I. INTRODUCTION

Our assignment was to condense the body of significant research into piano key touch into 45 minutes. Clearly, studies into the relationships between player, key touch, and instrument output have much to share regardless of whether the target instrument is a harpsichord, piano, clavichord, organ, or electronic keyboard.

First let’s quickly modify the title of the talk for a more accurate view of the topic to by looking inside the problem:

“From Player to Key to Action to Hammer to String to Spectra”,

which is closer to what we want, because the interaction between the hammer and string is critical to the perception of tone. Now, let’s step back for an overall view of the real issue and why we care:

“Recent Research in Piano Key Touch and Perceived Output”.

We have a player interacting with a function box that produces output, which is heard and responded to by the player and other people.

Because time is short for the amount of material we need to cover, I apologize in advance that we’re going to talk and move very fast so we can get to some high speed videos and
action simulation. We are going to start with a quick run down of some of the issues in piano key touch research. Then we will run you through a brief history of some of the notable relevant research projects, followed by a look at experimental methods that have been used. Finally, we'll give you a look at recent work at the PianoLab in Waterloo.

II. ISSUES IN PIANO KEY TOUCH RESEARCH

A. Physical difficulty with observations. Most of the action of a piano is completely hidden inside the piano. Experiments should be reproducible, but materials such as wood and cloth are sensitive to environmental conditions, changing the initial state.

B. Compliance within the system elements. Some components have significant flexibility. Contact interfaces are lined with compliant materials such as leather and felt that may exhibit hysteresis effects. All this complicates creation of simulation models.

C. Not affecting what you are measuring. It is difficult to make measurements and observations without affecting what is being measured due to added mass or other types of interference. Non-contact observation is best.

D. High Speed of components. Typically there is 2-4 ms of contact time of hammer to string. The entire key strike in an early piano can last as little as 10 ms in a strong forte.

E. Accuracy and resolution of data. We must be sure there are no extraneous effects showing up in our data, corrupting its meaning.

F. Consistency and accuracy of:
   1. Bench top mechanism. These are particularly difficult since antique instruments may have changed with time, and may not be set up in the present day as they originally were, plus there can be errors in drawings and plans.
   2. Computer simulation model. It is critical to accurately do the modeling and obtain appropriate parameters.

G. Simulating real playing. It is difficult to play a single (or several) key benchtop mechanism the same way as a real piano keyboard.

H. Interpretation of results. Qualitative vs quantitative descriptions. Scientific observation vs human perception. We humans perceive mechanical input and acoustic output and then interpret that. How do we change qualitative notions into quantitative descriptions? How do we tie scientific measurement and observation to human perception. How do we define qualitative terms such as Touch? For example, we found very different definitions of legato and staccato in the various published papers.

I. Reproducing touch input of the human part of the system. Touch and touch force are necessarily connected to the compliant finger, connected to the hand, wrist, arm, and so forth. Creating an appropriate automated actuation system for the key, as well as
simulating this human system is difficult, but using humans makes it difficult to get reproducible trials.

J. Motivation effects. Researchers must be very careful that their work is objective. We musicians and builders tend to be very passionate in our opinions.

III. A BRIEF HISTORY OF PIANO KEY TOUCH RESEARCH

A. Early 20th century

The touch-tone controversy is already evident in 1912, strongly continuing through the 1930s, and then re-appearing in the 1960. It is still an active debate between musicians and physicists (e.g. recently 1964 Clavier Magazine article reprinted in 19901 created a quite a stir).

1. In 1925, Dr. Otto Ortmann² from the Peabody Conservatory of Music in Baltimore completed a very famous study that started off a firestorm amongst teachers and players. He announced that only the intensity and duration of the sound produced made any difference regardless of touch, but he did note that different types of touch do give different types of key control.

2. In 1935 Báron and Holló³ observed that finger noise, as well as the noise of the key hitting the keybed, and the “upper noises” in the piano that develop when the key is released, such as dampers, are important parts of perceived tone quality. Note that a perception study by Goebl et al 2004, also showed that finger key noise is also part of aural touch recognition by different means.

B. Recent Research – we’re just going to mention a sampling of significant work since time is short.

1. Askenfelt & Jansson⁴

We’ll first look at the work of Anders Askenfelt and Eric Jansson of the Department of Speech Communication and Music Acoustics, Royal Institute of Technology in Stockholm, Sweden. They have been involved with a significant body of research with pianos, including articles on touch and sound.

Results: They came up with quite a few interesting results

2 The Physical Basis of Piano Touch and Tone, Dutton & Co., 1925.
1. Players are able to adapt to differences in action regulation that cause timing deviations on the order of 10ms or less, suggesting that regulation choices in the action have a significant effect for the feel of an action.

