Touch and temporal behavior of grand piano actions

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This study investigated the temporal behavior of grand piano actions from different manufacturers under different touch conditions and dynamic levels. An experimental setup consisting of accelerometers and a calibrated microphone was used to capture key and hammer movements, as well as the sound signal. Five selected keys were played by pianists with two types of touch ("pressed touch" versus "struck touch") over the entire dynamic range. Discrete measurements were extracted from the accelerometer data for each of the over 2300 recorded tones (e.g., finger–key, hammer–string, and key bottom contact times, maximum hammer velocity). Travel times of the hammer (from finger–key to hammer–string) as a function of maximum hammer velocity varied clearly between the two types of touch, but only slightly between pianos. A travel time approximation used in earlier work [W. Goebl, J. Acoust. Soc. Am. **110**(1), 563–572 (2001)] derived from a computer-controlled piano was verified. Constant temporal behavior over type of touch and low compression properties of the parts of the action (reflected in key bottom contact times) were hypothesized to be indicators for instrumental quality.

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I. INTRODUCTION

The universe of expressive music to be played on the modern grand piano[1] is produced by sophisticated acceleration of the (usually) 88 keys, none of which travels through a distance greater than one centimeter, combined with the use of the pedals. The piano action provides the pianist the only point of contact to the strings; it is therefore both an extremely important as well as a highly elaborate and complex mechanical interface. It allows accurate control over the speed at which the hammer arrives at the strings over a vast dynamical range from the very pianissimo to the ultimate fortissimo. Since not only the intensity of tone, but also the precise onset timing of the outcoming sound is crucial to expressive performance, it can be assumed that trained pianists are intuitively well acquainted with the temporal behavior of a piano action, and that they take it into account while performing expressively.

The piano action functions as follows: The movement of the key is transferred to the hammer via the whippen, on which the jack is positioned so that it touches the roller (knuckle) of the hammer shank. During a keystroke, the tail end of the jack is stopped by the escapement dolly (let-off button, jack regulator) causing the jack to rotate away from the roller, and thus breaking the contact between key and hammer. From this moment, the hammer travels to the strings with a small deceleration due to gravitation and friction, strikes them, and rebounds from them ("free flight of the hammer").

The roller falls back to the repetition lever, while the hammer is caught by the back check. For a fast repetition, the jack slides back under the roller when the key is only released half-way, and the action is ready for another stroke. More detailed descriptions of the functionality of grand piano actions can be found in the literature (Askenfelt and Jansson, 1990b; Fletcher and Rossing, 1998, pp. 354–358).

A. Temporal properties of the piano action

Temporal aspects of the piano action have been investigated recently by Askenfelt and Jansson (1990a,b, 1991).[2] The time interval from the key's initial position to key bottom contact ranges from about 25 ms at a *forte* keystroke (approximately 5 m/s FHV) to 160 ms at a *piano* tone (or 1 m/s final hammer velocity FHV, Askenfelt and Jansson, 1991, p. 2385).[3] In a grand piano, the moments of hammer contact (when the hammer excites the strings) are temporally shifted in comparison to key bottom contact. Hammer contact occurs 12 ms before key bottom contact at a *piano* tone (1 m/s FHV), but 3 ms *after* the key bottom contact at a *forte* attack (5 m/s FHV, Askenfelt and Jansson, 1990a, p. 43). However, Askenfelt and Jansson (1990a,b, 1991) provided measurement data solely for a few example keystrokes.

The timing properties of the piano action can be modified by changing the regulation of the action. Modifications, e.g., in the hammer–string distance or in the *let-off distance* (the distance of free flight of the ham-

mer, after the jack is released by the escapement dolly), alter the timing relation between hammer–string contact and key bottom contact or the free flight time, respectively (Askenfelt and Jansson, 1990b, p. 57). Greater hammer mass in the bass range (Conklin, 1996, p. 3287) influences the hammer–string contact durations (Askenfelt and Jansson, 1990b), but not the timing properties of the action.

Data on timing properties of a baby grand piano action were provided by Repp (1996) who worked with a Yamaha Disklavier (Mark II series, similar to the one used in the present study) on which the "prelay function" was not working.[4] This gave him the opportunity to measure roughly a grand piano's travel time characteristics. He measured onset asynchronies at different MIDI velocities in comparison to a note with a fixed MIDI velocity in the middle register of the keyboard. The time deviations extended over a range of about 110 ms for MIDI velocities between 30 and 100 and were fit well by a quadratic function (Repp, 1996, p. 3920).

A function similar to the Disklavier's prelay function was obtained from a Bösendorfer SE290 computer-controlled grand piano by Goebl (2001). He accessed data from an internal memory chip of the SE system that presumably stored information on the travel time intervals for each of the 97 keys and seven selected FHVs. An average travel time function (against FHV) was derived from these data (Goebl, 2001, Fig. 5, p. 568). It was applied to predict the amounts of note onset asynchronies to be expected at given dynamic differences between the voices of a chord.

There have been several attempts to model piano actions (Gillespie, 1994; Gillespie and Cutkosky, 1992; Hayashi *et al.*, 1999), also for a possible application in electronic keyboard instruments (Cadoz *et al.*, 1990; Van den Berghe *et al.*, 1995). Gillespie and colleagues developed a virtual keyboard that simulates the haptic feel of a real grand piano action using motorized keys (Gillespie, 1994; Gillespie and Cutkosky, 1992). Van den Berghe *et al.* (1995) performed measurements on a grand piano key with two optical sensors for hammer and key displacement and a strain gauge for key force. Unfortunately, they provided only a single exemplary keystroke of their data. Hayashi *et al.* (1999) tested one piano key on a Yamaha grand piano. The key was hit with a specially developed key actuator able to produce different acceleration patterns. The displacement of the hammer was measured with a laser displacement gauge. They developed a simple model and tested it in two touch conditions (with constant key velocity and constant key acceleration). Their model predicted the measured data for both conditions accurately.

B. Different types of touch

While physicists and technicians argue that the sole factor that controls the sound and the timbre of the piano is the hammer velocity at which the hammer hits against the strings (Hart *et al.*, 1934; Seashore, 1937; White, 1930), it is of extraordinary importance for pianists, how they touch and accelerate the keys. As Ortmann (1929, p. 3) puts it: "The complex problem of physiological mechanics as applied to piano technique re-solves itself finally, into one basic question: the variations of force produced at the key-surface by the player." And in order to produce the forces at the key surface that entail a particular desired musical outcome, pianists have to practice for decades. Over this time period, they develop a tacit tactile knowledge of how piano actions behave under the various physical forces they apply to it. Thus, an integral part of what pianists perceive from a piano is the haptic-tactile response of the keys (including particularly key resistance and inertia) in relation to the physical force they apply and to the acoustical result they hear (Galembo, 2001).

An article in Nature by Bryan (1913) was the starting point of a lively discussion on piano touch. Bryan puts the "single-variable hypothesis" (the timbre of a piano tone determined solely by FHV) into question with rudimentary experiments performed with a player-piano. His contribution entailed a discussion of 6 Letters to the Editor and 3 further replies by Bryan (all to be found in *Nature*, Volumes 91–92, 1913).

A first profoundly scientific investigation to this controversy contributed Otto Ortmann from the Peabody Conservatory of Music in Baltimore (Ortmann, 1925). He approached the "mystery of touch and tone" at the piano through physical investigation. With a piece of smoked glass mounted on the side of a piano key and a tuning fork, he was able to record and to study key depression under different stroke conditions. He investigated various kinds of keystrokes ("percussive" versus "non-percussive," different muscular tensions, and positions of the finger). He found different acceleration patterns for non-percussive (finger rests on the surface of the key before pressing it) and percussive touch (an already moving finger strikes the key). The latter starts with a sudden jerk, thereafter the key velocity decreases for a moment and increases again. During this period, the finger slightly rebounds from the key (or vice versa), then re-engages the key and "follows it up" (p. 23). On the other side, the non-percussive touch caused the key to accelerate gradually.

