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A MULTIDISCIPLINARY STUDY OF PIANOFORTE TOUCH AND TONE QUALITIES

Antonio Somma[1*, 2, 3]   **Jeanne Roudet**[2]   **Benoît Fabre**[3]

[1] Institut Collegium Musicæ, Sorbonne Université, France
[2] Institut de Recherche en Musicologie, CNRS, Sorbonne Université, France
[3] LAM, Institut Jean Le Rond ∂'Alembert, CNRS, Sorbonne Université, France

ABSTRACT

Historical pianos ("pianofortes") from the Romantic era differ significantly from what is commonly thought of as the standard modern piano in terms of construction as well as touch and tone qualities. Such a difference, as historically informed practice on pianoforte has demonstrated in recent decades, has its roots in a musical framework vastly different from ours. Any evaluation of its qualities requires a thorough understanding of the aesthetic aspirations and technical resources that characterized pianism at the time. The purpose of this research is to investigate the interaction between pianist and piano based on its construction parameters. The nature of such interaction was modeled using a comparative analysis of documentary sources on piano technique that were either "modern" or "historical" (and "historically informed"). A "mechanical arm" was thus built, capable of delivering motion at the front of a piano key depending on its moment of inertia and the applied force. Thus, the intensity of sound was investigated as a function of applied force and average key downward velocity. The findings show consistency in the degree of variation in the construction parameters of a pianoforte and a modern piano and differences in respective techniques, due to differences in aesthetic aspirations.

Keywords: *piano, pianoforte, musicology, performance studies, historically informed practice.*

Corresponding author:
antonio.somma@dalembert.upmc.fr.

1. INTRODUCTION

The term "touch" in piano playing refers to the complex relationship that pianists establish between their bodies and the instruments they play, in order to express themselves. Studies about the physics of piano touch confine the wide significance of such an expression to the extent of finger-key motion, focusing on the usual separation between "pressed touch" – when the finger motion starts at the key surface – and "struck touch" – when the finger hits the piano key with non-zero velocity – [1] with a strong emphasis on acoustically salient aspects [2]. These studies suggest that touch plays a minor role in the production of single piano tones at a given loudness. Despite some conjecture that the hammer's vibrations might alter the "timbre" of the sound created [3], the pianist's capacity to exercise deliberate and robust control over it through touch has never been proven. As a consequence, researches on the biomechanics of pianists examine touch as decoupled from its effect on tone production and mainly intend it as a means of minimizing fatigue and musculoskeletal disorders. To this aim, they advocate the use of struck touch, thought of as the most efficient [4]. Finally, research on the expressive scope of pianists' gesture is based on the assumption that it plays a negligible role in controlling single tone production [5].

The dramatic impact of the piano used and the pianists' schools is rarely emphasized. For their part, all piano schools strive for touch mastery. However, bodily involvement varies greatly depending on the school. While some relatively modern schools advocate for the pianist's upper limbs to be fully engaged, historically informed playing, confronted with lighter keyboards, necessitates fine control of movement.

The work of pianist, teacher and theorist Rudolf M. Breithaupt (1873-1945) *Die natürliche Klaviertechnik* ("The Natural Piano Technique" [6]), is representative of a style of touch that encourages the use of the "weight" of the arm segments. By using increasingly large masses, his technique aims to minimize the cost-benefit ratio between muscle fatigue and the intensity of the sound produced.

The ideas collected in Breithaupt's books were seen as the culmination of an effort to overcome the "old school" of piano playing. According to a popular belief, this process, thought once to be heuristic and now based on physiology and supported by knowledge of how piano action works, would have defeated an almost entirely digital technique characterized by immobility and rigidity beyond the elbow. Nevertheless, restoring justice to the 19th-century touch is one of the major challenges in contemporary historically informed practice [7].

