performance (Visentin and Shan, 2011), muscle activity related to the shoulder structure might be modified by different playing techniques. For instance, direction and type of the bowing movement of the right arm affect the activity of the deltoid in the case of violin (Shan and Visentin, 2004) and of the trapezius muscles in the case of both violin and cello (Afsharipour et al., 2016). In this sense, biomechanical features of struck and pressed touch during piano performance could be influenced by the choice of articulation, as the activity of more proximal muscles responsible for the key-release motion of isolated keystrokes could be affected by short or sustained finger-key interactions.

To the best of our knowledge, only a handful of studies on piano performance have included an EMG analysis (Furuya et al., 2012, 2011, 2009; Furuya and Kinoshita, 2008; Grieco et al., 1989; McCarthy, 2016; Oikawa et al., 2011; Welch, 2016; Yoshie et al., 2009). If the muscles targeted differ from one study to another, there is a tendency to focus on the activity of more distal muscles. Forearm muscles, namely flexor digitorum superficialis and extensor digitorum communis, were included respectively at least in seven and eight studies. Elbow muscles, the biceps brachii and the triceps brachii, appeared respectively in six and four studies. Shoulder muscles, anterior deltoid, posterior deltoid and upper trapezius were assessed in only three studies. Thus, EMG-based knowledge on the activity of pianists' upper-limb muscles while playing remain limited.

The above-cited studies on piano performance generally analyze the collected EMG data by extracting single-point values such as the peak and the mean EMG activation, *i.e.* they do not account for the time histories of muscle activity. Recently, statistical parametric mapping (SPM) appeared in the biomechanics literature (Pataky, 2012; Pataky et al., 2013) and overcomes limitations of previously used methods by allowing analysis of time-series values of continuous biomechanical features such as the EMG activation. The use of SPM might be then a better-adapted statistical tool to estimate the influence of performance parameters (*i.e.* touch and articulation) on muscle activity during the entire keystroke window.

The first purpose of this study was to evaluate the effect of touch and articulation on muscle activity in both proximal and distal upper-limb muscles. The second purpose was to assess the accuracy of the results obtained from statistical analysis performed on time histories of the EMG activity as well as on mean and peak EMG values.

Method

Twelve professional classical right-handed pianists (10 males and 2 females; 33.3±4.7 years old) volunteered to participate in this study. None were affected by PRMDs at the moment of the experimentation. They had completed (n=10) or were in the process of completing (n=2) their doctoral degree in piano performance at University of Montreal. Informed consent was obtained prior to the experiment and the study was approved by the University Ethics Committee (No. 18-086-CPER-D).

Participants were asked to perform four series of 40 isolated keystrokes (A4) on a Bösendorfer CEUS grand piano with the middle finger of the right hand at a slow tempo (30 bpm) and at a high intensity level (*forte*). The target tone was pre-recorded using the Bösendorfer CEUS reproducing system and played to participants at the beginning of the recording session. Intensity levels of tones produced by pianists were monitored with a sound level meter. Series of keystrokes were defined based on the four possible combinations of two types of touch (pressed or struck) and articulation (*staccato* or *tenuto*). Additionally, participants were asked to perform maximum voluntary contraction tests (MVC) against manual resistance for a 3-second period before the trials at the piano. MVC tests were finger isometric flexion and extension against a resistance on the metacarpals with the wrist in neutral position, elbow isometric flexion and extension at 90° of elbow flexion (Furuya and Kinoshita, 2008); scapula protraction at 90° of shoulder flexion (Ekstrom et al., 2005); and shoulder abduction 90°, shoulder flexion 90° and palm press (Dal Maso et al., 2016). During trials at the piano and MVC tests, EMG activity of the flexor digitorum superficialis, extensor digitorum communis, biceps brachii, triceps brachii, anterior deltoid, middle deltoid, great pectoral, upper trapezius and serratus anterior were collected using a Delsys Trigno™ Wireless system (Boston, MA, USA) at a sampling rate of 2100 Hz.