Ortmann (1925) found that these different types of touch provide a fundamentally different kind of key control. The percussive touch required precise control of the very first impact, whereas with non-percussive touch, the key depression needed to be controlled up to the very end. "This means that the psychological factors involved in percussive and non-percussive touches are different" (p. 23). "In non-percussive touches key resistance is a sensation, in percussive touches it is essentially an image" (p. 23, footnote 1). His conclusions were that different ways of touching the keys produced different intensities of tones, but when the intensity was the same, also the quality of the tone must be the same. "The quality of a sound on the piano depends upon its intensity, any one degree of intensity produces but one quality, and no two degrees of intensity can produce exactly the same quality" (p. 171).

The discussion was enriched by introducing the aspect of different noises that emerge with varying touch (Báron and Holló, 1935; Cochran, 1931). Báron and Holló (1935) distinguished between "Fingergeräusch" (finger noise) that occurs when the finger touches the key (which is ab-

sent when the finger velocity is zero as touching the key — in Ortmann's terminology "non-percussive touch"), "Bodengeräusch" (keybed noise) that emerges when the key hits the keybed, and "Obere Geräusche" (upper noises) that develop when the key is released again (e.g., the damper hitting the strings). As another (and indeed very prominent) source of noise they mentioned the pianist's foot hitting the stage floor (or the pedals) in order to emphasize a fortissimo passage. In a later study, Báron (1958) advocated a broader concept of tone quality, including all kinds of noise (finger–key, action, and hammer–string interaction), which he argued to be included into concepts of tone characterization of different instruments (Báron, 1958).

More recent studies investigated these different kinds of noise that emerge when the key is struck in different ways (Askenfelt, 1994; Koornhof and van der Walt, 1994; Podlesak and Lee, 1988). The hammer–impact noise ("string precursor") arrives at the bridge immediately after hammer–string contact (Askenfelt, 1994) and characterizes the "attack thump" of the piano sound without which it would not be recognized as such (Chaigne and Askenfelt, 1994a,b). This noise is independent of touch type. The hammer impact noises of the grand piano do not radiate equally strongly in all directions (Bork *et al.*, 1995). As three dimensional measurements with a two-meter Bösendorfer grand piano revealed, increased noise levels were found horizontally towards the pianist and in the opposite direction, to the left (viewed from the sitting pianist), and vertically towards the ceiling.

Before the string precursor, another noise component could occur: the "touch precursor," only present when the key was hit from a certain distance above ("staccato touch," Askenfelt, 1994). It precedes the actual tone by 20 to 30 ms and was much weaker than the string precursor (Askenfelt, 1994). Similar results were reported by Koornhof and van der Walt (1994). They called the noise prior to the sounding tone "early noise" or "acceleration noise;" it occurs closely in time with finger–key contact. They performed an informal listening test with four participants. The two types of touch ("staccato touch" with the early noise and "legato touch") could be easily identified by the listeners, but not anymore with the early noise removed. Unfortunately, no further systematic results were reported (Koornhof and van der Walt, 1994).

In a recent perception study (Goebl *et al.*, 2004), musicians could hardly identify what type of touch piano tone samples were played when the finger–key noises were included (only half of them rated significantly better than chance), but not at all, when finger–key noises were removed from the stimuli. This evidence suggests that finger–key noise, which occurs only with a percussive ("struck") touch, is responsible for pure aural touch recognition.

The different kinds of touch also produced different finger–key touch forces (Askenfelt and Jansson, 1992b, p. 345). A *mezzo forte* attack played with "staccato touch" typically has 15 N, very loud such attacks show peaks up to 50 N (*fortissimo*), very soft touches go as low as 8 N (*piano*). Playing with "legato touch," finger–key forces of about one third of those obtained with "staccato touch" are found, usually having a peak when the

key touches the keybed. At a very *pianissimo* tone, the force hardly exceeds 0.5 N.

In the piano acoustics literature, there are other ways of categorizing touch, as e.g., Suzuki (2003) who introduced a "hard–soft" antagonism, relying on a professional pianist's intuition how this distinction is realized on the piano. However, he did not control for this variable (human factor) in his experiments.

In the present study, two prototypical types of depressing the keys are used based on the criterion of the finger's speed when beginning the keystroke. These two types ("struck touch" and "pressed touch") are identical to the categories introduced by Askenfelt and Jansson (1991). However, the terminology was deliberately changed from "legato–staccato" (that was also used in earlier studies by the authors, i.e., Goebl and Bresin, 2003a,b; Goebl *et al.*, 2003) to "pressed–struck" (Goebl *et al.*, 2004) in order to draw a clear distinction between terms referring to touch and those referring to articulation (that is the length of each tone relative to its nominal value in the score, thus referring to the connection of tones). Especially in conversations with performing musicians, they get very quickly confused by "legato–staccato" used in a double sense. Nevertheless, there might be parallels between these two meanings of "legato–staccato." E.g., articulated and short tones may be more likely played with a struck touch and legato tones smoothly overlapping with each other might be more likely played from the key surface (pressed touch). However, these parallels occur only in very typical situations; pianists will have no difficulty in producing opposite examples, e.g., a short staccato tone played with a pressed touch and vice versa.

II. AIMS

The present study aimed to collect a large amount of measurement data from different grand pianos, different types of touch, and different keys, in order to determine and provide benchmark functions that may be useful in performance research as well as in piano pedagogy. The measurement setup with accelerometers was similar to that as used by Askenfelt and Jansson (1991). However, in order to obtain a large and reliable data set, the data processing procedure and the reading of discrete values was automated with purpose-made computer software. Each of the measured notes was equipped with two accelerometers monitoring key and hammer velocity. Additionally, a microphone recorded the sound of the piano tone. With this setup, various temporal properties were determined and discussed (travel time, key bottom time, time of free flight). Moreover, the speed histories of both key and hammer revealed essential insights into the fundamentally different nature of the two types of touch examined in this study.

In a study on tone onset asynchronies in expressive piano performance ("melody lead," Goebl, 2001), finger–key onset times were inferred from the hammer–string onset times through an approximation of the travel times of the hammer (from finger–key to hammer–string contact) as a function of FHV. This travel time function was obtained from data of an internal chip of a Bösendorfer SE290 reproducing system. The present study addition-

ally aims to reconsider that approximation.

III. METHOD

A. Material

Three grand pianos by different manufacturers were investigated in this study. Two of them were computer-controlled pianos, the same as in an earlier study (Goebl and Bresin, 2003b).

1. **Steinway grand piano,** (model C, 225 cm, serial number: 516000, built in Hamburg, Germany, in 1989),[5] situated at the Dept. of Speech, Music, and Hearing (TMH) at the Royal Institute of Technology (KTH) in Stockholm, Sweden.

2. **Yamaha Disklavier grand piano** (DC2IIXG, 173 cm, serial number: 5516392, built in Japan, approximately 1999), situated at the Dept. of Psychology at the University of Uppsala, Sweden.

3. **Bösendorfer computer-controlled grand piano** (SE290, 290 cm, internal number: 290–3, built in Vienna, Austria, 2000), situated at the Bösendorfer Company in Vienna.

Immediately before the experiments, the instruments were tuned, and the piano action and—in the case of the computer-controlled pianos—the reproduction unit serviced and regulated. The Steinway grand has been regularly maintained by a piano technician of the Swedish National Radio. At the Disklavier, this procedure was carried out by a specially trained Disklavier piano technician from the Stockholm "Konserthus." At the Bösendorfer company, the company's SE technician took care of this work.

B. Equipment and calibration

The tested keys were equipped with an accelerometer on the key[6] and another one on the bottom side at the end of the hammer shank.[7] The sound was picked up by a sound-level meter microphone[8] placed about 10 cm above the strings. The velocities of key and hammer and the sound signal were recorded on a multichannel DAT recorder (TEAC RD-200 PCM) with a sampling rate of 10 kHz and 16-bit word length. The data was transferred to a computer harddisk and analyzed with computer software written for this purpose. The recorded voltages were transformed to obtain required measures (m/s and dB SPL). The measuring equipment and the calibration procedure was identical as in Goebl and Bresin (2003b, p. 2274–75), so we do not repeat further details here.[9]

C. Procedure

Five keys distributed over the whole range of the keyboard were tested: C1 (MIDI note number 24, 32.7 Hz), G2 (43, 98.0 Hz), C4 (60, 261.6 Hz), C5 (72, 523.3 Hz), and G6 (91, 1568.0 Hz).[10] The first two authors served as pianists to perform the recorded test tones. Each key was hit at as many different dynamic levels (hammer velocities) as possible, with two different kinds of touch: one with the finger resting on the key surface (*pressed touch*), the other hitting the key from a certain

distance above, thus with the finger touching the key already with a certain speed (*struck touch*). Parallel to the accelerometer setting, the two computer-controlled grand pianos recorded these test tones with their internal device on computer hard disk (Bösendorfer) or floppy disk (Disklavier).

