Analysis of Piano Playing Movements Spanning Multiple Touches

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ABSTRACT

Awareness of playing movements can help a piano student to improve technique. We are developing a piano pedagogy application that uses sensor data of hand and arm movement and generates feedback to increase movement awareness. This paper reports on a method for analysis of piano playing movements. The method allows to judge whether an active movement in a joint has occurred during a given time interval. This time interval may include one or more touches. The problem is complicated by the fact that the mechanical interaction between the arm and piano action generates additional movements that are not under direct control of the player. The analysis method is able to ignore these movements and can therefore be used to provide useful feedback.

1. INTRODUCTION

In the book "Famous Pianists and Their Technique" [8], Gerig provides an extensive survey of the different schools of piano playing and teaching that have evolved over the last centuries.

The early clavier methods [8, p. 9–34] can be characterized by a passive arm and active fingers. Arm movement is used to change the horizontal position of the hand. Some arm and hand movement is used for chord playing. This technique is appropriate for the harpsichord, which is a predecessor to the piano and has a very light touch in comparison. The loudness of the generated sound is mainly predetermined by the action of the harpsichord and can only minimally be changed with force. However, an application of large force results in typically unwanted percussive noise. Therefore, finger activity is preferred over the forces of the stronger arm.

The modern piano has a heavier touch and the percussive sounds are less noticeable. Despite of this, playing technique remained nearly unchanged during the transition from harpsichord to piano. The so-called finger school had a culmination in the work of Czerny (1791–1857) [8, p. 103–120]. Czerny's ètudes, which to the present day have a place in the curriculum, are effective for training finger independency and for becoming accustomed to reoccurring musical patterns like scales, arpeggios, etc.

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Deppe (1828–1890) was one of the first influential pedagogues to put emphasis on the role of the arm [8, p. 229–270]. Deppe contributed only few written records about his method but his teachings were spread by his students. After Deppe's death, a multitude of books that emphasized the functions of the arm were published. The most influential follower of that trend was Karl Maria Breithaupt (1873–1945), whose name is connected to the school of weight technique [8, p. 329–359]. An important aspect of the Breithaupt's method is the use arm weight to execute touches. Breithaupt has been criticized for marginalizing the role of the fingers. He saw fingers main function to be to transduce arm forces to the keys. Furthermore, he has been criticized to overly emphasize the role of weight and muscle relaxation and to marginalize the role of active muscle work.

Ortmann (1889–1979) [8, p. 407–445] was one of the first to examine piano technique with scientific methods. For this purpose he used various devices, some of them he invented himself, to record playing movements. One of his contributions is to conciliate finger and weight school. Both the advantages of finger activity and arm activity should be used. Fingers are ideal when speed is needed but lack the strength and control of the arm. The arm on the other hand lacks the speed of the fingers because of its inertia.

The exercise book "20 Lessons in Keyboard Choreography" [1] by the piano pedagogue Seymour Bernstein contains a collection of movement lessons. Each movement lesson starts with a brief description of the movement and provides exercises subsequently. The exercises are typically small pieces enriched with various notation marks to indicate the movement (see Table 1).

The notation marks in Bernstein's exercises can be grouped according to the timing of the described movement. There are marks that relate to a single touch (movements 1 to 6), marks that relate to movements that span several successive touches (movements 12 to 14), marks that describe preparatory movements that occur before a touch (movements 15 and 16), and marks that describe a preparatory movement followed by a touch movement (movements 9 to 12). Movements that relate to a single touch can be analyzed with the Probabilistic Arm Model (PAM) [11]. This paper presents a method to analyze movements that span several successive touches.

2. RELATED WORK

2.1 Analysis of piano playing

For quite some time, measurements have been used to examine piano playing movements. Early examples are the works by Binet & Courtier, who determined continuous key position by measuring the pressure in a rubber tube [2], Ortmann [15, 16], who developed various devices to record key,

Table 1: Bernstein's movement notation

	Movement	Sign
1	Wrist up	$\uparrow$
2	Wrist down	$\downarrow$
3	Rotate right	R
4	Rotate left	L
7	Wrist up, rotate right	$\curvearrowright$
8	Wrist up, rotate left	$\curvearrowleft$
5	Wrist down, rotate right	$\searrow$
6	Wrist down, rotate left	$\swarrow$
9	Upper arm roll	$\overparen{\uparrow\downarrow}$
10	Double rotations	$\overparen{LR}$ $\overparen{RL}$
11	Double rotations and upper arm rolls	$\overparen{\curvearrowright\swarrow}$ $\overparen{\swarrow\curvearrowright}$
12	Continuous upper arm movement	$\overparen{\uparrow\uparrow\uparrow}$ $\underparen{\downarrow\downarrow\downarrow}$
13	Continuous rotation	$\overparen{RRR}$ $\overparen{LLL}$
14	Continuous upper arm movement and rotation	$\overparen{\curvearrowright\curvearrowright\curvearrowright}$ $\underparen{\swarrow\swarrow\swarrow}$
15	Fingers are placed on the keys	P
16	Horizontal movement	$\rightarrow$

finger, and arm movement, and Bernstein & Poppova, who used recorded lights that were placed on the player's body with a camera system [12]. Modern studies of piano playing movements are typically performed with motion capture technology.