Sensors employ four silver bar contacts of 5 mm long that are set 10 mm apart. Differential EMG detection mode was used with a common mode rejection ratio inferior to 80 dB. Electrodes were placed at the estimated motor point respecting the fascicle muscle direction according to SENIAM (Stegeman and Hermens, 2007). Location and orientation of EMG sensors with respect to anatomical references are given in Table 1 to allow replication of the study as suggested by recent guidelines (Merletti R., Muceli S., 2019). To reduce the impedance, the skin was shaved, abraded and cleaned with 70% isopropyl alcohol prior to the recording. Fingertip kinematic of the third finger was recorded using an 18-camera VICON™ optoelectronic motion analysis system (Oxford Metrics Ltd., Oxford, UK) at 150 Hz and a reflective marker placed on the nail. EMG and kinematic data were synchronized by Nexus 2.8.2 software. An illustration of the experimental setup is given in Appendix 1.

Table 1: Anatomic description of all EMG sensors orientation and location.

Muscle	**Name**	**Electrode orientation and position**
FDS	flexor digitorum superficialis	From the medial epicondyle of the elbow to the middle finger. Three fingers under the medial epicondyle of the elbow.
EDC	extensor digitorum communis	From the lateral epicondyle of the elbow to the middle finger. Two fingers under the lateral epicondyle of the elbow.
Bi	biceps brachii	From the medial acromion to the fossa cubit. Halfway.
Tri	triceps brachii	From the posterior acromion to the olecranon. Halfway.
AD	anterior deltoid	From the medial acromion to the antecubital fossa. Two fingers under the acromion.
MD	middle deltoid	From the lateral acromion to the lateral epicondyle of the elbow. Two fingers under the acromion.
GP	great pectoral	From the axillary hollow to the sternum gladiolus. One third from the axillary hollow.
UT	upper trapezius	From the C7 vertebra to the acromion. Halfway.
SA	serratus anterior	Along the 5rd thoracic rib. On the rib grill under the axillary hollow.

Data processing

The beginning of the key descent (t_0=0 ms) was estimated by comparing the vertical component of the marker placed on the nail in relation with a marker placed on the keyboard. According to the International Society of Electrophysiology and Kinesiology recommendations (Merletti, 1999), EMG data (obtained during trials at the piano and MVC tests) were filtered using a 2nd order Butterworth band-pass filter with cut-off frequencies of 5-500 Hz. The signal envelope was obtained using a sliding root mean square with a 30 ms window (Appendix 2-A). EMG time histories were cut into 40 cycles of 1500 ms centered at t_0. To mitigate the effects of unwanted perturbations on the results (skin temperature, sweating, movement artefacts or external sources (Besomi et al., 2019)), only the 10 cycles nearest to the mean EMG activation were selected for each series (Appendix 2-B). To normalize these EMG data, the MVC value was calculated using the median of the maximum values obtained over a period of one non-consecutive second considering all MVC tests performed. The amplitude of the envelope was normalized with respect to the MVC value, so activations were expressed as a percentage of MVC (%MVC). In addition to the time history analysis, two unidimensional parameters commonly used in the pianistic literature were computed over the whole keystroke window (*i.e.* 1.5 s): 1) the peak EMG activation (pEMG) and 2) the mean EMG activation (mEMG).

Statistics

A nonparametric two-way analysis of variance (ANOVA) with repeated measures on muscle activations was performed to determine the effect of the two independent parameters: touch and articulation. Significance was set at $p \leq 0.05$, and corrected with false discovery rate (FDR) (Benjamini and Hochberg, 1995) procedure for multiple comparisons (q=0.10; FDR=10%). To account for the time histories of EMG activation during piano performance, the *spm1d* package was used to compute statistical inferences (Pataky, 2010). Nonparametric testing was chosen as it leads to results qualitatively identical to parametric testing, while being robust to non-normal and non-spherical data (Pataky et al., 2015). Period of significant differences occurring less than 50 ms apart were pooled together and significant differences lasting less than 10 ms after pooling were removed. Due to inconsistent EMG data, one participant was removed for triceps brachii, anterior deltoid and pectoralis major analysis. As an additional parameter, the effect size (Cohen's d), was calculated. The Cohen's d is a quantitative measure of a phenomenon where d(0.01)=[very small], d(0.2)=[small], d(0.5)=[medium], d(0.8)=[large], d(1.2)=[very large] and d(2.0)=[huge] (Sawilowsky, 2009).