For each of the five keys, both players played in both types of touch from 30 to 110 individual tones, so that a sufficient amount of data was recorded. In case of the two computer-controlled devices (Bösendorfer and Yamaha), the internally recorded file was reproduced by the grand piano immediately after each recording of a particular key, and the accelerometer data was recorded again onto the multi-channel DAT recorder. However, for the sake of clarity and due to limited space, we restricted this paper to the human data. For the Steinway, 595 individual attacks were recorded, for the Yamaha Disklavier 996, and for the Bösendorfer 756 (not counting the keystrokes repeated by the reproducing devices).[11]

D. Data analysis

In order to analyze the three-channel data files, discrete measurement values had to be extracted from them. Several instants in time were defined as listed below and automatically read off with the help of Matlab scripts prepared by the first author for this purpose. This method allowed to obtain timing data without specially having to install additional sensors or contacts into the piano action (as e.g. done by Askenfelt and Jansson, 1990b), only by processing the key and hammer trajectory and the sound information.

The **hammer–string contact** was defined as the moment of maximum deceleration (minimum acceleration) of the hammer shank (hammer accelerometer) which corresponded well to the physical onset of the sound, and conceptually with the "note on" command in the MIDI file.[12]

The **finger–key contact** was defined to be the moment when the key started to move. It was obtained by a simple threshold procedure applied on the key velocity track. In mathematical terms, it was the moment when the (slightly smoothed) key acceleration exceeded a certain threshold. Finding the correct finger–key point was not difficult for struck tones; they showed typically a very abrupt initial acceleration. However, automatically determining the right moment for soft pressed tones was more difficult and sometimes ambiguous. The threshold was optimized iteratively by hand. It was found that softer tones required a smaller threshold than louder ones; therefore it was coupled to the hammer velocity by a linear function. When the automatic procedure failed, it failed by several tens of milliseconds—an error easy to discover in explorative data plots.

The **key bottom contact** was the instant when the downwards travel of the key was stopped by the keybed. This point was defined as the maximum deceleration of the key (MDK). In some keystrokes, the MDK was not the actual keybed contact, but a rebound of the key after the first key bottom contact. For this reason, the time window of searching MDK was restricted to 7 ms before and 50 ms after hammer–string contact. The time window was iteratively modified depending on the maximum
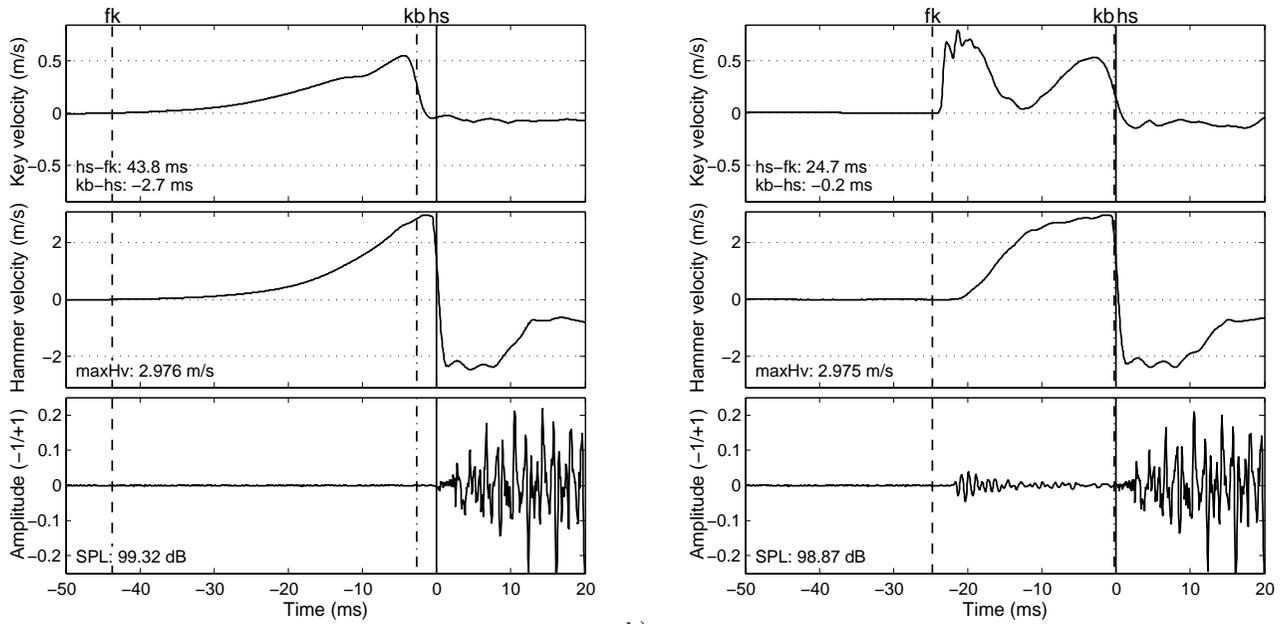
FIG. 1. Two *forte* keystrokes (C4, 60) played on the Yamaha grand piano with a pressed touch (left) and struck touch (right). The top panels show key velocity, the middle panel hammer velocity, and the bottom panel the amplitude of the sound signal. Both keystrokes exhibit similar MHVs and peak sound levels. Finger–key contact time ("fk"), hammer–string contact ("hs"), and key bottom contact ("kb") are indicated by vertical lines.

hammer velocity until the correct instant was found. The indicator MDK was especially clear and non-ambiguous when the key was depressed in a range of medium intensity (see Fig. 1).

The **maximum hammer velocity** (MHV, in meters per second) was the maximum value in the hammer velocity track before hammer–string contact.

The **escapement point** was defined as being the instant after which the hammer travels freely (with no further acceleration) towards the strings. It was approximated by fitting a line onto the hammer velocity track between the point of MHV and hammer–string contact. The slope of this line was set to the theoretical deceleration caused by gravity ($-9.81\ m/s^2$), disregarding any influence of friction. This instant in time was measurable only at soft and very soft touches. At MHVs exceeding approximately 1.5 m/s, it virtually coincided with the moment of MHV.

To inspect the recorded key and hammer velocity tracks and the sound signal, an interactive tool was created in order to display one keystroke at a time in three panels, one above the other. The user could click to the next and the previous keystroke, zoom in and out, and change the display from velocity to acceleration or displacement. Screen shots of this tool are shown below (see Fig. 1). The data was checked and inspected for errors with the help of this tool.

IV. RESULTS AND DISCUSSION

In this section, measurement results of the three investigated pianos are presented and compared. Recall that these data apply to specific instruments and de-

pend strongly on their regulation so that generalization to other instruments of the same brands may be problematic.