Sakai et al. examined the role of finger and arm movements of pianists performing scales and chord repetitions [20]. Riehle et al. examined the finger movements of a pianist performing a repertoire piece [19]. Engel et al. studied the role of coarticulation on pianist's finger movements [4]. Wristen et al. studied compared movements when sight-reading and perfoming a repertoire piece [21]. Ferrario et al. studied differences in the amount of kinetic energy that is used for tone production and extraneous movements between concert pianists, piano teachers, and students [5]. Goebl & Palmer studied the role of tactile information gained when hitting the key from above for timing accuracy [9]. Loehr & Palmer studied the effects of mental chunking [13] and finger independency [14]. Furuya et al. analyzed octave repetition movements by calculating the inverse dynamics of the arm [7]. This allows to assess the gravitational, key-reaction, limb interaction, and muscular torques that are present in the arm and finger joints. A further study examined differences in proximal-to-distal coordination of playing movements between novices and expert pianists [6].

2.2 Instrument performance mining

Peiper et al. developed a method that distinguishes five bowing patterns using electromagnetic motion capture data, namely détaché, martelé, staccato, spiccato, and legato [17]. The patterns are distinguished by a decision tree based on geometric features, like initial bow position, and movement features, like velocity, acceleration, and movement continuity.

Rasamimanana et al. developed a method to distinguish three bowing patterns based on accelerometer data, namely détaché, martelé, and spiccato [18]. Minimal and maximal acceleration and velocity during a bow stroke are determined and used for classification with k-NN. For this purpose the velocity signal is computed by integrating the acceleration signal.

Young developed a method to distinguish six common bowing techniques, namely accented détaché, détaché lancé, louré, martelé, staccato, and spiccato [22]. The classification is based on 6DOF inertial bow movement sensing and measurement of vertical and lateral bow forces. The dimensionality of the sensor data is reduced using principal component analysis. A stroke is classified in the resulting low-dimensional space using k-NN.

A method to distinguish German and French drum grip was developed by Bouënard et al. [3]. The method identifies characteristic local extrema of the stick trajectory in the movement signal. The grips are distinguished using k-nearest-neighbor (k-NN) based on the timing and the height of the extrema of the stick trajectory.

3. PROBABILISTIC ARM MODEL

We coin conscious, goal-directed movements as primary movements. Examples for primary movement in piano playing are the movements of the fingers, hands, and arms that are used to press down the keys, reposition the hands, or make a communicative gesture. Secondary movements are movements that are not directly controlled. They are the inevitable byproducts of the primary movements and are due to the mechanical interaction with the piano action and anatomical constraints of the body. The Probabilistic Arm Model (PAM) [11] models primary and secondary movement and is the basis for the analysis method described in Section 4. Therefore, it will be briefly reviewed here.

The human arm has mainly seven degrees of freedom. When a note is played, the amount of movement in each joint is computed from sensor data over a fixed time interval of 0.08 s. These measurements, which are denoted F_1 to F_7, are composed of primary (M_{Pi}) and secondary (M_{Si}) movements and measurement error (E_i):

$$F_i = M_{Pi} + M_{Si} + E_i \tag{1}$$

The sum of secondary movement and measurement error is modeled as normally distributed, i. e., $M_{Ui} + E_i \sim \mathcal{N}(\mu_i, \sigma_i)$. The mean μ_i and standard deviation σ_i of the distribution are computed by evaluating an automatically learned function f. Because a primary movement in a joint can generate secondary movements in other joints f is a function of the primary movements of all other joints. The function f also depends on the velocity of the pressed key (F_v), which is computed from the MIDI signal. As true measurements of primary movements are not available, f is evaluated using F_1 to F_7 as approximations for the primary movements.

$$(\mu_i, \sigma_i) = f_i(M_{P1}, ..., M_{Pi-1}, M_{Pi+1}, ..., M_{P7}, F_v) \tag{2}$$

$$\approx f_i(F_1, ..., F_{i-1}, F_{i+1}, ..., F_7, F_v) \tag{3}$$

The function f can be learned through maximum likelihood estimation from a data-set of examples (see [11] for details). By evaluating the learned function f the mean μ_i and standard deviation σ_i of the secondary movement can be determined.