Results

The reported differences in EMG activations are expressed using as a reference struck touch and *tenuto* articulation (a positive difference meaning that EMG activations during pressed or *staccato* conditions were greater than during struck or *tenuto* conditions). No interaction between touch and articulation was revealed by pEMG, mEMG and time history analysis (all $q>0.1$, Table 2).

Peak and mean EMG

The pEMG activation ranged from 2.7±1.5%MVC for the biceps brachii to 34.9±13.1%MVC for the flexor digitorum superficialis (Table 2). The activity of the flexor digitorum superficialis (+14.5%MVC, $d_{pEMG}=1.1$ [very large]) and the triceps brachii (+4.8%MVC, $d_{pEMG}=1.4$ [very large]) was greater in pressed touch conditions compared to struck touch conditions. The activity of the biceps brachii was greater during *staccato* articulation (+1.6%MVC, $d_{pEMG}=0.66$ [medium]).

The mEMG activation did not exceed 4.9±2.8%MVC considering all muscles and only small to medium effects were found (Table 2). In pressed touch conditions, mEMG of the flexor digitorum superficialis (+0.4%MVC, $d_{mEMG}=0.29$ [small]), the triceps (+0.27%MVC, $d_{mEMG}=0.32$ [small]) and the upper trapezius (+0.64%MVC, $d_{mEMG}=0.23$ [small]) were greater than in struck touch conditions. In *staccato* conditions, mEMG of the biceps brachii (+0.29%MVC, $d_{mEMG}=0.46$ [small]) and the anterior deltoid (+0.71%MVC, $d_{mEMG}=0.62$ [medium]) were higher while the mEMG of the flexor digitorum superficialis (-0.79%MVC, $d_{mEMG}=0.54$ [small]) was lower than in *tenuto* conditions.

Table 2: Mean value and standard deviation of the peak EMG (pEMG; top value) and mean EMG (mEMG; bottom value) expressed as a percentage of the maximum voluntary contraction (%MVC). F value and p value corrected (q value) of nonparametric two-way ANOVA with repeated measures. Significance was set at **p≤0.05** and corrected with false discovery rate procedure for multiple comparisons **(q≤0.1)**.

FDS=flexor digitorum superficialis, EDC=extensor digitorum communis, Bi=biceps brachii, Tri=triceps brachii, AD=anterior deltoid, MD=middle deltoid, GP=great pectoral, UT=upper trapezius and SA=serratus anterior.

