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Abstract: Piano actions are striking mechanisms whose functioning is based on dynamic principles; producing a sound on a struck keyboard instrument by pressing a key slowly is impossible because the hammer needs momentum to hit the strings. This is also the reason why mechanisms intended for struck keyboard instruments are difficult to study; their normal functioning speed is beyond human observation capabilities. For this reason, many modern studies on the piano take advantage of engineering tools in order to measure the exact behaviour of their actions in terms of time response, involved forces and displacement values. A complementary approach to study piano actions consists in modelling them, giving us a virtual mechanism to work with. In this case, the above mentioned motion and behaviour are computed instead of being measured. The modelling technique used and described in this paper, called multibody dynamics, consists in computing the motion and the forces acting upon each component of the action. Subsequently, the response of the mechanism to a certain key stroke can be computed and a slow-motion animation can be produced.

The aim of this paper is to give an overview of an ongoing research project in which two distinctive piano actions are modelled. Each of them is studied with a different objective in mind. Starting with the most modern, well-known but also most complex, the model of a double escapement action found in grand pianos is used to explain its functioning. This pedagogical goal is achieved with three progressive models; the first one is a simplified version of the action to which components of the complete action have been (virtually) removed. The stepwise progression leads to a single escapement action for the second model, and finally to the full double escapement action for the third. Timing of the action events and response to different types of touch are studied and compared with literature. The results show that our model is able to reproduce the same behaviour as real actions.

Going back in time, the second instrument that is studied is a Prellzungenmechanik built by Johan Andreas Stein at the end of the 1780's. In this context, a model has been achieved to evaluate the influence of the so-called "escapement height" (a regulation parameter of the action) on the playing characteristics of the action. As with the grand piano action, timing analysis and touch comparison are performed with the model.

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Historical and dynamical study of piano actions: a multibody modelling approach

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Abstract

Piano actions are striking mechanisms whose functioning is based on dynamic principles; producing a sound on a struck keyboard instrument by pressing a key slowly is impossible because the hammer needs momentum to hit the strings. This is also the reason why mechanisms intended for struck keyboard instruments are difficult to study; their normal functioning speed is beyond human observation capabilities. For this reason, many modern studies on the piano take advantage of engineering tools in order to measure the exact behaviour of their actions in terms of time response, involved forces and displacement values. A complementary approach to study piano actions consists in modelling them, giving us a virtual mechanism to work with. In this case, the above mentioned motion and behaviour are computed instead of being measured. The modelling technique used and described in this paper, called multibody dynamics, consists in computing the motion and the forces acting upon each component of the action. Subsequently, the response of the mechanism to a certain key stroke can be computed and a slow-motion animation can be produced.

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Keywords

Multibody dynamics, modelling, piano mechanism, piano action, double escapement action, grand piano, Johann Andreas Stein, Prellzungenmechanik, Arnaut de Zwolle, dulce melos.

1. Research aims

The aim of this research project consists in studying the dynamic behaviour of modern and ancient piano actions by means of the so-called "multibody" modelling approach. Most musicological studies concerning piano actions are limited to a static observation or subjective evaluation of their performance. A multibody model enables to predict the time evolution of the physical parameters of the action (relative displacements, force between components …). The computation of these variables can help to quantify these performances. In the general framework of this interdisciplinary project, three different actions are envisaged: the double escapement action found in modern grand pianos, an 18th century *Prellzungenmechanik* by Johann Andreas Stein and Henri Arnaut de Zwolle's striking mechanism. The present paper focusses on the two first actions.

2. Introduction

The history of the piano is a succession of inventions. Apart from the *gravecembalo col piano e forte* of Bartolomeo Cristofori which was a very complex but accomplished instrument, the global evolution of the instrument pictures a continuous increase in sophistication. This observation is particularly true for the action, the part responsible for transmitting the musical intention of the pianist through his fingers all the way up to the strings. Even if there exists a great diversity of action designs, their common point is that their functioning relies on highly dynamic principles. Unfortunately, this characteristic also limits our ability to grasp the details of their functioning. Indeed, under normal playing conditions, it is impossible to visualise the sequence of motion of the action because of its very high working speed. When the key is depressed slowly, the hammer will not gain enough momentum to hit the strings. For this reason, many excellent studies concerning the piano take advantage of engineering tools like high-speed imaging and force sensors to observe their behaviour [1, 2, 3].

The present paper highlights a modelling method called multibody dynamics which enables to compute the motion of any polyarticulated system and to virtually interact with the action. Besides imitating the one shot experiments in which data are measured, with a model, it is possible to compare actions in which some parts have been virtually modified through simulations in identical situations. These simulations enable to compute the data that were highlighted in [1, 2, 3] rather than measuring them. Moreover, a 3D visualisation system provides the user with a user-friendly graphical tool to observe the action from the desired viewpoint.

The objective of this paper is to give an overview on an ongoing research project concerning two types of piano actions (Figure 1), via the use of the multibody approach. The first one is the modern grand piano action, for which much technical literature is available. Even if it is the most complex one from a morphological point of view, it is certainly the best-known action. Second, we are interested in an 18th century *Prellzungenmechanik* by Johann Andreas Stein, typically used by the Viennese and South-German classical piano school. The instruments which use this kind of action are fairly well preserved and frequently rebuilt by piano makers.

3. Modelling piano actions

In this section, we introduce the main principles of multibody dynamics and its application to piano actions. Thereafter, we illustrate how the models are validated. Throughout this section, we use the double escapement action as a guideline. Needless to say, exactly the same techniques are applied to the other action.

3.1 Introduction to Multibody dynamics

Multibody dynamics is a branch of mechanical engineering which consists in predicting the motion of poly-articulated bodies, that is, systems composed of multiple bodies connected by joints (e.g. hinges, telescopic, ball joints, etc.). Classical applications for this method range from road and rail vehicles to robotics, biomechanics, transmissions, etc. The piano action is also a poly-articulated system as it consists of multiple bodies linked to each other through rotational joints.