2. Different dynamic levels cause large changes in the timing patterns of the action as controlled by a player’s touch.

3. A pianist could produce almost identical final hammer velocities by delivering the main acceleration at different points in the hammer travel, i.e. by different types of touch. (Note this is what Dr. Ortmann showed as well in 1925).

4. Even when the pianist stated that differences in touch were large, giving large differences in hammer motion track, the perceived differences in sound were subtle if at all.

6. Modes, vibrations and oscillations: Even with modern large stiff piano action parts, modal vibrations and other significant movement can occur. For example, the hammer vibrates and the shank bends in ways that can affect string excitation. Their conclusion: “An influence …. on string excitation can be neither verified nor ruled out at the present state of research.”

2. Goebl, Bresin & Galembo. Results (quoted, although we do not necessarily agree with the conclusions):
   1. “Constant temporal behavior over touch and low compression properties of the action (reflected in key bottom contact times) were hypothesized to be indicators of instrument quality.

   2. “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 the acoustical result they hear.”

   3. Different types of touch produced different ranges of hammer velocity. Pressed touch caused less touch noise than striking a key. The relationship between hammer travel times and key bottom times change considerably with intensity of key depression. The complex temporal interactions between touch, intensity and the tone onset are all dealt with by the well trained pianist unconsciously.”

   4. Hammer-string contact can occur up to 40 ms before key bottom for very soft tones. For hard strikes, the hammer can hit the string 5 ms AFTER the key has bottomed. Note that 40 ms is within the range of noticeable difference for perceiving two separate events by humans. That is to say, playing well slowly and quietly is harder than fast and loud…which any serious pianist knows.

6 Key bottom time up to 230 ms.
7 Key bottom time as little as 20 ms.
We add the note here that human reaction response, ~40ms is possible by spinal loop (reflex), or 150ms when the brain is involved. So, excepting pianissimo playing, mechanical feedback from the key cannot be exploited actively and is used only for learning touch control. In other words, playing gestures are pre-determined before touch begins.

3. Hayashi, Yamane & Mori

We’re going to mention this study very briefly because of their key actuation methods that we will show later.

Their goal was to develop an automated piano with superior playback capability and with the ability to produce stable, soft tones, plus achieve fast repetition of the same key. These last abilities are beyond the capabilities of solenoid driven player systems.

4. B. Gillespie, PhD Thesis, Stanford University, CCRMA

His aim was to design a touchback keyboard, a virtual piano action, to re-establish the touch relationship between performer and instrument that is lost in currently available electronic keyboards (see below).

His motivation was the desire for an electronic keyboard instrument that truly feels, responds, and sounds like an acoustic grand piano, or other keyboard instruments of choice.

Methods:

This work reduced the human / instrument relationship to a model of a two-way flow of information. On the one hand you have player force and motion trajectories, and on the other hand you have instrument reaction force and response motion history. The simulation used a combination of inertia, dampers and compliances that excited vibration, along with three proportionality constants, one each for acceleration, velocity, and position.

Results: Side by side comparisons with real keyboards have “promising results”.

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10 Powered 8 key-keyboard. Each key with its own voice-coil type linear motor and driven by its own independent voltage controlled current amplifier. A PC hosts an 8 channel DSP motor control card with all necessary C/A, A/D and decode hardware. The keys are equipped with optical encoders, strain gages, and tachometer.
IV. EXPERIMENTAL METHODS FOR PIANO ACTION STUDIES

First decision...is the experiment being done in a piano or on a benchtop mechanism?

A. Key actuation

1. Pianist control: Human subjects are used to record test strikes. Goebl requested multiple strikes with “pressed vs. struck” touch covering the “entire dynamic range”.

   This is not easily repeatable or predictable. It is also time consuming (e.g. Goebl’s 2300 recordings)

2. Passive mechanical control: A free falling mass strikes the key front. Askenfelt used a rubber tipped pendulum to roughly simulate a finger:
This IS consistently reproducible and simple ... but it is NOT a realistic key strike. The mass bounces on the key. Key release is not possible.

3. Active mechanical control: A mechanical finger presses the key. Reproducing pianos typically use solenoids to push the key tails. Hayashi pushed the key front with moving coil actuators servo-controlled by position feedback:

... 88 of them:

Actuator response to reaction forces through the key strike will be different because human biomechanics are not represented. The actuator has to rest on the key surface to avoid unrealistic impact transients. Key front vs. tail can undergo significantly different response to applied force. It is difficult to control soft key strikes ... a well-known problem with reproducing pianos.
B. Component contacts
In piano actions the components undergo intermittent contacts, the hammer-string interaction being the most extreme example.

1. On-off switches: Sensors record the contact event between parts. Askenfelt used thin copper wires, copper foil, and/or graphite dispersion inserted in the component interfaces (see Askenfelt experiment shown above under Key Actuation).