Muscle		**Struck** ***Staccato***	**Struck** ***Tenuto***	**Pressed** ***Staccato***	**Pressed** ***Tenuto***	**Touch**	**Articulation**	**Interaction**
FDS	Peak	18.9±8.6	17.4±8.5	34.9±13.1	30.4±18.0	**F=21.9; q=0.006**	F=2.0; q=0.38	F=1.0; q=0.53
	Mean	2.6±1.2	3.5±1.7	3.1±1.1	3.8±1.6	**F=12.9; q=0.04**	**F=11.0; q=0.04**	F=0.2; q=0.92
EDC	Peak	19.6±29.0	19.6±21.1	15.7±8.0	14.6±5.8	F=0.6; q=0.68	F=0.08; q=0.90	F=0.06; q=0.90
	Mean	4.7±2.9	4.7±2.9	3.6±1.1	4.0±1.7	F=2.5; q=0.50	F=0.3; q=0.92	F=0.76; q=0.79
Bi	Peak	3.7±2.2	2.7±1.5	5.1±3.2	2.9±2.2	F=7.4; q=0.12	**F=19.9; q=0.006**	F=5.8; q=0.15
	Mean	1.3±0.7	1.0±0.6	1.3±0.8	1.0±0.5	F=0.03; q=0.96	**F=13.6; q=0.04**	F=0.04; q=0.96
Tri	Peak	3.6±2.0	4.1±2.4	8.7±4.3	8.7±4.3	**F=21.5; q=0.006**	F=0.2; q=0.80	F=0.4; q=0.68
	Mean	1.4±0.8	1.5±0.7	1.7±0.9	1.8±0.9	**F=9.3; q=0.05**	F=0.9; q=0.75	F=0.004; q=0.96
AD	Peak	9.6±3.1	8.2±2.5	11.0±5.1	7.8±1.6	F=1.5; q=0.41	F=4.5; q=0.18	F=2.9; q=0.30
	Mean	3.8±1.3	3.1±0.8	3.8±1.5	3.1±0.9	F=0.003; q=0.96	**F=8.2; q=0.08**	F=0.06; q=0.96
MD	Peak	6.6±4.5	6.2±3.4	7.1±4.7	5.8±3.1	F=0.04; q=0.90	F=1.8; q=0.38	F=1.5; q=0.41
	Mean	2.8±1.8	2.5±1.2	2.7±1.6	2.5±1.4	F=0.01; q=0.96	F=1.3; q=0.70	F=0.17; q=0.95
GP	Peak	9.9±5.1	7.5±3.2	11.3±6.7	7.7±3.0	F=5.4; q=0.15	F=6.7; q=0.15	F=1.8; q=0.39
	Mean	4.0±1.9	3.5±1.6	4.1±2.0	3.6±1.6	F=2.3; q=0.50	F=4.1; q=0.27	F=0.4; q=0.92
UT	Peak	10.3±5.5	9.2±5.3	12.0±6.9	10.4±4.8	F=3.4; q=0.25	F=4.7; q=0.19	F=0.24; q=0.79
	Mean	4.2±2.6	4.1±2.9	4.8±2.9	4.9±2.8	**F=10.6; q=0.04**	F=0.004; q=0.96	F=0.25; q=0.92
SA	Peak	8.5±4.9	11.1±7.6	12.9±12.8	9.9±5.3	F=0.89; q=0.52	F=0.005; q=0.96	F=2.7; q=0.30
	Mean	2.9±1.1	3.4±1.3	3.3±1.6	3.3±0.9	F=0.9; q=0.76	F=0.5; q=0.92	F=1.4; q=0.64

EMG time histories

When comparing time histories of muscular activation, there were very large main effects of touch for the flexor digitorum superficialis and very large main effects of articulation for the anterior deltoid and the great pectoralis (Figure 1). Very small and small effects are not reported.

Before the key descent, touch affected the EMG of the biceps brachii (from -660 to -430 ms; -0.35%MVC and d=0.64 [medium]) and the upper trapezius (from -360 to -80 ms; +1.3%MVC and d=0.53 [medium]). Flexor digitorum superficialis activation was significantly affected by touch (1) right before and during the key descent from -20 to 12 ms (-3.8%MVC and d=1.3 [very large]), and (2) after the key descent from 60 to 100 ms (+12.9%MVC and d=1.3 [very large]) and from 210 to 260 ms (+1.75%MVC and d=0.63 [medium]). Triceps brachii activity showed also a touch-related significant difference during and after the key descent from 10 to 100 ms (+2.90%MVC and d=1.1 [large]). No effect of articulation was reported before the key descent. During and after the key descent, articulation affected the activity of the middle deltoid (0 to 20 ms; +0.80%MVC and d=0.52 [medium]), the upper trapezius (0 to 80 ms; +2.1%MVC and d=0.51 [medium]), the anterior deltoid (0 to 310 ms; +2.5%MVC and d=1.4 [very large]), the great pectoralis (30 to 50 ms; +3.8%MVC and d=1.3 [very large]), the biceps brachii (50 to 80 ms; +0.94%MVC and d=0.90 [large]) and the flexor digitorum superficialis EMG from (250 to 350 ms; -2.0%MVC and d=0.97 [large]). Towards the end of the keystroke window, the biceps brachii activation showed an articulation effect from 290 to 640 ms (+0.44%MVC and d=0.76 [medium]).