This paper aims to study an English pianoforte by William Stodart (ca 1820-1826), a hitherto neglected species of instrument in the field of musical acoustics. English and modern pianos – of the type attested from the turn of the 19th century onward – were long thought to be so alike that they could be assimilated [8]. However, among other very specific touch and tone qualities, pianofortes of this Stodart's type have in fact a fairly light keyboard compared to modern instruments [9]. No characterization of modern [1] and ancient [10, 11] pianos has so far attempted to retrieve the aesthetic significance of their construction parameters by describing the role of pianist's dynamic control over single tone production, which is the purpose of the present paper. Such an attempt demands to stand at the frontier of all the fields of studies mentioned above. Moreover, it must be preceded by a thorough understanding of a style of touch chronologically consistent with the Stodart period.

Carl Czerny's (1791-1857) pedagogical works are considered among the most valuable sources in historical piano performance studies. They allow us to reconstruct the fundamentals of piano touch in the 19th century. A comparative musicological analysis of the thought of Breithaupt and Czerny reveals a distance in the aesthetic aspirations underlying their ideas about touch (Section 2). The effect on tone production of different styles of touch can be compared on the common ground of a simplistic physical model of how a pianist controls a single keystroke, as far as tone production is concerned. The control parameters of such a model were retrieved from the descriptions of touch given in Breithaupt's treatises (Subsection 3.1). A "mechanical arm" has been devised for driving the piano keys. Its description is given in Subsection 3.2. Measurements were made on the Stodart pianoforte to observe how adjusting the retrieved control parameters affects tone production (Subsection 3.3). The results are discussed in the last part of the paper.

2. MUSICOLOGICAL INSIGHT

Rudolf Maria Breithaupt's publications were so well received that they establish him as a significant representative of the novel ideas about piano technique that had begun to emerge, particularly in the German region, since the end of the 19th century. His work is without a doubt the piano method of its kind with the most echo of his time, as shown by the popularity of the best-known translations, French and English, of the second part of his work, "*Schule des Gewichtspiels*" or "School of Weight-Touch" [12]. [1] His treatise stands out as the most remarkable effort at positivist systematization of concepts dear to early 20th-century pianism: those, inextricably linked, of "weight" and "relaxation". The ideal of a "natural" piano technique, avowedly based on physiology, which fell under the association of these two terms within the vocabulary of piano technique, was so deeply rooted in the spirit of the time that it was unhesitatingly traced back to such illustrious and unlikely prophets as Anton Rubinstein (1829-1894) and even Franz Liszt (1811-1886). Ferruccio Busoni (1866-1924), who endorsed Breithaupt and recognized his own experience in the theorist's work, seems to have first introduced the term "weight", meaning the conscious use of gravity in piano technique. Busoni and the entire German intelligentsia of the time were captivated by the philosophical idea that natural laws governed musical activity. Breithaupt intended to synthesize this fundamental ideal with an anchoring in piano practice and musical common sense, with an effort that was sometimes clumsy but never equaled. Effort that has been rewarded, for the terms "weight" and "relaxation" and their association, as well as the belief in the importance of relaxation in preventing muscle fatigue and improving touch, have now entered variously into world-wide piano language.

Breithaupt claims that the "old" finger technique, which engages small muscles, is obsolete, as the new instruments and music halls of his time require abnormal efforts to deliver enough sound volume towards the audience. Stating that the tone volume is a pure function of the "load" ("*Be-*

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[1] Refer to [13, pp. 329–59] and [14, pp. 625–47] for an exposition of Breithaupt's thought and its reception.

lastung") required to achieve it, he advocates the "weight force" ("*Schwerkraft*") of the arm, loosely hanging from the shoulder, as the fundamental keystroke force in piano technique. It produces a "throw" ("*Wurf*")[2] movement and provides enough sound intensity for ordinary piano playing. According to Breithaupt, the throw movement saves active muscle work, with an associated "relaxation" that reduces joint friction. Throw movements from the elbow or wrist, capable of lesser tones, are also permissible, as long as care is taken to use progressively larger arm segments as the dynamics increase.