A. Two types of touch

The recorded three-channel data of two example keystrokes performed on the Yamaha grand piano are plotted in Fig. 1. They both exhibit an almost identical MHV (2.976 and 2.975 m/s, respectively) and a similar peak sound level (99.32 and 98.87 dB, resp.).[13] In musical terms this corresponds roughly to a *forte* dynamic. The first keystroke (Fig. 1a) was played from the key with a "pressed touch." From the beginning of the keystroke, the key velocity increases gradually; the hammer velocity grows in parallel. The hammer reaches its maximum velocity immediately before it arrives at the strings. Hammer–string contact is characterized by a very sudden deceleration (Fig. 1, indicated by vertical solid lines). Key bottom contact shows a slightly less abrupt deceleration and occurs immediately before hammer–string contact. On the other hand, the keystroke produced with a "struck touch" (Fig. 1b) shows a very sudden jerk at the beginning of the key movement that has no correspondence in the hammer movement, but can be seen in the audio data ("touch precursor").[14] The hammer starts its travel to the strings with a delay of several milliseconds. It receives a first, larger acceleration by this initial blow applied to the key; later the key "catches up" (Ortmann, 1925, p. 23) and brings the hammer to its final speed. The whole striking procedure needs roughly 20 ms less time with a "struck touch" compared to the "pressed touch," both with almost identical intensities.
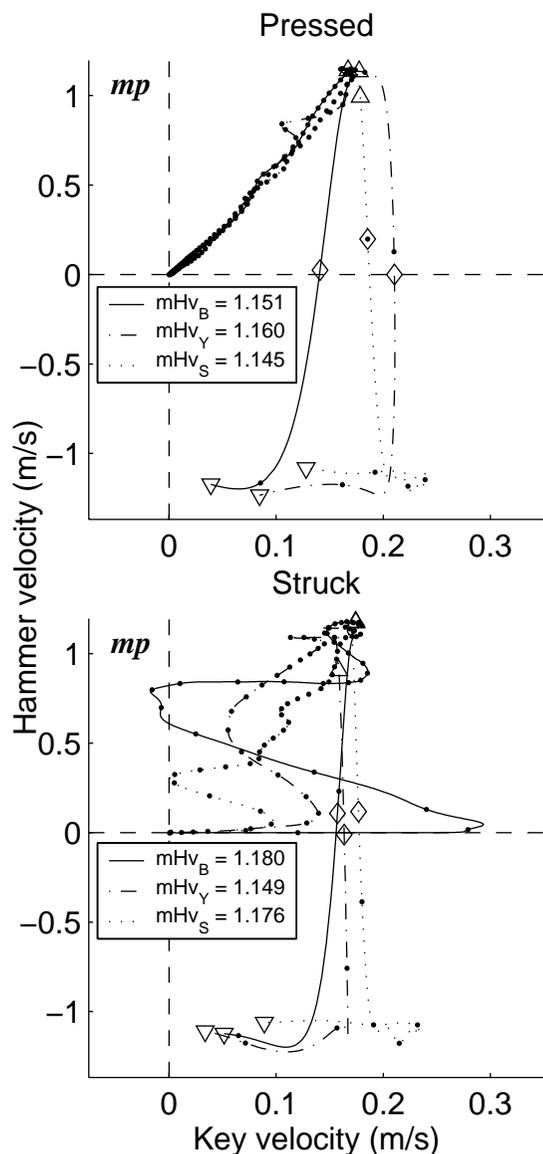
FIG. 2. Touch trajectories of *mezzo-piano* keystrokes at the C5 (72) on three pianos played with pressed touch (upper panel) and struck touch (lower). Upward-pointing triangles denote the escapement point, diamonds hammer–string contact, and downward-pointing triangles key bottom contact times. Small filled circles are plotted on the trajectories in 2-ms intervals to indicate time.
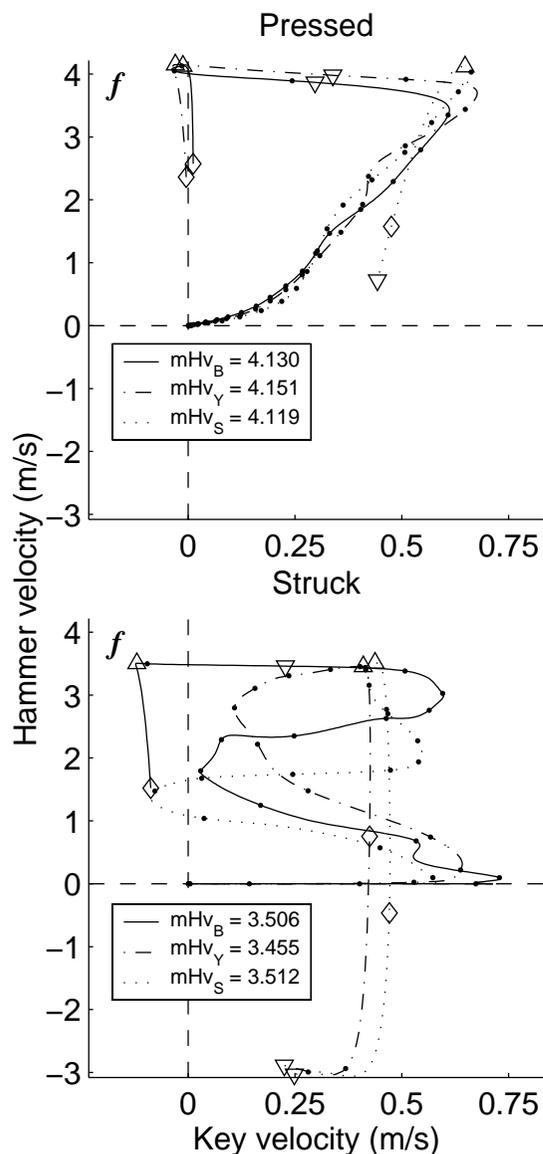
FIG. 3. Touch trajectories of *forte* keystrokes at the C5 (72) on three pianos played with pressed touch (upper panel) and struck touch (lower). Symbols and axes proportions as in Fig. 2.

B. Relation between key and hammer movement

In order to demonstrate the behavior of the hammer in relation to the key movement under two touch conditions, so-called "touch trajectories" of pressed and struck keystrokes are plotted in Figs. 2–4. These plots depict the progression of hammer velocity against key velocity from finger–key contact to key bottom or hammer–string contact (depending on which of these two points was later). Each panel compares keystrokes with almost identical MHV values played at the C5 on all three pianos. Marked on the trajectories are escapement point (upward trian-

gle), hammer–string contact (diamond), and key bottom contact (downward triangle), as well as elapsing time (filled circles every 2 ms). Fig. 2 contains *mezzo-piano* keystrokes, Fig. 3 *forte*, and Fig. 4 *fortissimo*, which can only be achieved with a struck touch.

The pressed keystrokes develop fairly linearly until the escapement point (top panels in Figs. 2 and 3). The average slope of this part of the trajectory for all recorded pressed tones is 5.6 for Steinway and Yamaha, and 5.3 for the Bösendorfer. In the softer pressed example (Fig. 2 top), the key–bottom occurs after hammer–string contact (the trajectories drop at the right before going leftwards), while at the *forte* example (Fig. 3 top) the key–bottom is
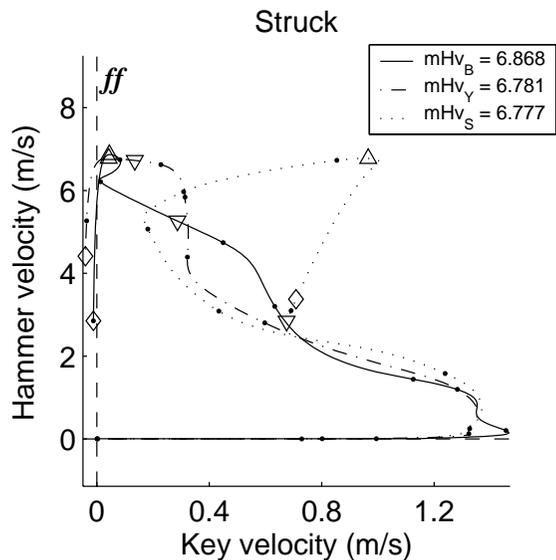
FIG. 4. Touch trajectories of *fortissimo* keystrokes at the C5 (72) on three pianos played with struck touch. Symbols and axes proportions as in Fig. 2.
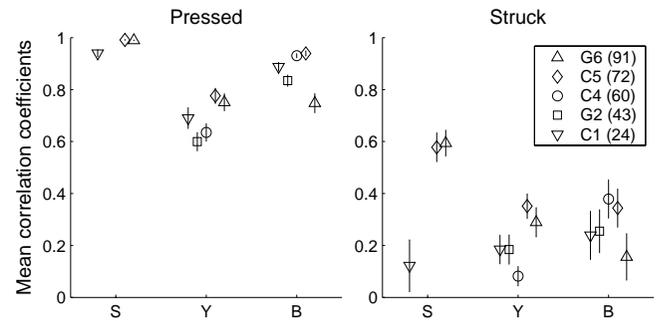

FIG. 5. Mean correlation coefficients of the touch trajectories (key and hammer velocity histories from finger–key through the escapement point) by touch (panels), piano (x axes: Steinway, Yamaha, Bösendorfer), and pitch (marker shape). Error bars denote 95% confidence intervals.

before hammer–string (trajectory moves left before dropping downwards). The exception here is the keystroke at the Steinway, at which the key–bottom contact is still after hammer–string contact (though the time difference is negligible) and therefore the trajectory still drops first.