4. MOVEMENT ANALYSIS

This section presents a method that detects movements that are spread over several notes. The method is based

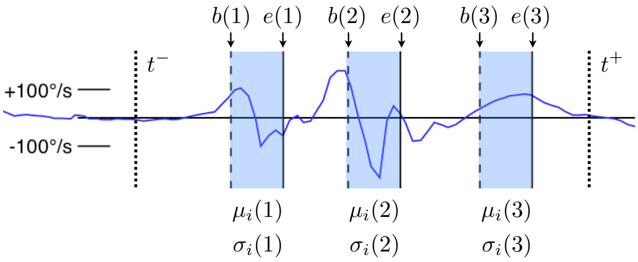

Figure 1: The movement is spread over multiple notes.

on the output provided by PAM. PAM is used to compute the mean and standard deviation of the secondary movement for all notes that occur between the beginning t^- to the end t^+ of the examined time interval (see Figure 1). The determined means and variances for joint i are denoted $\mu_i(1), \mu_i(2), \ldots, \mu_i(N)$ and $\sigma_i(1), \sigma_i(2), \ldots, \sigma_i(N)$, where N is the number of touches in the analysis interval. The estimation of secondary movement by PAM for a touch refers to the movement during a short time interval that ends when a note-on event is reported by the keyboard. The beginning of that time interval for the n-th note is denoted $b(n)$ and the end, $e(n)$.

A movement in joint i is recognized if the movement $F_{i,total}$ that is accumulated from t^- to t^+ exceeds the total mean of the secondary movement $\mu_{i,total}$ more than a constant c times the total standard deviation $\sigma_{i,total}$, i. e., if $F_{i,total} > \mu_{i,total} \pm c \cdot \sigma_{i,total}$. The total mean and the total standard deviation are computed from the means and standard deviations of the single notes, which are provided by PAM. When no note is played, the secondary movement is set to zero since there is no mechanical interaction with the piano action. In Figure 1, no secondary movement is expected during the time intervals $[t^-, b(1))$, $(e(1), b(2))$, $(e(2), b(3))$, and $(e(3), t^+]$.

Let $m_i(t)$ be the sensor angular rate of the movement in joint i, then $F_{i,total}$ is the integral from t^- to t^+ of $m_i(t)$.

$$F_{i,total} = \int_{t^-}^{t^+} m_i(t)\ dt \tag{4}$$

In the following two possibilities of computing the total mean $\mu_{i,total}$ and total standard deviation $\sigma_{i,total}$ will be explained: a restricted version and a generalized version. The restricted version requires that the beginning t^- and the end t^+ does not intersect any interval $[b(n), e(n)]$. The generalized version however does not require this.

In the restricted version the total mean of secondary movement is computed by

$$\mu_{i,total} = \sum_{n=1}^{N} \mu_i(n) \tag{5}$$

and total standard variance by

$$\sigma_{i,total} = \sum_{n=1}^{N} \sigma_i(n)^2 \tag{6}$$

according to the way of adding normally distributed random variables.

The mean $\mu_i(n)$ and the standard deviation $\sigma_i(n)$ of the secondary movement of the n-th note refer to the secondary movement accumulated over the time interval $b(n)$ to $e(n)$. In order to compute $\mu_{i,total}$ and $\sigma_{i,total}$ in the generalized form, it is necessary to distribute the values $\mu_i(n)$ and $\sigma_i(n)$ over the continuous time interval given by $b(n)$ to $e(n)$. For this purpose, $\mu_i(n,t)$ and $\sigma_i(n,t)$ are introduced. They are the continuous mean and standard deviation in joint i based on the PAM analysis of the n-th note.
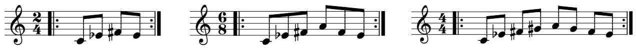
Figure 2: Four-note motif (left), six-note motif (center), and eight-note motif (right)