The pedagogical work of Viennese pianist Carl Czerny, still a noteworthy source in most piano schools today, provides authoritative documentation of the so-called "digital" piano technique of the first half of the 19th century that, less than a century later, would be criticized by the proponents of the "natural" technique. Czerny's brief apprenticeship under Beethoven profoundly influenced the aesthetic-stylistic vision that permeates the pages of his monumental library on piano teaching. His 1839 *Pianoforte-Schule* [15], translated the same year into French, English and Italian, had a wide following throughout Europe; a similar impact had his teaching influential students from diverse backgrounds, such as Teodor Leschetizky (1830-1915), Alfred Jaëll (1832-1882), and the aforementioned Liszt.[3]

In line with 19th-century pedagogy's strong focus on practice, in Czerny's thought the achievement of technical-expressive exercises provides the student with the bodily resources needed to master them. In particular, Czerny develops the problem of *piano* and *forte* as an expressive one, to which he devotes a revealing introduction in the third volume "*von dem Vortrage*" ("On Playing with Expression") of his *Pianoforte-Schule* [15, 3:1-5]. The goal of his method is to train "clumsy" ("*ungeschickte*") and "gross" ("*plumpe*") fingers to control the hundred and more different degrees of tone that can be obtained from a single piano note.

The various ways of articulating the problem of the piano dynamics testify to the different aesthetic aspirations of two such different piano techniques. While Breithaupt's goal is to use the body's resources as efficiently as possible in order to achieve maximum sound intensity with the

minimum effort, Czerny's goal is to master nuances, that is, the dynamic sensitivity of the pianist-piano system, for expressive purposes.

3. METHODS

The following section describes the determination of a simple, controllable and repeatable experimental protocol, capable of reproducing the most salient effects of pianists' bodily involvement on tone production. Breithaupt's positivist formulation of the pianist's movement aimed at tone production allows us to infer a model from his discourse. The human upper limb has been modeled here in a simpler way than state-of-the-art in biomechanics [16]. It will be considered as a two-dimensional chain of levers, whose masses are constant, with perfectly loose – i.e., frictionless – or perfectly rigid joints. Furthermore, it is assumed that sets of more proximal levers can remain virtually immobile while more distal levers are set in motion. Despite its simplicity, this model allows us to retrieve the significant control parameters involved in the actuation of a piano key, which ultimately produces a sound. The behaviour of the "mechanical arm", an actuation tool designed for measurements, mirrors the proposed model. The species of key actuation aimed at measurements, namely the choice of set of values for the retrieved control parameters, is similarly informed by the ideal control strategy advocated in Breithaupt's treatise.

3.1 A Model for Controlling Tone Production

In his treatise [12], Breithaupt introduces a systematic array of parameters, describing the forces ("*Kräfte*") and movements ("*Bewegungen*") involved in tone production. Among these parameters, to the extent of describing a "throw" movement starting at the surface of the keyboard – what might be called a "pressed weight touch" – we have selected the "weight of the [engaged] mass" ("*Schwer der Masse*") and the "retention" ("*Hemmung*") of free energy release through gravity, via the use of antagonistic muscles in the shoulder. According to Breithaupt, pianists can voluntarily control muscular retention, resulting in a gradual reduction of sound volume.

Below, we propose a simplistic picture that takes into account only movements made through the application of weight force, varying the two parameters of the "mass" put into motion and the degree of "retention" applied by the muscles in order to reduce the force effectively acting on the key. The depression of a piano key, of depth D, can thus be seen as produced by the rigid rotation of the Nth

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[2] Although the term "fall" is more commonly used than "throw" to describe this type of keystroke, we have chosen the latter to follow Breithaupt, who rejects the former because it lacks the concept of "living motor force". [6, p. 46].