Struck tones show very different trajectories (bottom panels in Figs. 2–4). They deviate clearly from the diagonal; the initial acceleration of the key pushes the trajectories rightwards, before the hammer starts to move. After this first blow, the key stops for a moment and re-accelerates again, while the hammer still gets faster. This pattern is quite consistent across pianos and intensities (see Figs. 2 and 3). However, at very loud keystrokes the second acceleration of the key does not occur anymore (Fig. 4) so that the whole keystroke consists of one strong impulse and the acceleration of the hammer during retardation of the key (diagonal trajectory to the upper right). The exception is the Steinway which still exhibits a second key acceleration phase.

The struck touches compared here display almost identical MHVs (bottom panels Figs. 2–4). However, the effort spent for the keystrokes does not appear to be similarly identical: the initial blow (maximum key velocity) at the Bösendorfer is larger than at the other pianos for all three intensities; relatively the most in Fig. 2. A larger initial amplitude to the right denotes a larger energy loss in a keystroke due to compression of the parts in the action (e.g., cushions, dunnage) and bending of the key and hammer shank. Therefore, the Bösendorfer action exhibits the largest degree of compression (especially with soft tones) and the Steinway the least. To draw more profound conclusions from this finding, measurements on the touch form would have to be performed that include monitoring of finger speed and force applied to the key. However, the present data suggests that the

Bösendorfer requires more playing effort at struck touch forms to achieve the same dynamic level than the two other pianos.

In order to quantify the transformation effectivity of a keystroke, the correlation coefficient between the key and hammer velocity track (starting from finger–key contact until the escapement point) was introduced. The mean correlation coefficients for touch, pianos, and key are each plotted separately in Fig. 5. As this measure determines linearity between key and hammer movement, it may serve as a "touch index," distinguishing clearly between the two types of touch. It turned out that all pressed touches display coefficients beyond approx. 0.6 and struck ones below that value. In this sense, pressed touch is a more effective way of transforming finger force into hammer velocity than playing with a struck touch.

Moreover, this index may also hold for a measure of tone control for the pianist. With a struck touch, the action decompresses after compression (relaxing of compressed cushions, bent key, and the hammer shank). At very loud keystrokes, this must be the reason of the high acceleration of the hammer (the key decelerates clearly while the hammer accelerates up to 7–8 m/s, see Fig. 3). Therefore by striking a key, the tone intensity is controlled through the initial key or finger velocity; by pressing a key, the tone intensity is controlled through the key or finger velocity until the escapement of the jack ("early versus late impulse," cf. Askenfelt and Jansson, 1991).

C. Travel time

The time interval between finger–key contact and hammer–string contact is defined here as the *travel time*.[15] The travel times of all recorded tones are plotted in Fig. 6 against MHV separately for the three grand pianos (different panels), different types of touch (filling of symbols), and different keys (denoted by symbol).

Some very basic observations can be drawn from this figure. The two pianists were able to produce much higher MHVs on all three pianos with a struck attack (almost 8 m/s), whereas with a pressed tone, the MHVs hardly exceeded 5 m/s. There was a small trend towards higher hammer velocities at higher pitches (due to smaller hammer mass, see Conklin, 1996). The highest
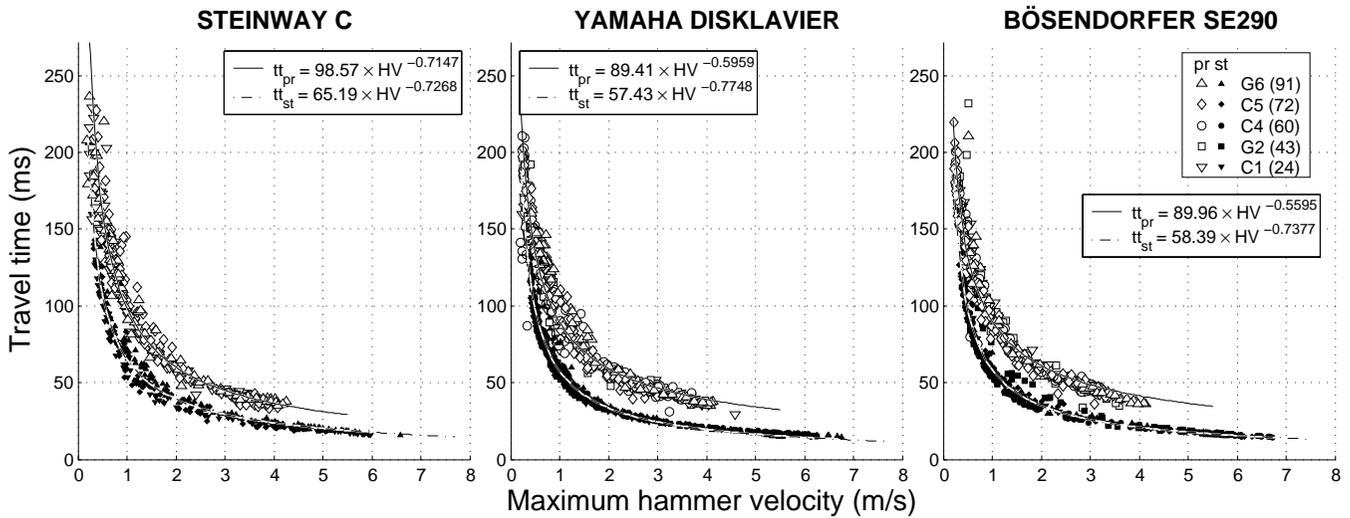
STEINWAY C **YAMAHA DISKLAVIER** **BÖSENDORFER SE290**

Legend (Steinway): $tt_{pr} = 98.57 \times HV^{-0.7147}$; $tt_{st} = 65.19 \times HV^{-0.7268}$

Legend (Yamaha): $tt_{pr} = 89.41 \times HV^{-0.5959}$; $tt_{st} = 57.43 \times HV^{-0.7748}$

Legend (Bösendorfer):

pr	st	
△	▲	G6 (91)
◇	◆	C5 (72)
○	●	C4 (60)
□	■	G2 (43)
▽	▼	C1 (24)

$tt_{pr} = 89.96 \times HV^{-0.5595}$; $tt_{st} = 58.39 \times HV^{-0.7377}$

FIG. 6. **Travel time** (from finger–key to hammer–string contact) against MHV for the three grand pianos (three panels), different types of touch (*pressed* and *struck*), and different keys (from C1 to G6, see legend). The two types of touch ("pr" and "st") were approximated by power functions (see legends).

velocities on the Yamaha and the Steinway were obtained at the G6, but at the middle C on the Bösendorfer. The lowest investigated key (C1) showed slightly lower MHVs by comparison to the fastest attacks (loudest attacks on the Steinway: C1: 6.8 m/s versus G6: 7.5 m/s, on the Yamaha: C1: 6.4 m/s versus G6: 7.8 m/s, and on the Bösendorfer: C1: 6.0 m/s versus G6: 6.6 m/s and C4: 7.6 m/s). The variability between the intensity distributions of the keys could be due to the fact that the tones were played by human performers.

The travel times ranged from 20 ms to around 200 ms (up to 230 ms on the Steinway) and depicted clearly different patterns for the two types of touch. The travel time curves were independent of pitch although lower keys have much greater hammer mass than in the high register (Conklin, 1996).