Multibody dynamics is based on equations known since the 18th century, namely Newton's equation of motion which yields $\boldsymbol{F} = m\,\ddot{\boldsymbol{x}}$, and its equivalent in rotation, Euler's law $\boldsymbol{T} = \boldsymbol{J}.\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \boldsymbol{J}.\boldsymbol{\omega}$ written for each body of the system. In the previous equations, $\boldsymbol{F}$ and $\boldsymbol{T}$ respectively stand for the external applied force and torque resultant with respect to its mass centre, m and $\boldsymbol{J}$ are the mass and the inertia tensor of the body with respect to its mass centre and $\ddot{\boldsymbol{x}}$ and $\dot{\boldsymbol{\omega}}$ represent the absolute linear and angular accelerations of the body. Whatever the formalism used to generate these equations of motion for the multibody structure, the system kinematics is always described in terms of so-called generalized coordinates, $\boldsymbol{q}$, from which position, orientation, velocities and accelerations will depend. In particular, $\ddot{\boldsymbol{x}} = \ddot{\boldsymbol{x}}\,(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}})$ and $\dot{\boldsymbol{\omega}} = \dot{\boldsymbol{\omega}}(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}})$.

Using these generalized coordinates as system variables, the multibody equations of motion can be written in the following matrix form:

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{F}\,(\boldsymbol{q}, \dot{\boldsymbol{q}}, \boldsymbol{f}, \boldsymbol{\tau}) = 0 \qquad (1)$$

where $\boldsymbol{M}$ is the so-called mass matrix and $\boldsymbol{F}$ contains the centrifugal, Coriolis and gyroscopic effects as well as the forces $\boldsymbol{f}$ and torques $\boldsymbol{\tau}$ applied to the bodies.

The system of equations (1) can be written by hand for small academic examples, but becomes too complex for large and realistic systems for which the equations are generally non-linear with respect to $\boldsymbol{q}$ and $\dot{\boldsymbol{q}}$. We therefore use an in-house software called Robotran [5]. Starting from the system to analyse (Figure 2a), a schematic representation can be achieved; in the schematic representation of a multibody system in Figure 2b, ellipses stand for bodies and lines for joints. Then, on the basis of a formalism and given all the system parameters (dimensions, mass, centre of mass, inertia, etc.), Robotran automatically writes the equations of motion (1) in a symbolic manner (Figure 2c).

At this stage, by analogy with a model of the human body, the user has in his possession a human body in free fall and without muscles, but with the correct body characteristics and joint kinematics. The next step consists in writing the law forces $\boldsymbol{f}$ and torques $\boldsymbol{\tau}$ appearing in (1) according to their underlying physical laws.

Once forces and torques are fully described, the differential system (1) can be easily simulated with a suitable numerical time integrator to provide the desired results (Figure 2d).

3.2 Multibody modelling of piano actions

The main hypotheses underlying the action models are the following: the motion is planar, bodies are rigid[1], joints are geometrically perfect (no backlash) and the string damper is not considered.

In the multibody model of a grand piano action (Figure 3), the various rotational motions of the bodies are the generalized coordinates of the model: $\boldsymbol{q} = (\boldsymbol{\theta}^k, \boldsymbol{\theta}^w, \boldsymbol{\theta}^r, \boldsymbol{\theta}^j, \boldsymbol{\theta}^h)$. The body parameters (mass, centre of mass, inertia, etc.) have been experimentally identified by unmounting the components of the action. They have then been weighted and their centre of mass have been evaluated via static measurements. Their inertia has been found submitting them to small pendulum movements; in these conditions, the equations of motion can be linearized. Thanks to the expression of the natural frequency of this linearized system, one can retrieve the value of the body inertia with respect to the fixed pivot:

$$I^0 = \frac{mgd}{(2\pi\nu)^2} \tag{2}$$

where m is the mass of the component, g the gravity, d the distance between the pivot and the centre of mass and ν the natural frequency of the pendulum. When parts could not be dismounted, the inertia has been computed with the help of a CAD software, on the basis of their scanned shape and their material.

An important part of the work refers to the force laws. For the three envisaged piano actions, forces taken into account are the friction in all the pivots (e.g. friction in the hammer shank pivot) and the forces between the interacting bodies (e.g. the hammer and the string, the key and the wippen, etc.). To model these interactions, the first step consists in assessing whether a physical contact exists between two bodies. This is achieved by approximating their contours with simple geometric shapes such as lines, circles or a combination of these. Next, we compute the location of an equivalent contact point on the body contours and deduce the interpenetration depth and velocity of the

[1] Regarding the body rigidity assumption, the hammer shank flexibility has also been neglected. Its flexibility will be considered in future work.

colliding bodies. Knowing this, one can apply the appropriate constitutive laws, according to models issued from the literature [6, 7] (i.e. felt, leather, wood or metal). We can then compute the interacting forces between bodies, both in normal and tangent direction of the contours, and introduce them ($\boldsymbol{f}$ and $\boldsymbol{\tau}$) in system (1).

3.3 Experimental data

Experimental validations of the models have been performed for different parts of the actions. The models are compared with reality using a high-speed camera (3000 b/w fps). The motion of the system is retrieved using checkerboard patterns pasted on the bodies, for which the position of each square corner is tracked (Figures 4a, 4b) all along the trajectory.

The friction of the hammer shank pivot is an important parameter that technicians regulate: if there is too much friction, the action will feel heavy and the motion of the hammer will be too slow. Conversely, too few friction is also negative because the action will lack resistance. In this first experiment, the hammer is dismounted from the action and suspended by its flange. Then we make it oscillate by releasing it form a certain height (Figure 4a). The friction parameter of the constitutive law is then tuned in order to match the tracked result (Figure 4c).

The next step consists in observing the overall behaviour of the entire action. For the sake of repeatability, this is achieved with a mass of 1 kg which is flush with the piano key and then let off so as to depress the latter (Figure 4b). The motion of the key is tracked and serves as the input motion of the model. We then compare the simulated and measured motion of the hammer (Figure 4d). Different phases of motion can be observed; the first sequence, corresponding to the upward motion of the hammer towards the strings, is in good agreement with the experiment. The hammer hits the string when it is horizontal ($\theta \sim 0$), after which it rebounds and gets caught by the back check. At this point, the slight oscillation of the key causes a release of the hammer and the behaviour of the action is less well caught by the model. The hammer is thus blocked somewhat further from the string, but exhibits the same residual oscillations as the real action (Figure 4d).

4. Results and discussion

This section is organized around the two different thematic subjects we are interested in. The first one refers to the double escapement action which equips modern grand pianos and the second concerns a *Prellzungenmechanik* originally conceived by Johann Andreas Stein.