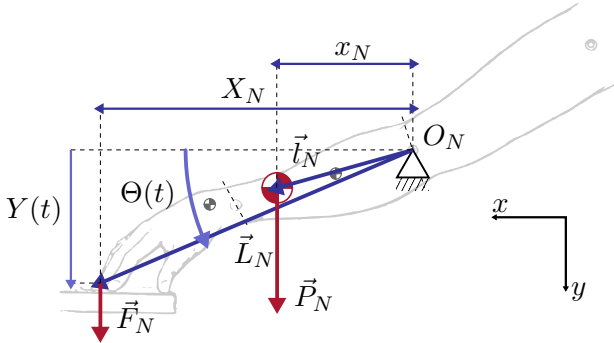[3] Refer to [14, pp. 244–54] for further details.

Figure 1: The control model in the case of rotation around the elbow ($N = 2$). Arm sketch from [12, p. 23].

arm segment around the fixed pivot O_N – $N = 1, 2, 3$ meaning, in distal-proximal order, hand around wrist, hand plus forearm around elbow, or the whole arm around shoulder. As shown in Fig. 1, the weight $\vec{P}_N$ of the engaged segment set in rotation, applied at its center of mass $\vec{l}_N$ with respect to O_N, is transmitted onto the key surface as an equivalent downward force of modulus F_N, applied at $\vec{L}_N$ with respect to O_N. The actual force on the key can vary from zero to F_N, depending on the muscular retention applied. Therefore, the control parameters involved in tone production are the key depression force F, which ranges from zero to its maximum F_N, and the engaged rotational inertia, or equivalent inertia of the actuator, M_N. F_N and M_N can be estimated by knowing the mass distribution of the engaged segment and its geometry. With reference to Fig. 1, the static downward force F_N, observed at the finger-key contact point at equilibrium, is given by the following expression:

$$F_N = \frac{x_N}{X_N} \left| \vec{P}_N \right|, \tag{1}$$

where x_N and X_N are the x-components of $\vec{l}_N$ and $\vec{L}_N$ respectively. We now free the endpoint of the arm segment (i.e., the fingertip). The equation of motion for the rigid rotation of the unconstrained segment is written:

$$J_N \ddot{\vec{\Theta}}(t) = \vec{l}_N \wedge \vec{P}_N, \tag{2}$$

where J_N is the moment of inertia of the engaged segment, relative to its center of rotation O_N, and $\ddot{\vec{\Theta}}(t)$ its rotation vector, clockwise in Fig. 1. The above vector Equation 2 projects onto an y-component expression of

the form $M_N \ddot{Y}(t) = F_N$. If F_N is imposed as the static force in (1), it leads to:

$$M_N = \frac{J_N}{X_N^2}. \tag{3}$$

The control parameters F_N and M_N are assumed constant during the motion in the limit of small rotations ($X_N \gg D$).

In the following, the piano key will be viewed as driven by a mechanical actuator whose equivalent inertia, "felt" at the key front, is M, through the application of a constant downward force F. The actuation motor work $W \equiv FD$ imparts kinetic energy to the key and, through the velocity of the hammer at the time of string contact, indirectly causes vibration at the piano soundboard, producing sound. Following [1], we expect that our measurements will confirm that the average downward key velocity V (which is roughly proportional to the inverse of the key depression time) is strongly correlated to the maximum hammer velocity for a pressed touch, and that the sound intensity can be expressed as a monotonic function of V.

3.2 The Mechanical Arm

The "mechanical arm" is an actuation and measurement tool designed to press piano keys. Despite its conceptual similarity to the one described in [17], it has been modified in order to allow for independent control of the equivalent actuation force, F, and the equivalent inertia, M, engaged by the system. It is essentially a lever, pivoted around a fixed point (see Fig. 2). Its equivalent "weight" at any end, in the spirit of a Roman balance, varies with the position of appropriately suspended masses along either lengths of its two sides. This instrument applies a known force at the point where its "finger" is laid. It is equipped with an electromagnetic triggering system to control the initial conditions of its rotation. For example, the mechanical arm is initially in horizontal position and in contact with the key, which is not pressed. Its displacement is then triggered by turning off a DC generator, delivering the magnetic force that initially holds it stationary.