The data plotted in Fig. 6 were approximated by power curves of the form $tt = a \times HV^b$ separately for each type of touch ("pr," "st") and each of the three pianos. The results of these curve interpolations are shown in the legends of Fig. 6. Struck touch needed less time to transport the hammer to the strings than a pressed touch which smoothly accelerated the key (and thus the hammer). The travel times were more spread out when the tones were pressed, indicating that there was a more flexible control of touch in this way of actuating the keys (also reflected by the lower R^2 values of the curve fits). On the Steinway, the struck data showed higher variability, almost similar to the pressed data.

The present data were generally congruent with findings by Askenfelt and Jansson (1991) and Hayashi *et al.* (1999). The travel time approximations used in Goebl (2001, $tt = 89.16 \times HV^{-0.570}$) were very similar to the curve fit of the Bösendorfer's pressed data. The impact of this updated travel time function on the melody lead predictions was rather negligible; it is discussed elsewhere (Goebl, 2003, p. 74 onwards).

D. Key bottom time

Fig. 7 displays the key bottom contact times relative to hammer–string contact ($t_{kb_{rel}} = t_{kb} - t_{hs}$). Negative values indicate key bottom contacts *before* hammer–string contact, positive values key bottom contacts *after* the hammer hits the strings (see overview display in Fig. 9). The keybed was reached by the key up to 35 ms *after* hammer–string contact in very soft tones (up to 39 ms at the Bösendorfer) and as early as 4 ms before in very strong keystrokes. This finding coincides with Askenfelt and Jansson (1990a,b)'s results, but since much softer tones were measured in the present study (as low as 0.1 m/s), the key bottom times extended more after hammer–string contact.

Key bottom contact times varied with the type of touch. Keys played with a pressed touch tended to reach the keybed earlier than keys hit in a struck manner. This was especially evident for the Bösendorfer and for the Yamaha, but not for the Steinway. Askenfelt and Jansson (1992b, p. 345) stated that the interval between key bottom and hammer–string contact varies only marginally between "legato" and "staccato touch." They obviously refer with this statement to one of their earlier studies (Askenfelt and Jansson, 1990b), where the investigated grand piano was also a Steinway grand piano.[16]

Power functions were fitted to the data as depicted in Fig. 7, separately for the two types of touch and the different pianos (see legends). Since the data to fit contains also negative values on the y axis, power functions of the form $kbt = a \times HV^b + c$ were used. The data spread out more than in the travel time curves (reflected in smaller R^2 values) and showed considerable differences between types of touch, except for this Steinway, where touch did not divide the data visibly. This finding suggests that struck keystrokes tend to compress the parts of the action more than pressed ones that this behavior was least at the Steinway piano.
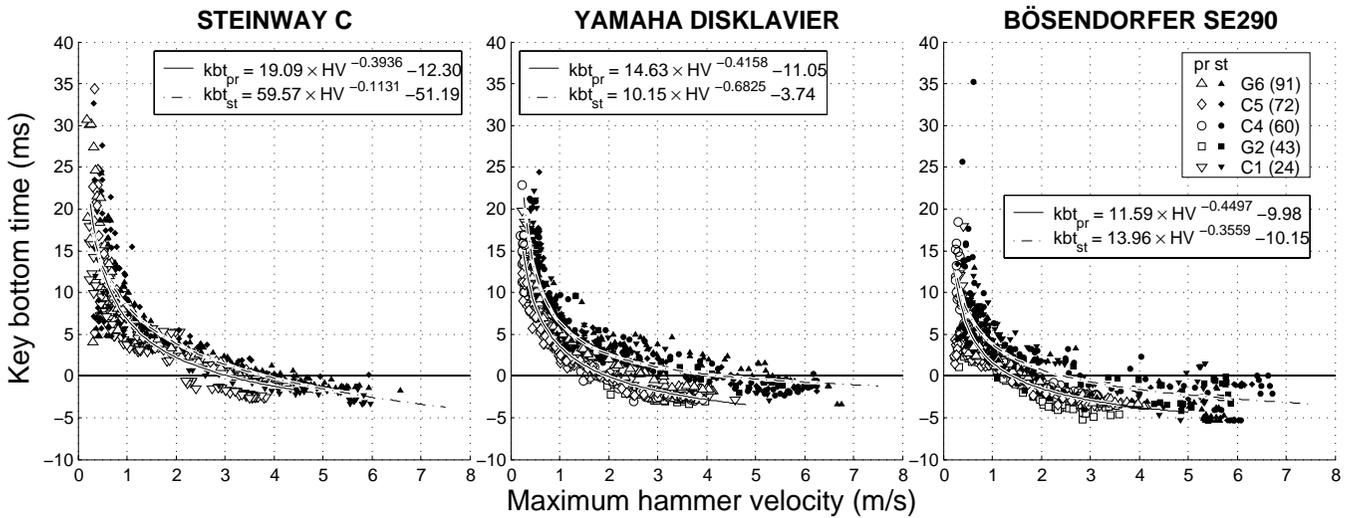
FIG. 7. **Key bottom time** relative to hammer–string contact against MHV. Negative key bottom values denote instants *preceding* hammer–string contact. Legends list power curve fits of the data separately for pressed touch ("kbt$_{\text{pr}}$") and struck touch ("kbt$_{\text{st}}$").

Askenfelt and Jansson (1990b) considered key bottom times as being sensed with the fingertips by pianists and thus as being important for the vibrotactile feedback in piano playing. Temporal asynchronies of the order of 30 ms are in principle beyond the temporal order threshold (Hirsh, 1959), so at very soft keystrokes key bottom contact and hammer–string contact could be perceived as two separate events by the pianists. But for the majority of keystrokes these time differences are not perceptually distinguishable; however, they may be perceived subconsciously and perhaps as part of the response behavior of a particular piano. Especially, the different key bottom behavior for the different kinds of touch might be judged by the pianists as part of the response behavior of the action (Askenfelt and Jansson, 1992b). Hammer–string contact occurs earlier relative to key bottom contact when the key was struck compared to when it was pressed. For a pianist, a struck touch produces a tone earlier than a pressed touch with comparable intensity, both relative to key bottom contact and relative to finger–key contact, and thus may be perceived as being louder and more direct.

E. Escapement point

Shortly before the hammer crown arrives at the strings, the tail end of the jack gets pushed away from under the roller by the escapement dolly and the pianist loses physical contact with and thus control over the hammer, which is then moving freely along a circular path to the strings. This measurement point was comparatively difficult to extract automatically from the data, since at many keystrokes this point was not obvious at all. The higher the hammer velocities, the more it tends to coincide with the instant of MHV. Only at soft and very soft dynamics, the hammer might reach its maximum speed considerably earlier than the jack is escaped.

An example of a very soft keystroke is displayed in Fig. 8. In addition to the display in Fig. 1, the point
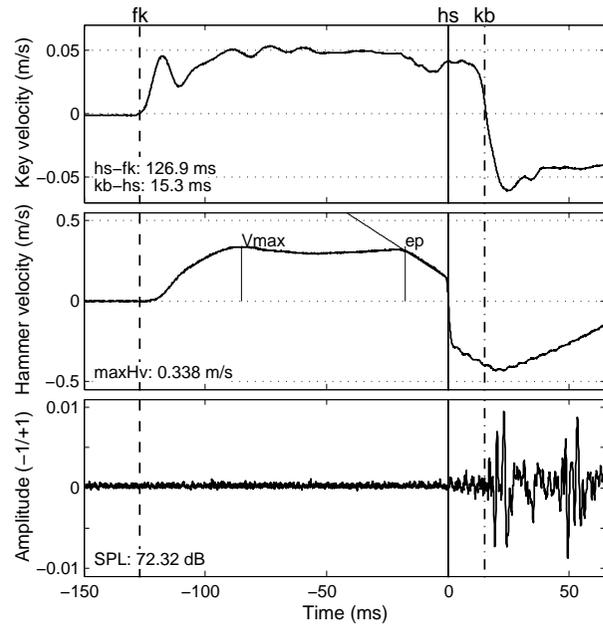

FIG. 8. A struck pianissimo keystroke at C2 (24) played on the Steinway grand piano. Additionally indicated are the point of MHV ("Vmax") and the estimated escapement point ("ep"). The skewed line in the middle panel denotes expected deceleration according to gravity.

of MHV ("Vmax") and the escapement point ("ep") are sketched, as well as the line of gravity fitted in the hammer track between escapement point and hammer–string contact. At this *pianissimo* tone, the hammer reaches its maximum speed quite soon after the begin of the keystroke (after 31.9 ms), travels another 78.7 ms with connection to the jack, and decelerates approximately by

TABLE I. Power curve approximations of the form $fft = a \times HV^b$ for the free-flight time data, separately for pressed and struck touches and the three pianos.