2. Forces: Pressure sensitive materials can be used to estimate force in the interface. There is very limited reporting of internal contact forces.

Anything interfering between contact surfaces affects interface properties.

C. Key and hammer motion

1. Optical interference: Motion of the action components interrupts a beam. Askenfelt attached LEDs to key and hammer and monitored with position sensitive photodetectors. Reproducing pianos determine pre-impact velocity by shutters interrupting an infrared beam.

2. Optical encoders: A standard mechanical sensor to convert motion to a digital signal. Gillespie’s touchback keyboard has these on-board fixed to keys.

A one-piece unit is too bulky to be useful. 2-part encoders are subject to alignment errors. Most important, either pure linear or pure rotational motion is assumed.

3. Laser displacement measurement: Measures distance from target to detector using interferometry. Hayashi observed the hammer shank from above:
Motion must be viewed in line. 1-D methods are used to approximate a 2-D trajectory.

4. **Accelerometer**: A standard mechanical sensor used to measure ... acceleration. Frequently used on key and hammer shank (e.g. Askenfelt, Goebl).

   Sensors mounted on key or hammer will add mass (accelerometers <1 g are available = 15% increase in touch weight).

   Data processing is also not straightforward. Acceleration data must be integrated to get velocity and position that is inaccurate due to DC drift. Position data must be differentiated to get velocity and acceleration (numerical issues).

D. **Acoustic response**

1. **Recorded sound**.

   This is an indirect representation that includes the response of everything else in the piano, as well as the room acoustics. Psychoacoustic issues also complicate the relationship between perceived and actual response.

2. **Observing string motion directly**: Electromagnetic pickups are perhaps the most familiar (e.g. Askenfelt’s system11). Other options are piezoelectric or optical pickups.

   Magnetic field feedback can influence the motion of the string. Piezoelectric pickups are too sensitive and cannot isolate specific vibration.

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11 A concentrated horizontal magnetic field supplied by two magnets mounted in a U-shaped armature and applied across the strings at the selected observation point. This produced a voltage proportional to vertical velocity at the position of the magnet. Displacement was calculated by integrating the velocity signal in an RC network.
The PianoLab at Waterloo is funded mainly through grants from Canadian federal and provincial sources, as well as an industrial sponsor. We are studying the piano from an engineering perspective, asking how its dynamics and musical capabilities are influenced by design factors and materials. “Piano” is interpreted in the widest possible sense, including modern and historical keyboard instruments of all types. A post-modern piano is also being designed and constructed from first principles utilizing new engineering methods and materials.

One of our aims is to model the dynamics of the piano from pianist through to acoustic response. Here’s that blackbox opened up a bit to show the structure of the main subsystems and their interactions:

All of the models developed are supported by extensive experimental studies for which we have developed some novel methods. This has led to related research in characterizing material properties, and particularly dynamic felt compression, piano hammer design and hammer-string interaction.

Now, focusing on piano action research, I’ll describe the experimental methods and the action model.

1. Piano Action Experiments.

Our approach uses single key action and string mechanisms that we construct from scratch for the experimental study. This is an involved process to ensure full geometric and dynamic accuracy as compared to the original:
For key actuation, finger force can be recorded at the key surface using various types of touch. This same force profile can be replicated accurately using a high torque brushless DC motor with a short arm that pushes the key front. We are currently investigating ways to include the pianist dynamics with this system.

Component motion ...(ALL components) ... is observed using mostly non-contact methods based on high-speed imaging techniques:

The position of markers is tracked frame-by-frame using image processing. Even components mounted on moving frames (e.g. jack) can be monitored this way. Synchronized multiple cameras can simultaneously record at high resolution in widely separated locations, such as the key front and hammer:

[This approach would be useful in studying organ key and pallet/pipe response.]
Subjects that have been studied include various modern Boston and Steinway grand and upright actions, as well as some familiar historical actions – the Viennese, English grand, and Erard actions:

It is interesting to compare the dynamics and touch-response of all these. Harpsichord research is waiting in the wings. We’ve done a little preliminary work on that.

2. Piano Action Dynamic Model

A multi-body dynamic model is used to represent the action mechanism:

with customized contact and friction forces represented at interface surfaces:
Flexibility of components such as the hammer shank can be included in simulations. The equations of motion are derived symbolically, allowing parameters to be adjusted easily for simulation. This can be done with the software interface we have constructed for our industrial sponsor.

**Conclusion:**

We've presented a rapid summary of the highlights of research on piano key touch and actions. The historical question of whether a pianist can affect tone using different touches is still an open question. Still, new techniques have revealed much about the inner workings of piano actions and the effects of changes in touch and regulation. Recent work in simulating action behavior has included models of the separating compressible interfaces and flexible components for more useful action study than has been previously possible. Some of the techniques are clearly applicable to tracker organ research.