With reference to Fig. 2, following a procedure such as in Subsection 3.1, one can determine the "finger" force of the mechanical arm F and its equivalent inertia M. They depend on the suspended masses m_1 and m_2 and their
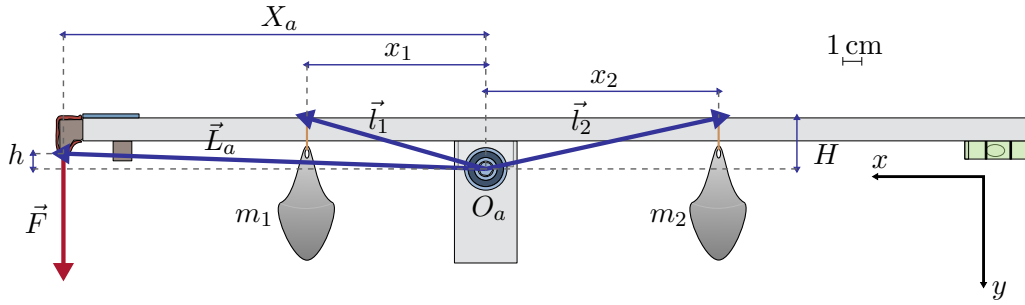
Figure 2: The prototype sketch of the devised mechanical arm, allowing the application of a downward force $\vec{F}$ at its "finger" (left end in the figure).

Table 1: The estimated equivalent weight F_N and equivalent inertia M_N for the three considered engaged arm segments: 1) Hand, rotating around the wrist joint; 2) Hand plus forearm, rotating around the elbow joint; 3) The whole arm, rotating around the shoulder joint.

N		F_N [gram-force]	M_N [grams]
1	("Wrist")	170	147
2	("Elbow")	664	460
3	("Shoulder")	1283.5	921

horizontal positions, x_1 and x_2 respectively:

$$F(m_1, m_2, x_1, x_2) = \frac{m_1 x_1 - m_2 x_2}{X_a} g, \qquad (4)$$

$$M(m_1, m_2, x_1, x_2) = \frac{J_a}{X_a^2} + \sum_{i=1}^{2} m_i \left(\frac{x_i}{X_a}\right)^2, \qquad (5)$$

where g is the acceleration of gravity and J_a is the moment of inertia of the lever with respect to O_a – the torque due to the lever weight is negligible by design, as the x-position of its center of mass is the same as O_a.

3.3 Measurement Protocol

In accordance with Breithaupt's picture, we gathered information about a possible configuration of a pianist's arm during a keystroke through an illustration found in his method (see Fig. 1). The estimation of the control parameters, based on Equations 1 and 3, is based on the anthropometric measurements proposed in [18] for the first author's upper limb. The results are reported in Tab. 1. [4]

In the Stodart keys actuation, we realized three isoinertial species of actuation, each of which has the equivalent actuator inertia M constant and equal to the three values of equivalent inertia of the engaged arm segment M_N, reported in Tab. 1. Then, the force of actuation F is set to vary between zero and the equivalent weight of the engaged arm segment F_N, reported in Tab. 1 as well. These three species of actuation are referred to as "Shoulder", "Elbow" and "Wrist".

We measured the key downward motion via a Fiberoptic Displacement Sensor, placed at a fixed distance from the key pivot. The measured signal, lasting 2.5 seconds, was hence scaled to obtain the displacement of the key front. The key displacement D was estimated as the difference between 10% and 90% displacements with respect to the difference of the key start and stop positions (see Fig. 3). Finally, the average key velocity was estimated as the ratio of the displacement D to its duration T. The tone produced was measured through the mean signal coming from a pair of microphones, placed about 30 cm above the piano soundboard. From the acoustic pressure signal, the tone volume L was estimated as the maximum of its time-varying loudness [19].