4.1 The modern grand piano action

As mentioned earlier, the advantage of a model is that one can virtually remove parts of a mechanism and observe how it would behave with and without them. The multibody model and the associated computer tools can thus be judiciously exploited to explain with a pedagogical purpose how a piano action works. Due to its complexity, it would be illusory to explain the functioning of a piano action with the help of a complete grand piano action. Consequently, we suggest a process in three progressive steps, each of them having noticeably enhanced the performances of struck keyboard instruments.

(1) Before the appearance of the piano, one finds stringed instruments (like the dulcimer and the clavichord) in which the string is struck, but without any escapement. For instance, when pressing a key of a clavichord, the tangent (equivalent to the hammer of the piano) strikes the string and remains in contact with it as long as the key is held. (2) The invention of the single escapement action by Cristofori in 1700 has been a major breakthrough for stringed keyboard instruments. (3) Finally the double escapement action, the predecessor to those used in modern grand pianos, is patented by Érard in 1821. In line with this, from a historical point of view, a more logical and rigorous approach would have been to model actions of authentic instruments that were contemporary with those inventions. However, the three above-mentioned steps can be explained directly from the multibody model of the grand piano action in which some articulations are intentionally locked and/or from which some components are removed. This way, the inventions can be explained step-wise on one single action, instead of three completely different mechanisms. The learner can thus focus his attention solely on the mechanical evolution and interest of these inventions without being disturbed by the changing aspect of three different actions.

4.1.1 No-escapement Action

By virtually degenerating the grand piano action model, a no-escapement action can be easily produced (Figure 5, Video 1). It consists of three articulated bodies: the key (angle θ_k), a rigidified transmission (angle θ_{tr}) and the hammer (angle θ_h). To suppress the escapement, all we have to do is to remove the escapement dolly (or escapement button) and to rigidly fix the jack of the wippen, constituting to the so-called “transmission” (Figure 5).

With this first morphology, as the key is pressed, its rotational motion is propagated to the hammer via the transmission. Although the hammer is independent of the transmission, both of them will stay in permanent contact. Unless the pianist plays in a staccato manner, the hammer will be pressed on the string (configuration of Figure 5) and the note will be immediately muffled because the hammer prevents the string from vibrating freely.

4.1.2 Single Escapement Action

With respect to the previous mechanism, the single escapement action contains three additional components: the back check, the jack and the escapement dolly (Figure 6a, Video 2). The jack is articulated on the wippen via a revolute joint (angle θ_j) and held in place by a return spring whose role is to re-position the jack in its rest configuration against a stop mounted on the wippen. Thanks to these new components, the key motion is transmitted to the hammer via the two articulated bodies of the transmission: the wippen and the jack. The escapement dolly works as a mechanical stop whose function is to trip the jack up: as the jack toe collides with the escapement dolly, the jack tilts with respect to the wippen (clockwise rotation θ_j) and loses its contact with the roller of the hammer when the latter is very close to the string (Figure 6b): this is the escapement principle. From that moment, the hammer being completely decoupled from the transmission can freely strike the string with a sharp impulse (Figure 6c). After the impact, as long as the key is fully depressed, the hammer is pushed back by the string and caught via dry friction by the back check mounted on the key (Figure 6d). The main function of the back check is to avoid parasitical rebounds of the hammer on the string (denoted as “jingling”).

4.1.3 Double Escapement Action

For this last morphology, two new components are needed and thus appear in our model: the repetition lever and the drop screw (Figure 7a, Video 3). The combination of these components is the fruit of the invention of the Frenchman Sébastien Érard at the beginning of the 19th century. In a similar way to the jack, the repetition lever is articulated on the wippen via a revolute joint (angle θ_r) and a return spring whose function is to support the hammer weight when it lies on the repetition lever. Let us note that the name “double escapement” is inappropriate as the hammer of this action escapes only once. The difference with the single escapement action lays in the fact that it allows a faster repetition of the note after the first impact, as explained hereafter.

The double escapement action works exactly the same way as the single one until the hammer has hit the string and has been caught by the back check (Figure 7b). Therefore, let us start with this configuration: the key tip is kept in its lowest position after a finger blow (full stroke). Then, if the key is slightly released, friction between the back check and the hammer becomes too weak and the contact is lost: thanks to the return spring, the repetition lever is able to push the hammer upwards to a limit position defined by the drop screw (Figure 7c). From this position, the key requires to be released only slightly more so that the jack can re-position itself right under the roller: the key stroke required for throwing the hammer on the string a second time is thus much shorter than in the single escapement action (Figure 7e). A shorter stroke consequently means a faster repetition capability of the same note.

4.1.4 Response to different types of touch

We have studied the response of our model when it is subjected to different types of key strokes; a “pressed” and a “struck” touch. The first reflects a keystroke during which the finger starts on the key (Figure 8 left), the second starts at a certain distance from the key surface (Figure 8 right). Data for the speed of the key provided by Goebl *et al.* [3] have been time integrated and differentiated in order to respectively obtain its displacement and its acceleration. Both impulses of Figure 8 represent an equivalent of a *forte* dynamic. The key used in [3] is a C4 from a Yamaha Disklavier grand piano, whereas our multibody model represents a LUO piano action. As it is built for demonstration purposes, it isn’t stated for which note it has been built, but the dimensions of the hammer suggest it corresponds to a bass note (around C1). The virtual action has been regulated, so that its hammer in rest position lies at the same distance with respect to the string as in the experimental data of [3].

Predictably, the response of the two actions (real [3] and simulated) are somewhat different. This can be explained to a large extent by the fact that the two actions differ. Although their design is almost identical, small variations in size and materials of the components at their interacting surfaces logically lead to different functioning properties.

The consequences of these differences are reflected in the form of an offset in the response of the hammer. The goal being to compare motion time history but also to track interacting events of the action, the results are deliberately presented such that the time zero reference for the experimental [3] and simulated curves corresponds to the impact of the hammer on the string. As in [3] the hammer-string contact is taken as the maximal acceleration of the hammer travel, which does not necessarily coincide with the first hammer-string contact.

The curves for hammer velocity show that the model is able to catch the difference in touch of the two inputs (Figure 8). Indeed, the simulation results for a pressed response display the typical gradual increase of speed of the hammer. At 10 ms, after hitting the string, the hammer of the model is abruptly caught by the catch, whereas the hammer of [3] seems to be slowed down without being blocked. The model also gives good motion predictions for a struck touch. The curve is marked by a later and steeper increase in speed of the hammer, but the concavity is the same as for the action studied in [3]. Moreover, in both cases (struck and pressed), the speed amplitudes are similar, and except for the time offset which could be due to different felt compression characteristics, the timing of the hammer responses are very similar. Let us finally note that the modelling results do not show the oscillations found in the measured curves of Goebl *et al.* This is probably in part due to the rigid-body assumptions of our model.