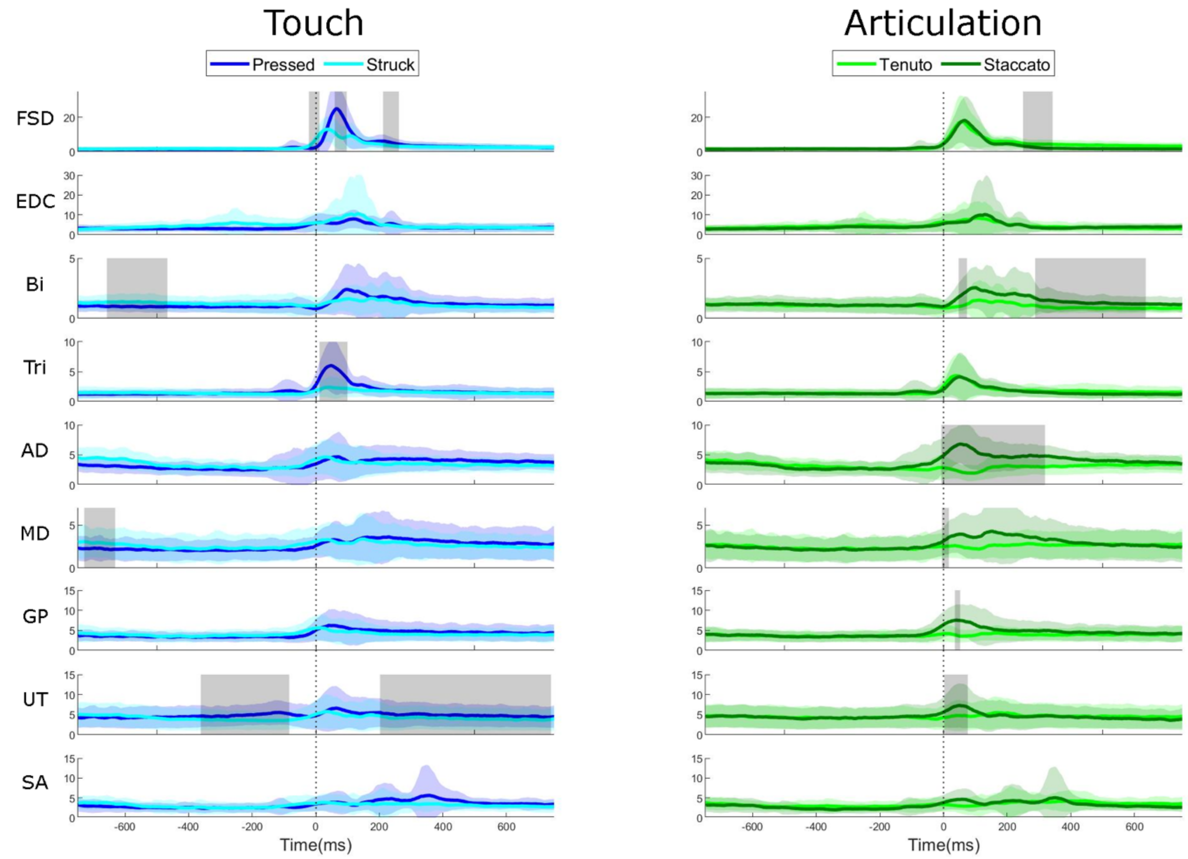

Figure 1: Time histories of muscle activations and main effect of the nonparametric two-way ANOVA with repeated measures. Color lines and clouds represent respectively mean muscular activations plus or minus one standard deviation in %MVC of all subjects regrouped by performance parameters. Grey boxes represent the periods of significant difference. The vertical dotted line indicates the beginning of the key descent. FDS=flexor digitorum superficialis, EDC=extensor digitorum communis, Bi=biceps brachii, Tri=triceps brachii, AD=anterior deltoid, MD=middle deltoid, GP=great pectoral, UT=upper trapezius and SA=serratus anterior.