4. RESULTS AND DISCUSSION

Preliminary measurements carried on two extreme notes of the Stodart pianoforte, C_2 (two octaves below the middle C of piano keyboards) and F_6, allow us to draw some interesting conclusions. As it can be seen in Fig. 4, the

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[4] Note that forces are expressed in gram-force in this article, in line with the tradition of expressing "touch weight" in pianos in grams.
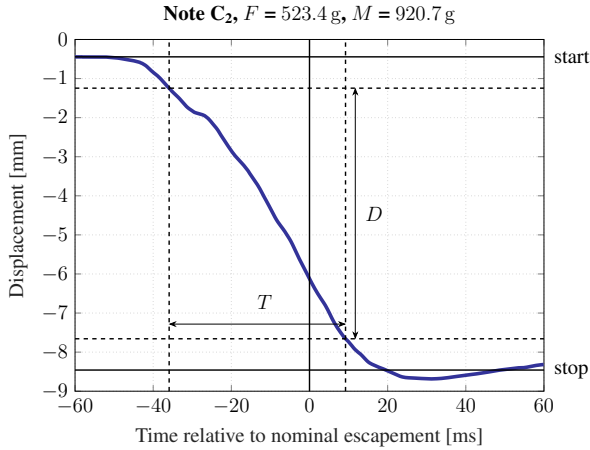
Note C$_2$, $F = 523.4\,\text{g}$, $M = 920.7\,\text{g}$

Figure 3: Graphic display of the retrieving process for the key displacement D and its duration T. The signal is windowed at $60\,\text{ms}$ before and after the nominal escapement time for the sake of readability.
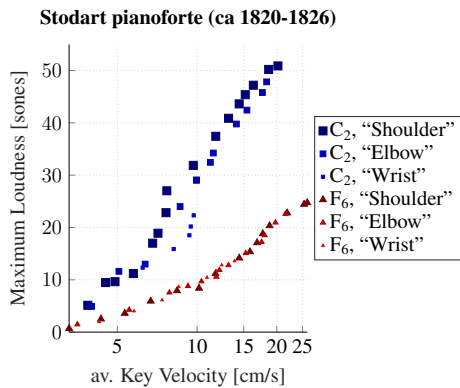

Figure 4: Maximum Loudness as a function of Average Key Velocity, for the two notes C$_2$ and F$_6$.

Table 2: Sensitivity of the squared average key velocity to the actuation work, $S \equiv d\left(V^2\right)/dW$ (expressed in kg^{-1}), estimated as the slope coefficients of the linear regressions shown in Fig. 5.

	C$_2$	F$_6$
"Wrist"	2.0(3)	3.4(4)
"Elbow"	1.39(7)	1.58(4)
"Shoulder"	0.77(3)	1.14(5)

tone volume L of a piano key note merely depends on the average velocity V reached by the key: $L = L(V)$. It does not depend on the species of actuation, that is, the actuation work W and the actuation inertia M that produced V.

Instead, when observing the squared average velocity as a function of the motor work, the effect of engaging different amounts of equivalent inertia becomes apparent (see Fig. 5). The measured points split into three distinct linear curves, depending on the actuation species. We recall Breithaupt's claim that engaging increasing masses allows more intense tones to be delivered. The geometry of the arm and its mass distribution are such that his statement, according to our observations, holds true. Nevertheless, by reducing the equivalent inertia M of the actuator, two main effects can be observed: first, higher average velocities V (i.e., louder sounds) can be reached for the same motor work W; second, the slope of the curves $S \equiv d\left(V^2\right)/dW$, estimated via a simple linear regression, increases. Key inertia also seems to play a significant role, since the lower note C$_2$, having a heavier hammer, shows lower slopes than the higher F$_6$ (see Tab. 2). Given the indirect dependence of L on the actuation work W through V, a salient acoustic parameter is the sensitivity of the sound intensity to changes in W at a given velocity (i.e., a given sound volume):

$$\left(\frac{dL}{dW}\right)_V = \frac{L'(V)}{2V}\,S. \tag{6}$$

This latter increases as the inertia of the key-actuator system is reduced.