4.1.5 Timing of the action

Thanks to the geometrical computation of contact between components of the action (see in Section 3.2), one can perform a timing analysis of the interaction between components. The *forte* pressed touch used in the previous section serves as the input for the model. Our results are compared on the basis of a 20 ms time window, centred on the impact of the string.

Under normal regulation settings (Figure 9, middle), the first notable event is the contact between the jack and the escapement dolly, 5 ms before the string impact. This causes the jack to flip back and releases the hammer. The repetition lever is the first to loose contact with the hammer roller, closely followed by the escapement jack. The hammer is released 0.5 ms before string contact and flies freely towards it. After the hammer has rebounded on the strings (~1.5 ms contact duration), it is first intermittently slowed down by the repetition lever (2 ms after impact), then the jack (7 ms after impact). As the key is kept depressed for some time, the hammer is finally blocked by the catch (~8 ms after string impact).

It is interesting to highlight the differences in timing of this modelled *forte* key stroke with the results of [1] for the same dynamics. Let us note that the definition of hammer impact in [1] is given as the first contact with the string, not the peak in acceleration as we have chosen. The timing results of Askenfelt *et al.* discussed in this paper are thus shifted in time by ~1 ms and will be referred to as "corrected time". Most notable is the offset in time for the escapement; in [1], the contact between jack and roller is lost after the first contact of the hammer with the string, but before the string impact event (approximately -0.8 ms in corrected time). In our model, hammer string contact occurs before the first string impact. String contact is slightly longer in [1]; 2 ms versus 1.5 ms in the multibody model. After the hammer rebounds from the string, the timing is different: the repetition lever catches the roller ~1 ms later in the multibody model, but the jack-roller contact occurs even later (1 ms vs 8.5 ms in the model). One of the possible causes of this difference might be due to different initial key height. Indeed, the key motion (Figure 8) has been obtained by time integrating the experimental key velocity, which can only provide a vertical travel but not the initial configuration. Consequently, if the key is depressed too deeply (further than the key-bottom felt), the jack is tripped too far away from the roller as shown in Figure 9. This hypothesis could also explain why the simulated hammer is caught by the catch whereas it is not in the experimental case (Figure 8, between 10 and 20 ms).

4.1.6 Influence of the escapement height on the timing of the action

Pianists are very keen on the touch a piano confers when its key is being depressed. Technicians can meet this sensitivity by carefully tuning parameters related to the geometry and stiffness of certain components. An example of the refinement of the regulations is found in the notion of escapement height. The escapement height is defined as the distance between the hammer and the string once the hammer has escaped from the rest of the action and flies freely towards the strings. Pianists are extremely sensitive to this parameter, as a greater or smaller escapement height leads to a smoother or stiffer sensation of control.

We compared the response of our model to variations in let-off distance with the results of Askenfelt *et al.* [1]. It was chosen to keep the same regulations as in [1]; a normal, short and long setting for which escapement respectively occur at 1.8 mm, 0 mm and 3.8 mm. Being limited to the data available in literature, we use the pressed touch with *forte* dynamics of [3] (Figure 8, left), contrary to Askenfelt *et al.* who perform their comparison at *piano* level dynamics. However, according to [1], the only major influence of dynamics lies on the timing of the key-bottom contact which occurs earlier regarding the string impact in the case of louder dynamics. In the same vein, lower dynamics appear to have characteristic longer delays between the events.

Let us now compare the influence of setting the let-off distance at different heights (Figure 9). The escapement height is increased by lowering the escapement dolly, it is thus logical to observe that the jack is tilted later with the decrease in escapement distance. When escapement is set close to the string, the jack intermittently loses contact with the escapement dolly. The contact between the repetition lever and the escapement dolly is fairly consistent over the entire time range, apart from some rebounds of the hammer when set in normal and close configuration. The fact that contact is lost and restored at the same moments of time is due to the drop screw which limits the motion of the repetition lever. Contact with the repetition lever will consequently always be lost at the same point. The jack-roller contact gives the same tendencies as in [1]: free flight before string impact diminishes with escapement height. The same can be said for free flight after the impact, but as indicated above, the jack is probably too far from the escapement dolly, delaying its contact with the hammer roller. Hammer-string contact and hammer-catch contact are not visibly influenced by a change in let-off height.

4.2 The *Prellzungenmechanik*

The *Prellzungenmechanik* (PZM) we have modelled is a copy based on the 1788 Johann Andreas Stein *pianoforte* held at the Germanisches Nationalmuseum (MIR1097). The name *Prellzungenmechanik* comes from the fact that the working principle of the action is based on the rebound (*prellen* in German) of the hammer beak on the so-called "pawl" (*Prellzunge* in German, Figure 10). PZM actions have been largely used throughout Vienna and northern Germany from 1770 to the end of the 19th century, up to a point where the mass of the hammers became so large that they became too sluggish compared to other types of actions which were powerful and agile at the same time.

In this section, we first compare how the regulations made by technicians affect the behaviour of the PZM. Next, we analyse the response of the action to three different inputs corresponding to various playing styles; a pressed touch, a struck touch and a falling mass.

4.2.1 Regulation of the escapement height

The model of Stein's PZM enables us to confront simulation results with the experience of piano technicians used to regulate this kind of actions. More precisely, we are looking at the influence of the regulation of the action on its behaviour. This kind of analysis has never been formally quantified for PZM actions. In Viennese actions, the escapement height is defined as the distance between the hammer (Figure 10 above, (a)) and the string once the beak has escaped from the pawl (Figure 10 above, (b)) and flies freely towards the string. As in Section 4.1.5, we illustrate this with the regulation of the escapement height. In the early Stein actions, technicians had to adapt the escapement height by adding or suppressing plies of paper of different thicknesses between the pawl and the stop which limits its movement (Figure 10 above, (c))[2].

When performing this regulation in the model, one can notice a very high sensitivity by inspecting the linear relation with a 1/20 slope between the escapement height and the number of plies of paper (Figure 10 left). In other words, moving the stop 1 mm will cause a 2 cm displacement of the escapement height. Furthermore, the admissible regulation range is very limited as the action stops functioning when too many plies of paper are added or removed (grey area in Figure 10 left). Knowing that the regulation of the escapement height must be carried out with a precision of about 1 mm, one can easily imagine the delicate tuning work of the technicians for setting up such instruments. Time-event diagrams analysis were also carried out, but the results did not provide significant variations for the different regulations leading to a playable instrument.