The distribution of a random variable that is generated by adding normally distributed random variables is also a normally distributed random variable. The mean of the new distribution is given by the sum of the original means, i. e., $\mu_{sum} = \sum_i \mu_i$, and the standard deviation is given by $\sigma_{sum}^2 = \sum_i \sigma_i^2$. In order to distribute the mean and standard deviation computed by PAM over the time interval $[b(n), e(n)]$, the following equations, which are continuous counterparts of the previously discussed formulas, have to be satisfied:

$$\int_{b(n)}^{e(n)} \mu_i(n,t)\ dt = \mu_i(n) \tag{7}$$

$$\int_{b(n)}^{e(n)} \sigma_i(n,t)^2\ dt = \sigma_i(n)^2 \tag{8}$$

Therefore, $\mu_i(n,t)$ and $\sigma_i(n,t)$ are computed in the time interval from $b(n)$ to $e(n)$ as follows:

$$\mu_i(n,t) = \mu_i(n)/(e(n) - b(n)) \tag{9}$$

$$\sigma_i(n,t) = \sigma_i(n)/\sqrt{e(n) - b(n)} \tag{10}$$

Outside the time interval $[b(n), e(n)]$ the continuous mean $\mu_i(n,t)$ and the continuous standard deviation $\sigma_i(n,t)$ are set to zero.

The continuous mean $\mu_i(n,t)$ and the continuous standard deviation $\sigma_i(n,t)$ are needed to handle eventual temporal overlaps between secondary movements. The estimation of the secondary movement of a note n by PAM refers to the time interval $[b(n), e(n)]$. For two notes these time intervals can either be separated in time or overlap. If the time intervals overlap, the secondary movement generated by the two touches are superimposed.

It is now possible to compute the total mean

$$\mu_{i,total} = \int_{t^-}^{t^+} \sum_{k=1}^{N} \mu_i(k,t)\ dt \tag{11}$$

and the total variance

$$\sigma_{i,total}^2 = \int_{t^-}^{t^+} \sum_{k=1}^{N} \sigma_i(k,t)^2\ dt \tag{12}$$

5. EVALUATION

To determine the accuracy of serial analysis, the proposed method was evaluated based on recorded movement with our inertial sensors [10] and MIDI data from a pianist. The pianist played small musical motifs without primary movement of the arm and the same motifs but with forearm rotation movement that was spread over several touches. Since pitch, rhythm, loudness, and articulation can be varied, there exist a prohibitively high number of combinations so that the serial analysis has to be evaluated with exemplary motifs. The used motifs (see Figure 2) were modified according to parameters that have a distinct influence on the movement:

Number of notes: The first motif contained four notes, the second, six, and the third eight notes. The motifs, which were played with the right hand, begin with ascending intervals, which may be played with supination, and end with the equal amount of descending intervals, which may be played with pronation. Since

Table 2: Results of the evaluation

Played / Recognized	Rotation	No rotation
Rotation	96.7%	3.03%
No rotation	2.84%	97.16%

secondary movement is generated through mechanical interaction with the piano action, a greater number of interactions leads to a greater amount of secondary movement, which makes primary movement detection more difficult.

Loudness: When playing louder, the amount of secondary movement is increased because the secondary movement is linked with the amount of mechanical interaction between the arm and the piano action. Therefore, the motifs were played with different loudness: piano, mezzoforte, and forte.

Tempo: The tempo has an effect on the primary forearm rotation. When playing faster, the rotation is performed with greater speed. Furthermore, the overall size of the movement could be reduced at greater speed, which would make primary movement detection more difficult. The motifs were recorded at different tempos. The quarter note was played with 60, 100, 140, and 180 beats per minute. To generate a recording that produces significant overlaps in the analysis, the player also arpeggiated the motifs. The player sustained the highest and lowest note. The ascending and descending intervals were then played in rapid succession.

The mentioned variations result in 45 combinations. Each combination was repeated 10 times with and 10 times without forearm rotation movement so that 900 samples were recorded in total.

In the four-note motif, the following movement was used: The player begins to supinate shortly after playing c. The e flat and f sharp are played while the forearm supinates. Shortly after the note f-sharp is reached, the player reverses the movement direction and plays the e-flat and c with pronation. The six- and eight-note motifs are executed similarly. The player supinates when playing ascending intervals and pronates when playing descending intervals.

To use the method, it is necessary to define the analysis interval $[t^-, t^+]$. For detecting the supination movement, the beginning of the analysis interval t^- was defined halfway between the first and second note of a motif. The end of the analysis interval t^+ is the onset time of the highest note. For detecting pronation movement, t^- and t^+ were placed correspondingly, the beginning of the analysis interval t^+ was defined halfway between the highest note and the following note. The end of the analysis interval t^+ was defined as the onset time of the lowest note.

A primary movement was detected if the total movement $F_{i,total}$ exceeds the total mean $\mu_{i,total}$ more than a four times the total standard deviation $\sigma_{i,total}$, i.e., if $|F_{i,total} - \mu_{i,total}| > c \cdot \sigma_{i,total}$ with $c = 4$. The results are shown in Table 2.

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