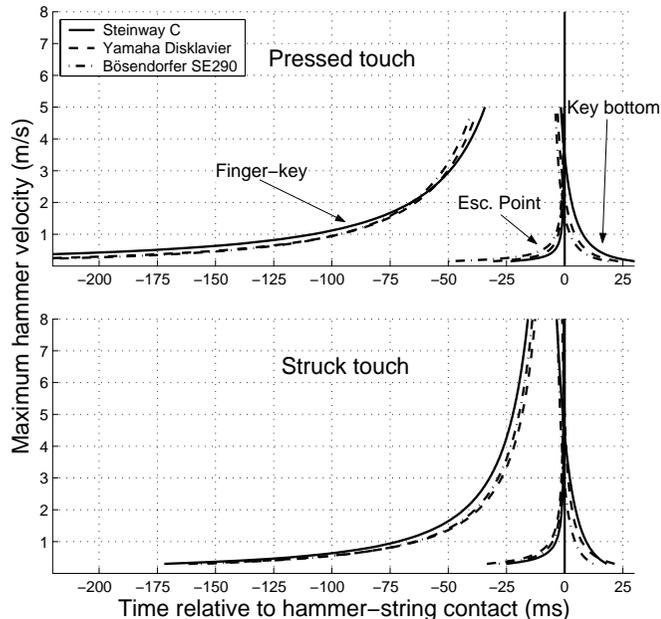| $fft =$	Pressed	Struck
Steinway	$1.63 \times HV^{-1.403}$	$3.04 \times HV^{-1.581}$
Yamaha	$2.78 \times HV^{-1.266}$	$5.27 \times HV^{-1.384}$
Bösendorfer	$3.21 \times HV^{-1.353}$	$4.32 \times HV^{-1.404}$

FIG. 9. Temporal properties of three grand piano actions. Power curve approximations for the three pianos (line style), the two types of touch (panels), and for finger–key (left), escapement point (middle), and key bottom times (right) relative to hammer–string contact.

gravity for a period of 16.3 ms.

F. Free flight of the hammer

The time interval from the escapement point until hammer–string contact is called here "the free flight of the hammer."[17] The individual data points are not plotted here due to space limitations, but they were fitted by power curves separately for the type of touch. The formulas are provided in Table I. The free flight of the hammer ranges from almost zero at louder tones up to 20 ms at very soft keystrokes, with some outliers up to around 40 ms at the Yamaha piano (struck touch). Generally, pressed touches exhibit shorter free flight times than struck touches. This finding coincides with the above stated proposition that a pressed touch provides generally a better control over the tones than a struck touch. Of all three actions, the Steinway action showed the shortest free flight times (see Fig. 9).

G. Comparison among tested pianos

In Fig. 9, all power curve approximations reported above (Figs. 6, 7, and Table I) are plotted in a single display, separately for the type of touch (panels) and

the three tested piano actions (line style) against time (in seconds) relative to the hammer–string contact. The temporal differences between extremes in intensity were largest for the finger–key times and smallest for key bottom times (both relative to hammer–string contact). The differences of the curves between the pianos by different manufacturers were small compared to the differences introduced through the type of touch. The finger–key curve of this Steinway action was the left-most except for loud pressed tones. Also our Steinway's key bottom curve was the right-most of the three actions. Thus, the Steinway action needed more time for the attack process than the other two pianos, except for very loud pressed tones. At the free flight time approximation, the Steinway showed the shortest of all tested actions.

These data apply only to the tested instruments and temporal behavior changes considerably with regulation (especially key–bottom contact and the time of free flight, see Askenfelt and Jansson, 1990b; Dietz, 1968). We do not know how different the temporal behavior of other instruments of these three manufacturers will be. Changes in regulation (hammer–string distance, let-off distance) resulted in changes of the key–bottom timing and the time interval of the hammer's free flight, respectively, of up to 5 ms (for a medium intensity, see Askenfelt and Jansson, 1990b, pp. 56–57). The differences between piano actions in the present data are approximately of the same order.[18]

It can be concluded that the temporal behavior of the tested piano actions by different manufacturers were similar. However, no definitive conclusions can be drawn whether or not these (comparably small) differences in temporal behavior were crucial for the pianist's estimation of the piano's quality and whether they apply also to other instruments of these manufacturers.

V. GENERAL DISCUSSION

This study provides benchmark data on the temporal properties of three different grand pianos under two touch conditions (*pressed* and *struck touch*). Prototypical functions were obtained for travel time, key bottom time, and the time of the hammer's free flight by fitting power curves to measured data. The temporal properties varied considerably between type of touch, only marginally between pianos, and not at all between the different tested keys. The latter was not surprising, since piano technicians generally aim to adjust a grand piano action so that all keys show similar and consistent behavior over the whole range of the keyboard.

Different kinds of actuating the keys produced different ranges of hammer velocity. Very soft tones could only be achieved with a pressed touch (minimum 0.18 m/s or 50.0 dB–pSPL) and the extremely loud attacks only with a struck touch (maximum 6.8 m/s or 110.4 dB–pSPL). Playing from the keys (pressed) did not allow MHVs beyond around 4 m/s, thus for some very loud intensities hitting the keys from above was the only possible means. The free flight times were shorter for pressed touch than for struck touch which suggests a better tone control for the pianist when playing with pressed touch. Moreover, depressing a key caused less touch noise than striking a

key which is commonly regarded as a desired aesthetic target in piano playing and teaching (cf. e.g., Gát, 1965).

The two types of touch (in the present terminology pressed and struck touch) do represent two poles of a variety of possible ways to actuate a piano key (i.e., late acceleration versus early, hesitating in between, or accelerating directly at the escapement point). It must be assumed that a professional pianist will (even unconsciously) be able to produce many different shades of touch between pressed and struck.

The travel times and the key bottom times changed considerably with intensity of key depression. A soft tone may take over 200 ms longer from the first actuation by the pianist's finger to sound production compared to a very sudden *fortissimo* attack. Moreover, travel times and key bottom times changed considerably with touch. A struck tone needed around 30–40 ms less from finger–key to hammer–string than a pressed tone with a similar MHV. These findings were not surprising (since they follow a very basic physical law), but the performing artist has to anticipate these changes in temporal behavior while playing in order to achieve the desired expressive timing of the played tones. The pianist not only has to estimate before playing a tone, how long the keystroke will take for what desired dynamic level, but also for what intended way of actuating the key. These complex temporal interactions between touch, intensity and the tone onset are dealt with and applied by the pianist unconsciously; they are established over years of intensive practising and extensive self-listening. Immediately, musical situations come to mind in which loud chords tend to come early with pianists at beginning or intermediate level; or that *crescendo* passages tend to accelerate in tempo as well, because each keystroke is performed with a harder blow and thus quicker in order to achieve the *crescendo*, but the time intervals between finger activity were not correspondingly increased.

A keystroke starts for the pianist kinesthetically with finger–key contact (the acceleration impulse by the finger)[19] and ends at key bottom, but it starts aurally for pianist and audience at (or immediately after) hammer–string contact. Typical intensities (at an intermediate level) in expressive piano performances (i.e., as measured in Goebl, 2001) fall between 40 and 60 MIDI velocity units (0.7 to 1.25 m/s) and thus typical travel times are between 80 and 108 ms, thus varying as much as about 30 ms. At such keystrokes, the key bottom times are between 3.5 and 0.5 ms before hammer–string contact, thus a range of the order of 3 ms. It can be assumed here that with such moderate intensity levels (and a default touch which is likely to be pressed rather than struck), the changes in travel times due to varying intensity might not be directly relevant for the player since they are small and at the threshold of perceivability. Nevertheless, they are sufficiently large to produce the typical *melody lead* (Goebl, 2001).