The global motion of the hammer also gives a good idea of the consequences of the set-up of the pawl. Two different cases have been studied and compared with a reference where the action is well tuned (Figure 10 right, continuous). In the first case, the pawl has been shifted 1.13 mm to the left (Figure 10, right dotted). Because the hammer escapes early, it is also rapidly subjected to gravity without any further driving force to propel it

[2] Johann Andreas Stein's daughter Nannette introduced screws to adjust the escapement soon after taking over her fathers' shop [8].

towards the strings. This means that the hammer decelerates over a longer period of time and hits the strings with less force. As a consequence, the bouncing of the hammer on the string is of lesser intensity, and the hammer also falls down more slowly. In the second case, the hammer has been shifted 0.15 mm to the right (Figure 10 above, dashed). Even if this value is very close to the functioning limit of the action, the consequence of this shift on the hammer motion is not as impressive as in the first case; up to 0.75 s, the two curves are almost identical. The smaller amplitude of the hammer bounce after 0.75 s can be explained by the increase in friction between the hammer beak and the pawl due to the new resting position of the latter. Because of this increase in friction, the hammer loses more speed when falling back in rest position and logically bounces less on the felt loops located at the middle of the action.

4.2.2 Response to different types of touch

Following the same principles as in Section 4.1.4, we have applied three different types of key-stroke to the PZM action (Figure 11). For the pressed and struck touch, the speed curves of [3] have been scaled so that the total key-dep would reach the 47 mm of our Stein action. The third type of key-depression is imposed by a falling cylindrical mass of 400 g placed on the key surface. The escapement height has been set to 2.5 mm.

Before analysing the simulation results, let us discuss the issues of imposing either a displacement or a force at the key front. Be it in the form of motion or force, measurements can only be reused with a certain degree of certitude as input data in a model. Indeed, the force that the pianist applies on the key is directly dependant of the resistance the action opposes. Consequently, the motion of the key and the force needed to put it in motion are directly linked to the resistance it offers. In our case, with the displacement driven-models, it could very well be that the displacement of the key is at moments too slow or too fast, simply because the resistance of the double escapement action differs from the PZM, according to their respective stage of motion. Since we lack precise data concerning PZM key strokes, we use the “falling mass” simulation as a reference curve. Even if [1] has shown for the grand piano action that a falling mass (or equivalent mechanical system) does not reproduce human touch, this kind of input can illustrate how the action reacts when subjected to a gravity-type input. Indeed, contrarily to a human force input, a falling mass can be considered as a neutral input since its effect is independent from all the mechanical events in the action**.** More precisely, it can give us an idea of the resistance felt by the pianist.

Let us analyse the simulation results for the falling mass in depth (Figure 11 left). During the first 20 ms (from -33 ms to -14ms), the mass sets the key in motion, but the hammer barely moves; its velocity is almost zero and it is in contact with the felt loop that supports it. This can be explained by the design of the PZM (Figure 10 above) ; one has to wait until the hammer beak hits the pawl before the hammer starts to rise significantly. At -14 ms, the hammer steeply accelerates thanks to this interaction. At that stage of the movement, the velocity of the key is slightly diminished because of the supplementary mass of the hammer that has to be propelled. With a 400 g mass, the effect is marginal, but when lowering this mass (corresponding to softer dynamics), the speed decrease is far more pronounced. Even with less heavy masses, the light hammer takes advantage of the momentum of the key and is sharply accelerated. Once put in motion, its speed increases linearly until contact with the pawl is lost (-1 ms, ES on Figure 11 left). The hammer is then in free flight for about 1 ms before it hitting the string; the slope of the hammer velocity becomes negative as it is subjected to gravity. Shortly after the impact of the string, the key reaches the key-bottom (2 ms, KB on Figure 11 left). As in [3], key-bottom contact is taken as the maximal acceleration of the key when it is in contact with the stop that limits its movement. The effect of the 400 g weight is not sufficient to continuously keep the key in its lower position; after hitting the key-bottom, the key rebounds before reaching equilibrium (the equilibrium state is not visible in Figure 11). Also, as the key is constantly depressed, the hammer beak is kept against the vertical side of the pawl. The hammer falls down and rebounds on the felt loops.

Comparing these results with those obtained for the double escapement action, we can already outline three characteristics of the PZM; the hammer accelerates (1) suddenly but (2) with a certain delay compared to the motion of the key and (3) the abrupt increase in speed of the hammer causes a slowdown of the key (this effect of resistance can be felt when playing a real PZM action). The differences in behaviour are mainly due to the fact that the hammer of the PZM is directly hinged on the key and that the component responsible for the propulsion (the pawl) is not initially in contact with the hammer.

Looking at the results for the pressed touch (Figure 11, middle), one can observe the same tendencies in hammer response; a fast acceleration followed by a steadier acceleration phase that has a shape similar to the key velocity. The escapement of the hammer and the key-bottom event occur approximately at the same time (-0.54 ms and -0.34 ms, respectively ES and KB on Figure 11). With this input pattern, the hammer loses speed even before having escaped. This is due to the speed profile of the key which displays a deceleration before the hammer-string impact. As long as the hammer has not escaped, the influence of key motion is very important since it is directly coupled with the hammer through the beak-pawl contact. Once the hammer has escaped, the lever effect is lost and the motion of the key has a limited influence on the hammer; from that point on, the speed curve displays a constant slope, mainly influenced by gravity.

Using the scaled struck touch profile of the grand piano action (Figure 11 right) shows an interesting case in which the hammer "outruns" the action; since the first impulse causes a violent shock when the hammer and the pawl collide, the light hammer is immediately propelled at a higher speed than the key. The normal interaction, during which the beak and the pawl are continuously in contact, is interrupted at -17 ms. At that point, the hammer escapes a first time by outrunning the pawl, but is steadily slowed down by gravity. This deceleration allows the key and pawl to catch up with the hammer beak; a second impact occurs at -3 ms, followed by the geometrical escapement[3]. The loss of contact is clearly visible both in the time-event diagram and the hammer velocity graph (Figure 11 right). This profile shows a case where the action is outrun, but then caught up again, resulting in a two-phase, unstable acceleration of the hammer. It can also happen that the hammer outruns the action up to the point where it hits the string without being caught again by the pawl.