Discussion

This study evaluated the effect of touch and articulation on the activity of nine upper-limb muscles during repetitive isolated keystrokes. Statistical analysis was performed on the time histories of EMG activity and on mean and peak EMG values to compare the accuracy of the results obtained. Our results suggest that struck/pressed touch and *staccato*/*tenuto* articulation implicate distinct profiles of muscle activation. The initial velocity of the fingertip obtained by the gravity drop of the arm during struck touch was compensated by an increased activation of the triceps and the flexor digitorum superficialis during pressed touch.

Effect of touch

Struck touch (striking the key from a certain height) and pressed touch (pressing the key with the fingertip initially in contact with the key) might generate identical hammer velocities to produce the same tone intensity but they entail different muscle activations (Goebl, 2017). Flexor digitorum superficialis EMG activations showed very large touch-related effects. The timing of these effects suggests that, as in the case of experienced typists (Dennerlein et al., 1998), the activity of this muscle was more related to the stabilization of finger joints rather than to the downward acceleration of the finger during the attack. Goebl et al. (2005) showed that struck and pressed touch entail two types of key velocity control. In struck touch, sound intensity mostly relies on the key velocity burst produced by the initial finger/key impact. In the case of pressed touch, pianists control sound intensity through a smooth key downward acceleration during the key descent until the escapement of the hammer. Our results are in line with these observations and indicate that pianists used higher activations of the flexor digitorum superficialis muscle to stabilize finger joints during the initial finger/key impact of struck touch and during the later key/key-bed impact of pressed touch.

Our study revealed a progressive deactivation of the biceps brachii and middle deltoid before the attack of the key during struck conditions. Furuya et al. (2009) showed that, in expert pianists, the deactivation of the biceps brachii coupled with no activity of the triceps brachii before struck keystrokes corresponded to the use of the gravitational force to produce an elbow extension and thus a downward acceleration of the fingertip. Our findings support this idea and indicate that pianists might also use gravity to produce a shoulder adduction during struck touch. The reported progressive deactivations of the biceps brachii (elbow flexor) and the middle deltoid (shoulder abductor) before the attack of struck keystrokes suggest in fact that both elbow extension and shoulder adduction were induced by the gravitational force as, simultaneously, no increase in triceps brachii (elbow extensor) and great pectoralis (shoulder adductor) activations were observed. A similar idea has been advanced in the case of violin, where empirical evidence shows that the right biceps and deltoid decrease their activity during the down-bow of the bowing process to take advantage of gravity (Shan and Visentin, 2004). Pressed touch was characterized by higher activations of the triceps brachii during and after the key descent and the upper trapezius (scapular elevator) before and after the key descent. To compensate for the impossibility to create arm and fingertip downward velocity before the attack, pianists seemed to use: 1) the triceps brachii muscle to rapidly extend the elbow and produce a downward acceleration of the fingertip during the key descent; and 2) the upper trapezius to facilitate an anticipatory upper limb elevation before the attack. An anticipatory upper limb elevation might help produce an ‘upstanding’ finger and hand posture which increases the attack angle and, therefore, reduces the mechanical stress imposed on finger joints during the key descent (Harding et al., 1993). Despite the reported touch-related EMG activation differences, our results suggest that elbow muscles had a primer executive function in the production of fingertip downward velocity. In struck touch, the fingertip was mostly accelerated by the reduction of anti-gravity activity of elbow flexor muscles previously activated to elevate the forearm. In pressed touch, a rapid fingertip downward acceleration was mainly obtained by a burst of the activity of elbow extension muscles during the key descent.

Biomechanical studies on piano touch in the context of isolated keystrokes generally concluded that struck touch is physiologically more effective than pressed touch (and should be preferred in a context of PRMDs risk prevention) because it reduces the load on distal muscles (Furuya et al., 2010; Kinoshita et al., 2007). If our study reported higher activations of the flexor digitorum superficialis in pressed touch, this greater activity seemed to be related to stabilization of finger joints during the attack. In addition, no effect of touch was reported in finger extensors muscles, which seem to be more susceptible to muscle fatigue than finger flexor muscles in the context of both piano performance (McCarthy, 2016) and repetitive typing activities (Lin et al., 2004). To avoid repetitive loading on the concerned structures, an increase of motor variability by using both types of touch might be a more effective performance strategy to prevent risks of PRMDs. Therefore, to prepare all muscular structures to practice and performance activities, warm-up routines should include exercises that take into account the distinct muscle loads of struck and pressed touch.