5. CONCLUSIONS

The present paper aimed to determine the framework for a multidisciplinary study of an English pianoforte, dating
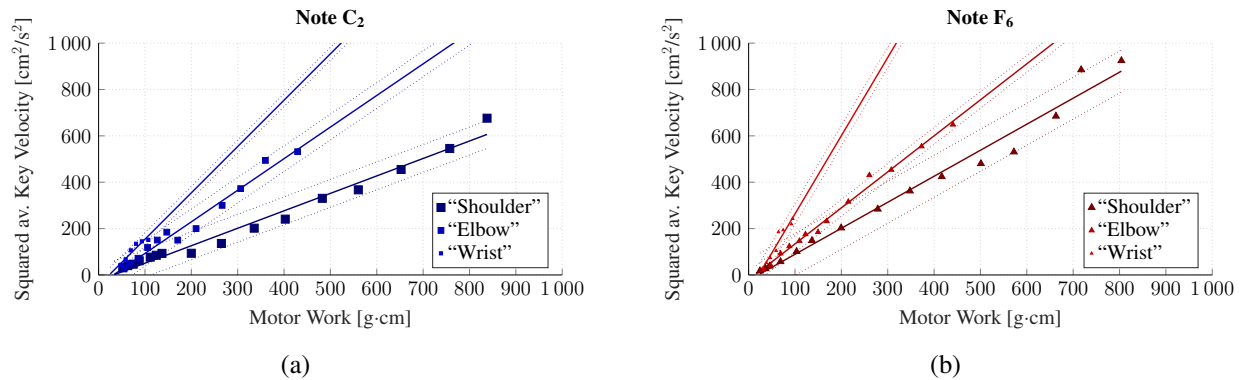
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Figure 5: Squared Average Key Velocity as a function of the actuation Motor Work, for the three notes (a) C_2, (b) F_6 for the three isoinertial species of actuation ($M = 921\,\mathrm{g}$ for 'Shoulder', $M = 460\,\mathrm{g}$ for 'Elbow', $M = 147\,\mathrm{g}$ for 'Wrist'). The dashed lines show 95%-confidence interval of the linear fit.

from the first half of the 19th century. We sought to recover the salience of its construction parameters through observation of the relationship between the control parameters that pianists modulate in making a "pressed" keystroke and their effects on tone production. We derived the control parameters from the analysis of keystroke movements descriptions found in the method of Rudolf M. Breithaupt, an advocate of the so-called "weight touch". The conclusion of the latter analysis shows the significance for pianists to describe touch aimed at tone production through bodily dynamics. In other words, pianists' discourse encourages introducing the force applied to the key surface and the inertia that is engaged during keystroke as mechanical control parameters relevant in tone production. This broadens the scope of the description of touch and its effects on tone production in the field of mechanics, as intended by pianists.

The preliminary observations outlined in this paper illustrate the consequences on tone production of touch types that engage pianists' bodies differently. They showed the richness inherent in pressed touch, which remains invisible in a kinematic framework. The sound sensitivity to the applied force (or to the motor work done) seems to be a salient acoustical parameter for describing the effects of this variety. While the key actuation protocol was inspired here by a weight-based control strategy, it is possible to generalize the conclusions of the present work to the case of an actuation strategy based on muscle activity. Such a control strategy could also allow more intense sounds to be achieved by engaging less inertia. In fact, the observations seem to suggest that the control strategy

through "weight playing", aimed at loudness, does not fit well with very light keyboards, which favor playing aimed at sensitivity. In Section 2 we attested to a similar discrepancy between the aesthetic aspirations underlying the relatively modern "weight" technique and the allegedly "digital" technique, as typified by the 19th-century pedagogue Carl Czerny: the first strives for sound intensity at minimum cost, while the latter aims to master the control of subtle variations in tone. Thus, the aesthetic relevance of the lightness of historical keyboards, as compared with modern standards, becomes apparent: it underlies a style of touch that has been obscured by the heavier modern keyboards.

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