5. Conclusions and prospects

This paper illustrates the interest in using multibody dynamics for studying the action of stringed keyboard instruments. A general introduction to multibody dynamics has been given and the workflow needed to obtain a model is illustrated with the guideline example of the double escapement action. Next, we have presented the validation procedure that has been carried out with the help of high-speed imaging.

The ongoing project concerns three different actions, each of which is being studied with a specific objective. The double escapement action is probably the best known of the

[3] The hammer beak is said to escape geometrically when it has passed the angled corner of the pawl and therefore loses contact with the horizontal side of the latter.

three, but is also the most complex to understand. For this reason, the main objective for this action is to exploit the model as a versatile tool for educational purposes. Thanks to the multibody approach which allows us to easily transform a given action into another one by virtually gluing, adding or removing components, the explanation of the escapement functioning has been achieved in a very progressive way. Besides the educational purpose, the model has also been exploited for achieving precise measurements in the form of timing of events, motion and/or forces. The model was precise enough to measure the different reactions of the hammer when the key is subjected to different types of touch. The comparison of these results also highlighted some improvements that need to be made in order to catch even more precise events. Above all, the need to work with exactly the same action in simulation and validation; using data from literature proved to be sufficient to highlight the general behaviour of the grand piano action, but also showed the uncertainties and unknowns they imply can lead to discrepancies in the results. Future work will thus take advantage of measurements on our own piano actions. A second improvement that would probably enhance our results is the inclusion of a flexible hammer shank. This is currently carried out using a multibody flexible formulation.

In the case of an ancient *Prellzungenmechanik* (PZM), the model has proven useful when evaluating the sensitivity of the regulations imposed on the action. It also allowed us to study the response of the action to different types of input patterns of the key. Besides the enhancements envisaged for the grand piano action which also apply to the PZM, the project envisions an issue in connection with the historical evolution of the PZM; in its early versions, the pawl is placed according to a different configuration than in the later versions of the instruments. This change of morphology leads to actions with **a** different dynamic behaviour. It is hoped that a multibody model will be able to shed light on the reasons of this evolution.

The last action in the scope of this project has not been treated in this paper. It concerns an action which has not survived in any physical form whatsoever. Indeed Arnaut de Zwolle’s fourth striking mechanism has reached us through a drawing in his manuscript [9]. Many unknowns concerning its dimensions and proportions still remain and it is uncertain whether Arnaut de Zwolle’s sketches refer to a working action that really existed. Therefore, a parametrized model of the action might end up with the best candidate for a working action. After the numerical investigation, if it appears the action is viable, it is planned to build a real exemplary in collaboration with the Musical Instruments Museum Brussels and the Hogeschool Gent.

6. References

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7. Tables with titles

8. Captions for Figures

Figure 1: The two actions studied in this paper: (a) a grand piano action with the double escapement system and (b) a *Prellzungenmechanik* by Johann Andreas Stein.

Figure 2: Typical workflow in order to create a multibody model. A real poly-articulated system (a) is schematically represented (b). The equations of motion (c) are then automatically generated by Robotran. The results (d) are obtained after a numerical integration of these equations.

Figure 3: The doubles escapement action possesses 5 generalized coordinates $\boldsymbol{q}$ in the form of 5 angles: θ^k the angle of the key, θ^w the angle of the wippen, θ^r the angle of the repetition lever, θ^j the angle of the jack and θ^h the angle of the hammer.

Figure 4: The piano action models are validated using targets placed on their components and tracked by a high-speed camera. The experiments and the simulation results are compared.

Figure 5: When the no-escapement action hits the string, all components of the action are in contact; the hammer continuously presses the string, muffling the sound.

Figure 6: Single escapement action: (a) initial configuration at rest; (b) just before the escapement; (c) after the escapement when striking the string; (d) final configuration, when the key is held fully depressed.

Figure 7: Double escapement action: (a) initial configuration at rest; (b) configuration when caught by the back check; (c) after a slight release of the key, the back check frees the hammer; (d) thanks to the repetition lever, the jack has slid under the roller whereas the key is not completely released: the action is ready to repeat the note; (e) the grey key represents the repetition position of the single escapement action.

Figure 8: The displacement caused by a pressed touch (left) and a struck touch (right) applied to a real action [3] have been used as an input for the modelled action. Speed profiles for the hammer are similar for the experimental and the simulated curves for both types of touch.

Figure 9: Contact duration for the grand piano action set up for a long, normal and close escapement height.

Figure 10: (above) Solidworks representation of the action modelled in Robotran. The real action is a replica held at the Brussels Musical Instrument Museum of the one found

in a pianoforte preserved at the Germanisches Nationalmuseum (MIR1097). (left) Inserting a sheet of paper of 1 mm induces a shift of the escapement height of 20 mm. The grey areas indicate the functioning limits of the action. (right) Compared to the reference case, when the pawl is shifted to the left, the hammer escapes sooner and thus slows down. The influence on the hammer trajectory of a shift to the right is more complex.

Figure 11: Response of the PZM model to a falling mass of 400g, a pressed touch and a struck touch. Three events are highlighted in the hammer velocity graph: escapement of the hammer (ES), hammer-string contact (HS) and key-bottom contact. The time-event graphs indicate when pairs of bodies are contacting: the pawl with the horizontal and vertical part of the hammer-beak (HB), hammer-string contact and interaction between the hammer and the felt loop that supports it.

***Detailed Response to Reviewers**

The authors thank the reviewers for their sound review of the article and the suggestions they made concerning the results that could be added. According to your suggestions, we have removed the last part concerning Arnaut de Zwolle, and we give more results for the Stein and the grand piano action, that we compared with literature. The reviewer's comments are addressed under their remarks hereunder.

Reviewers' comments:

Reviewer #1: The manuscript "Historical and dynamical study of piano actions: a multibody modelling approach" reports on an attempt to model three different piano actions using a dynamic multibody approach implemented by the academic modelling software Robotran. The authors wisely chose two historic (Zwolle, Stein) and a contemporary piano action (double escapement). For the modern action, they discuss various versions of the action (no, single and double escapement), for the Stein the let-off distance is demonstrated, but for the Zwolle (an action derived from drawings stemming from the 15th Century) no data is reported. The manuscript is sound, provides new work, is well-written and of wide interest for organologists and musicians. I have some suggestions to complement the data presentation with the current models (which I find to be essential for the manuscript) and some smaller things easily changed.