The effects of the articulation

Our study revealed a clear influence of the articulation on upper-limb muscle activity. Similar to the increased activity of right deltoid and trapezius muscles during the up-bow phase of slow violin bowing movements (Afsharipour et al., 2016; Shan and Visentin, 2004), *staccato* keystrokes produced a burst of the activity of almost all the shoulder muscles targeted (anterior deltoid, middle deltoid, upper trapezius and pectoralis major). Our results point to the fact that the behavior of shoulder muscles during and after the key descent highly depends on the articulation chosen when performing isolated keystrokes. Three ideas can be developed from this finding. First, observations made by previous studies comparing the biomechanical features of struck and pressed touch in the context of *staccato* articulation (see e.g. Furuya et al., 2010; Kinoshita et al., 2007) might not be applied automatically to other types of articulation. Second, treatment for pianists suffering from PRMDs at shoulder structures might include a reduction of the performance of pieces implicating repetitive *staccato* and loud isolated keystrokes (such as the Toccata op. 11 and the first and third movements of the sonata n. 7 op. 83 by S. Prokofiev). Third, as pianists and violinists shoulder-related muscle patterns seem to be similar between loud *staccato* keystrokes and the up-bow phase of slow bowing movements, respectively, strategies to prevent and treat PRMDs affecting the shoulder structure of these two types of performers might potentially be built on common grounds. Motion-dependent joint torques between extension of the thoracic spine (an attack-swing movement of piano keystrokes reported in Verdugo et al., (2020)) and the lifting movement of the upper-limb could be further investigated by studies focussing on kinematic strategies helping to prevent PRMDs of both pianists and violinists.

Touch-articulation interaction

No interaction between touch and articulation was found during isolated keystrokes. In slow-paced keystrokes, touch and articulation might be considered as rather distinct sequential motor elements. The integration and fusion of sequential elements into single units is defined as coarticulation (Gonzalez-Sanchez et al., 2019). By anticipating the next element, a spatial and temporal overlap creates a new entity that could be different from the sum of the elements that comprise it (Engel et al., 1997). Slow-paced loud keystrokes seem to be a simple performance task that does not induce interactions in upper-limb muscle activity when coarticulating different types of touch and articulation. Indeed, coarticulation depends on the duration and the rate of movement events (Gonzalez-Sanchez et al., 2019). In this sense, interactions in muscular activation could appear between touch and articulation in the context of faster tempi. Furuya et al. (2012) noted significant differences in pianists upper-limb muscle activations depending on the tempo of the task. It follows that observations made at a certain tempo must be validated before being extended to other tempi.

Temporal analysis benefits

This study integrated both a temporal analysis of pianists' muscle activations and analyses based on peak and mean EMG data. The choice of time history or single value analysis highly depends on the initial hypothesis (Pataky et al., 2015). In our study, the aim was to evaluate the impact of specific performance parameters on upper-limb muscle activations with the implicit hypothesis that the activity of all the targeted muscles could be impacted during the different phases of the keystroke. If conducting a scalar analysis could produce mistakes of statistical inference and lead to wrong conclusions, large effects are generally highlighted despite of the statistical analysis procedure chosen (Pataky et al., 2016). For instance, higher activations of the flexor digitorum superficialis and the triceps brachii in pressed touch (very large and large effects, respectively) during and after the key descent was highlighted by all statistical analyses. However, statistically higher activations of the flexor digitorum superficialis in struck touch before and during the key descent (very large effect) were only accounted by the temporal analysis, leading to a more complete understanding of the function of the reported greater activations of this specific muscle. In addition, the peak EMG analysis did not show the influence of articulation on the flexor digitorum superficialis and on the anterior deltoid reported by both mean EMG and temporal analyses. Statistical analysis based on time histories seems then to be a more reliable tool to account for differences in EMG activations in the context of piano performance.