At that typical dynamic range, key bottom times are even more unlikely to be perceived by the pianist separately from the sound (hammer–string), since those temporal differences are there of the order of a few milliseconds. However, the differences between key bottom and hammer–string can be up to 40 ms in extreme cases which is of the order of or just beyond *just noticeable differences* for perceiving two separate events (Askenfelt and Jansson, 1992b, p. 345). Also as Figure 9 made visually evident, the travel times were far larger than the time differences of the other readings (escapement point, hammer–string contact, key bottom contact), so it can be assumed that the pianist (especially in the dynamic middle range) only senses two points in time: the start of the keystroke (finger–key) and its end which coincides with the beginning of the sound.

Conceptually, the key bottom contact has to be *after* hammer–string contact. If it were the other way round, no soft tones could be played at all. The fact that key bottom contact moves towards and beyond (that is *before*) hammer–string contact with increasing hammer velocity (cf. Fig. 7) was due to the bending of the hammer shank and the compression of various parts in the action (i.e., cushions, dunnage) and a later unbending and decompression of those. The three actions showed different behavior as to when the key bottom line crossed the hammer–string line with changing hammer velocity (Fig. 9). According to the power curve approximations of the data (Fig. 7), the Bösendorfer's crossed at 1.4 m/s (pr) and 2.5 m/s (st), the Yamaha's at 2 m/s (pr) and 4.3 m/s (st), and the Steinway's at 3 m/s (pr) and 3.8 m/s (st). If we considered these values to be a measure of compressivity of the action, the Steinway would be the least compressive action (of the three), and the Bösendorfer the most for pressed touches. At struck touches, the Yamaha showed the least compressive behavior. A smaller compression behavior might be considered a criterion for the subjective quality of a piano action (see discussion further below). However, further investigation would be necessary to verify this hypothesis (e.g., measuring static compression behavior of the investigated keys).

Furthermore, senso-motoric feedback is considered an utmost important factor for pianists not only for judging the action's response, but also to judge the piano's tone (Galembo, 1982, 2001). In an extended perception experiment, Galembo (1982) asked a dozen professors from the Leningrad Conservatory of Music to rate the instrumental quality of three grand pianos under different conditions. The participants agreed that the Hamburg Steinway grand piano was superior, followed by the Bechstein grand piano, while the lowest quality judgment received a grand piano from the Leningrad piano factory. In different discrimination tasks, the participants were not able to distinguish between the instruments (although all indicated to be able to) only by listening to them when played by some other person behind a curtain. But they could very well discriminate between instruments when they played on them blindly or deaf-blindly (Galembo, 1982, 2001). This study implied that the hapto-sensorial feedback of the piano action to the playing pianist is crucial for the estimation of the instrumental quality.

Another important factor altering the hapto-sensorial feedback sensed by the pianist is the room acoustics (Bolzinger, 1995; Galembo, 1987). A piano action might feel easily to handle in a room with reverberant acoustic, while the same action feels intractable and tiring in a room without any reverberation. Similarly, the tim-

bre of that instrument might be judged differently with changing room acoustics. A pianist is usually not able to separate the influences of room acoustics from properties of the instrument and directly attributes room acoustics to instrumental properties (Galembo, 1987, 2001).

The reported temporal properties of the piano actions were derived from isolated piano tones (without pedal) such as they rarely occur in piano performances. For a new keystroke, the key does not necessarily have to come back to its resting position, but, due to the double repeating feature of modern grand piano actions, the hammer is captured by the check and the repetition lever stopped by the drop screw (Askenfelt and Jansson, 1990b). When the key is released approximately half way (of the approximately 10 mm touch depth), the jack is able to resile back underneath the roller and another keystroke can be performed. This occurs usually some 2–4 mm below the key surface. For such keystrokes, the key can travel only 6–8 mm, so the travel times can be expected to be shorter than with a pressed touch from the key's resting position. Also for such repeated keystrokes, it would be impossible to calculate or to determine a finger–key contact point in time. The study of such repeated keystrokes has to remain for future investigation.

An interesting issue with respect to the reported data is whether there is a relationship between the actions' temporal properties and the instrumental quality of the tested grand pianos. The authors' personal opinion as pianists was that from the three investigated grand pianos in this study the Steinway grand piano was qualitatively superior to the other two (in terms of the actions' responsiveness), although the Bösendorfer was a high-standard concert grand piano as well. The small Yamaha baby grand was the least interesting instrument also due to its size. However, all pianos were on a mechanically high standard and they were well maintained and tuned. It is assumed here that one of the most important features of a "good" piano is a precise and responsive action.

In the data reported above, some differences between the pianos could be observed that might influence the subjective judgment of instrumental quality and that support the authors' subjective preference for the Steinway. The Steinway showed (1) much less difference in key bottom times due to touch than the other two pianos; (2) late crossing of the key bottom approximations and the hammer–string contact line, indicating a low compressivity of the parts of the action; (3) shorter time intervals of free flight (already almost zero at keystrokes with a MHV of more than 1.5 m/s, while for the Bösendorfer it was around 2.5 m/s, for the Yamaha above 3 m/s). Moreover, the Yamaha showed many very early hammer velocity maxima at velocities between about 1 and 2 m/s, the Bösendorfer some, the Steinway almost none.

Although further evaluative investigations would be required to be able to state more conclusively any hypotheses on the relation of temporal behavior of grand piano actions and instrumental quality, it seems likely that a constant behavior over type of touch and late hammer velocity maxima are crucial for precise touch control and a subjective positive appreciation of instrumental quality.

[1] The term "modern grand piano" refers to what is nowadays commonly used by pianists in concert halls. However, it is not modern anymore, because, e.g., the Steinway model D grand was developed and introduced already in the second half of the 19th century and has remained essentially unchanged since then.

[2] The first three paragraphs are taken from Goebl (2001) and repeated here for the sake of completeness.

[3] Askenfelt and Jansson (1990b) measured the C4 on a Hamburg Steinway & Sons grand piano, model B (211 cm).

[4] The "prelay function" compensates for the different travel times of the action at different hammer velocities. In order to prevent timing distortions in reproduction, the MIDI input is delayed by 500 ms. The solenoids (the linear motors moving the keys) are then activated earlier for softer notes than for louder notes, according to a pre-programmed function.

[5] This particular piano was used in Askenfelt and Jansson (1992a).

[6] Brüel & Kjær Accelerometer type 4393 (2.4 g).

[7] Brüel & Kjær ENDEVCO Accelerometer Model 22 (0.14 g).

[8] Brüel & Kjær Sound Level Calibrator Type 4230.

[9] In order to account for the differences in radius between the accelerometer placement on the hammer shank and the actual striking point at the hammer crown, the hammer velocity data was corrected for that (resulting in values increased by 14%). This correction was not applied in Goebl and Bresin (2003b).

[10] Only three keys were tested at the Steinway piano (C1, C5, G6).

[11] The recordings were done between May 2001 and January 2002.

[12] This measurement was also used to find the individual attacks in a recorded file. All accelerations below a certain value were taken as onsets. The very rare silent attacks were not captured with this procedure, as well as some very soft attacks.

[13] The peak sound level was calculated by taking the maximum of the sound energy (max. RMS with a 10-ms sliding window).

[14] The intensity of the touch precursor depends strongly on the way a particular keystroke was played. It is possible to produce loud struck tones without clearly visible touch precursors (see also Goebl *et al.*, 2004).

[15] This terminology might be misleading, because "time" refers to a point in time, although in this case a time duration is meant. Terms like "travel time" or "time of free flight" were used according to the term "rise time" that is commonly used in acoustic literature (see, e.g., Truax, 1978).

[16] Askenfelt and Jansson (1990b) used a Steinway Model B, serial number 443001, built in Hamburg 1975.

[17] In Goebl *et al.* (2003) the time interval between the points of MHV and hammer–string contacts are plotted under the label "free flight of the hammer." We consider the present data display (escapement through hammer–string contact) to be more appropriate.

[18] Note that all three pianos were maintained and regulated by professional technicians before the measurement so that all pianos were in concert condition before the tests.

[19] Certainly the performing pianist may in some cases hear the finger–key noise as well.

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