Regarding the data presentation, it would be desirable to have more data discussed with the modern and the Stein action models:

1) the modern action model should also be exposed to different let-off settings as the Stein actions were, and compared with data reported in Askenfelt and Jansson 1990 (they measured a Steinway action).

2) You may also want to mention the effects of adjusting the repetitions lever screw (p. 8 bottom).

3) (!!) both Askenfelt/Jannson and Goebl et al address different types of touch applied by pianists to the key surface. It would not be hard to compare a keystroke with continuous acceleration to one with a sudden jerk onto the key surface on both action models (Double & Stein). Particularly, discussing the effects of touch on the Stein action (timing, vibration of the shank etc.) would really report something completely new in the field and would help to demonstrate the potential of the current approach.

Suggestions (1) and (3) seem very interesting for our project: we have improved the text accordingly, by carefully comparing the proposed literature experimental data with our simulation results. Regarding the hammer shank flexibility (mentioned in suggestion 3), we haven't studied the effect of touch on the hammer shank vibration as it is considered as a rigid body (cfr. hypothesis of our model). As mentioned in the prospects, shank flexibility will be added in future works.

Suggestion (2) has been omitted due to a lack of space, further to the above interesting comparison (suggestions 1 and 3).

Minor comments:

Please use always the full name: "Johann Andreas Stein" (see abstract 3rd par: "Johan" missing "n"; in the keywords: missing "Johann", Section 1: missing "Johann"; p.6: "Johan" missing "n")

This has been modified at the places mentioned by the reviewer and also in some other parts of the text where notation was incoherent.

p. 2 "the musical intention of the pianist's" remove apostrophe --> "of the pianists"

Ok

p. 6 "However, it would be anti-educational...analysing the one from the grand piano." I don't understand this phrase and the reasoning behind it (and the following paragraph). Please re-phrase to clarify.

The paragraph has been rephrased. The idea is that it is easier to explain three different principles on one single action, rather than using three distinct actions functioning with different mechanical principles.

p. 9, line 16/17: "Prelleiste" (=rebound bar) is not correct, as Stein's invention actually was about removing the bar and employing individual "tongues" (="Zunge"); thus --> "Prellzunge" would be the correct term.

Ok

p. 9, line 18f: "their size" probably better: "the mass of the hammers"?

Ok

p. 9, line 42: probably good to mention that soon after Johann Andreas Stein, his daughter Nannette introduced screws to adjust the escapement (cf. Latcham, M. (2007). The development of the Streicher firm of piano builders under the leadership of Nannette Streicher, 1792 to 1823. In B. Darmstätter, A. Huber & A. Hopfner (Eds.), Das Klavier bis 1850 (pp. 43-72). Tutzing: Hans Schneider.)

We totally agree with this remark, it has been added.

p. 12: please provide the URL to the online videos of the action examples. This would considerably enhance the reading experience.

Ok

Fig. 4 legends: "mesured" --> "measured"

Ok

Fig. 4c seems to represent data from 4b, 4d from 4a. Probably swab 4c and 4d to align the picture and the measured data column-wise.

Ok

Fig. 5, 6, and 7 are all called "Figure 5".

Ok

Figs. 8, 9, and 10 probably better combined into one figure.

Ok

Reviewer #2:
Manuscript Number: CULHER-D-15-00083

Title: Historical and dynamical study of piano actions: a multibody modelling approach

This is a very interesting and pedagogical paper that deserves to be published. It contains new aspects and original methods to study piano actions. The methods and the principles are well described. Figures and references are good. However, it is too limited in terms of results. Therefore the paper needs major corrections before resubmission. Additional comments are detailed below.

Comments
1. In the abstract, I would not write that "a more flexible manner to study piano actions (compared to measurements) consists in modelling them", since measurements and modelling are complementary tools. (Same remark in page 3, second paragraph).

We agree that both methods are complementary. The idea was to express that simulations did not require to install sensors or physical modification of the action. The idea of complementarity has been adopted in the revised version, however we left the second paragraph of page 3 as is, because we thought it expressed this idea with more refinement.

2. Page 2 "Research aims". The interest of modelling is not only to quantify the performances of a physical system, but also to predict the time evolution of the variables.

Ok, it has been added.

3. In the modelling part (page 4), one paragraph is missing where the assumption of "rigid body" for the hammer shank is justified and/or explained. It is well-known that the flexural vibrations of the shank are clearly visible on the measured accelerations of the hammer head. This feature has a notable influence on the hammer-string interaction. In other words, the hammer shank clearly behaves as a continuous beam rather than a rigid body. This latter assumption should then be more clearly highlighted in the paper, and presented as a simplifying approximation.

As mentioned above, we are aware of that (a more explicit sentence related to this hypothesis has been added in the text) and we plan to take flexibility into account in the next future.

4. Page 5. Section 3.2. There are not enough information here on the procedures used for "identifying the body parameters experimentally". Please add a precise paragraph on this important aspect of the modelling.

It has been added

5. Page 5. Same paragraph. Also precisely describe how the "location of the contact of the body contours are computed". The paper does not contain enough information on this point either.

As we only use circles, lines and points in order to find the potential location of contact, the method is straightforward and relies on basic geometry. Thus, given the number of characters that have been added due to the new results, we have finally decided to not include this because of its lesser interest.

6. Page 7. The last sentence of the first paragraph "The idea...principles" is too long and obscure. Please rewrite it more clearly.

It has been rewritten.

7. Page 11. Last paragraph of Section 4.3. I find it odd to read that a "multibody model will be elaborated". Just do it and report the results in the paper, or do not speak of it at all!

The part concerning Henri Arnaut de Zwolle has been completely removed from the body of the text. It only appears in the research aims as being part of the project, but out of scope of the article. It is also mentioned in the conclusions and prospects.

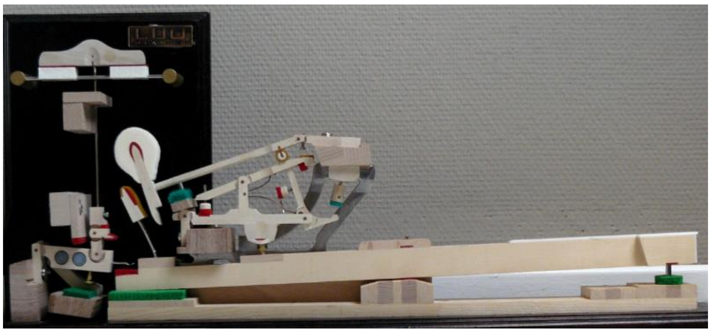
8. Page 12. Section 5 Conclusion. I find it frustrating to see so few quantitative results on the PZM in the paper. It is written, in particular, that "The change of morphology leads to actions with different dynamic behaviour". The authors should deepen this idea and describe (and discuss), at least, one convincing illustrating example.