Limitations

This study contributes to the understanding of pianists' muscle activity related to different types of touch and articulations. Some limitations should however be addressed by future research. Touch and articulation parameters were addressed in the context of isolated keystrokes to ensure standardization and comparison of the collected data between subjects. However, as pianists' motion might potentially be modified by the simplicity of the experimental task, further research is necessary to confront the presented results to actual excerpts of the piano repertoire that include different tempi and levels of sound intensity. Studies based on larger populations might also give useful insights on the scope of the obtained results.

Conclusion

Our study highlights that pressed and struck touch implicate distinct muscle loads and that *staccato* articulation induces a burst at shoulder muscles compared to *tenuto* articulation during repetitive and loud slow-paced isolated keystrokes. Not only touch-related differences but also articulation-related differences were observed during the key descent. The presented results suggest that both pianists' performance strategies and warm-up routines aiming to reduce risks of PRMDs might benefit from integrating the types of touch and articulation included in this study. *Staccato* articulation appears however to be an important risk factor of PRMDs located at the shoulder structure. Finally, in a context of piano performance with a large keystroke recording window, temporal analysis allows more reliable results than scalar analysis.

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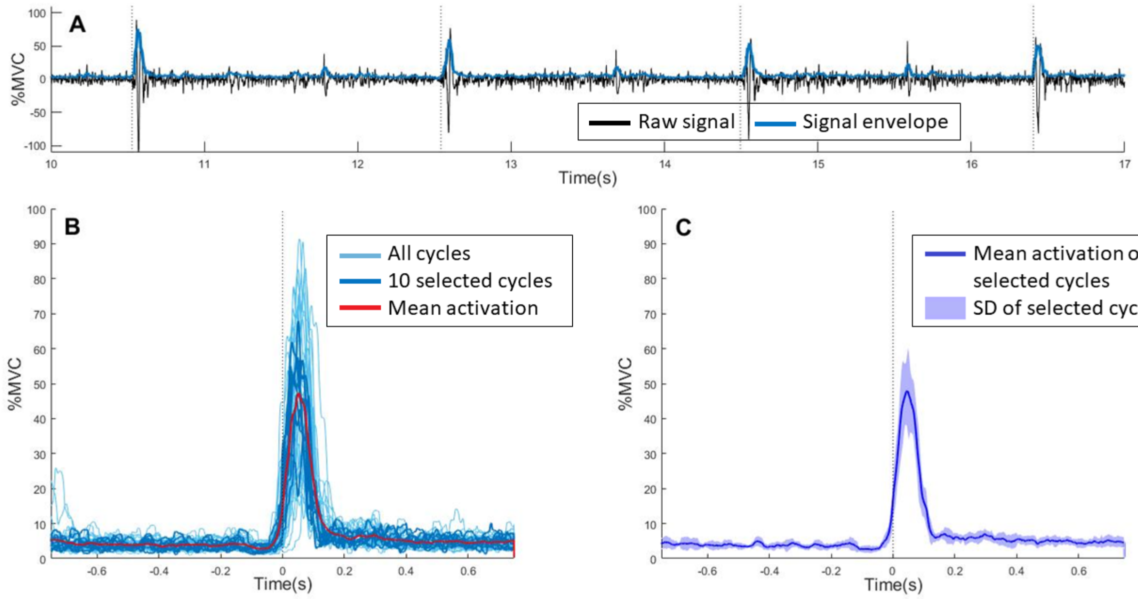
Appendix 1: Experimental setup.

The pianist was performing a single keystroke pressed and *tenuto*. EMG of extensor digitorum communis, biceps brachii, triceps brachii, middle deltoid, upper trapezius and serratus anterior are visible. Visualization of kinematic data related to fingertip marker can be found in Verdugo et al. 2020.

Appendix 2: Signal processing of the triceps brachii activation during pressed *tenuto* keystrokes of one representative pianist.

A: Signal processing (example on four cycles); B: Cycle selection and C: Representation of the data used. The vertical dotted line indicates the beginning of the key descent of each keystroke. The figures show the normalized signals to facilitate visualization and comprehension of the data presented.



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