We have added quantitative results that were combined with the suggestions of reviewer #1

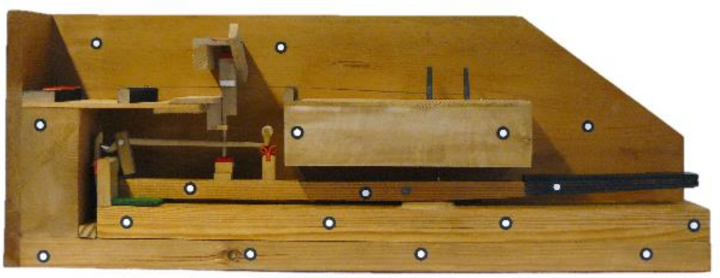
9. In this paper, it would be more appropriate to concentrate on the PZM, and let the description and study on the de Zwolle mechanism for a future paper. The author should remove Section 4.3 and just say a simple word on this mechanism in the conclusion. Section 4.3 should be rather devoted to the detailed description of the application of multibody approach to the study of PZM.

Ok.

Figure 1



(a)



(b)

Figure 2

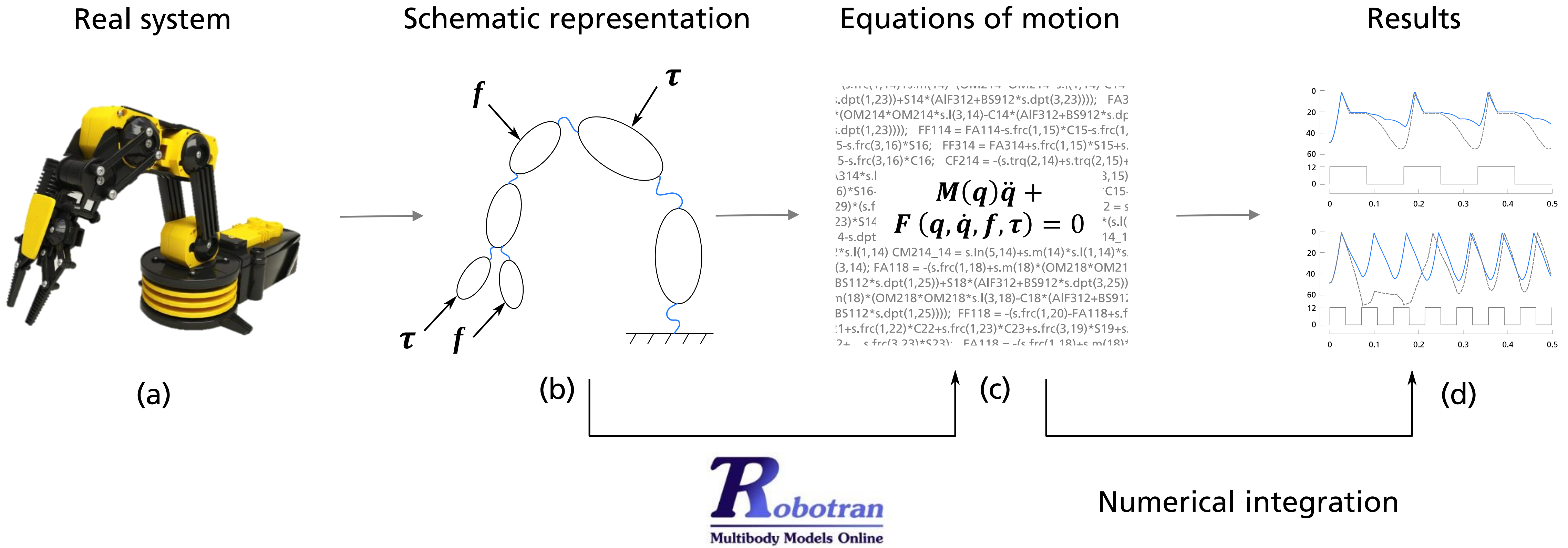

Real system
Schematic representation
Equations of motion
Results
f
τ
τ
f
$M(q)\ddot{q} +$
$F(q, \dot{q}, f, \tau) = 0$
(a)
(b)
(c)
(d)
Robotran
Multibody Models Online
Numerical integration

Figure 3

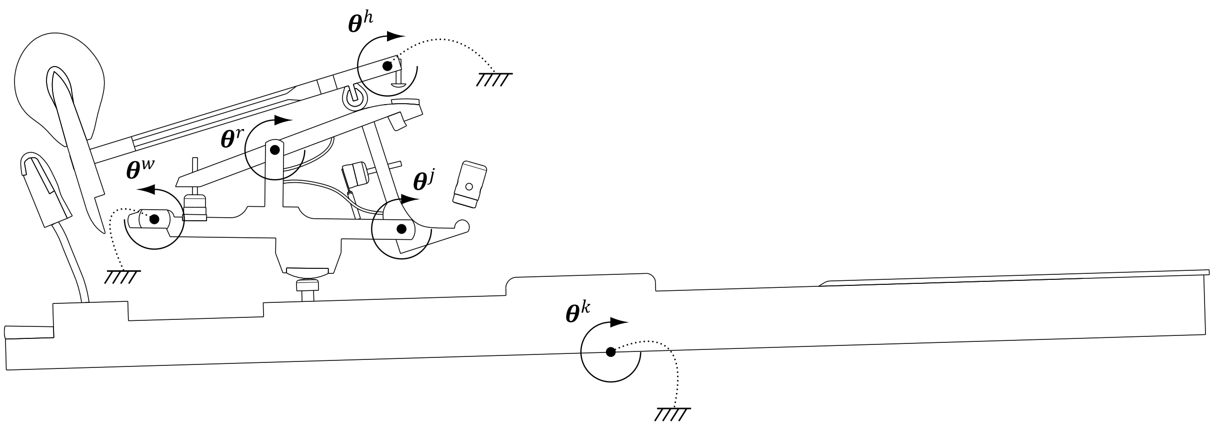
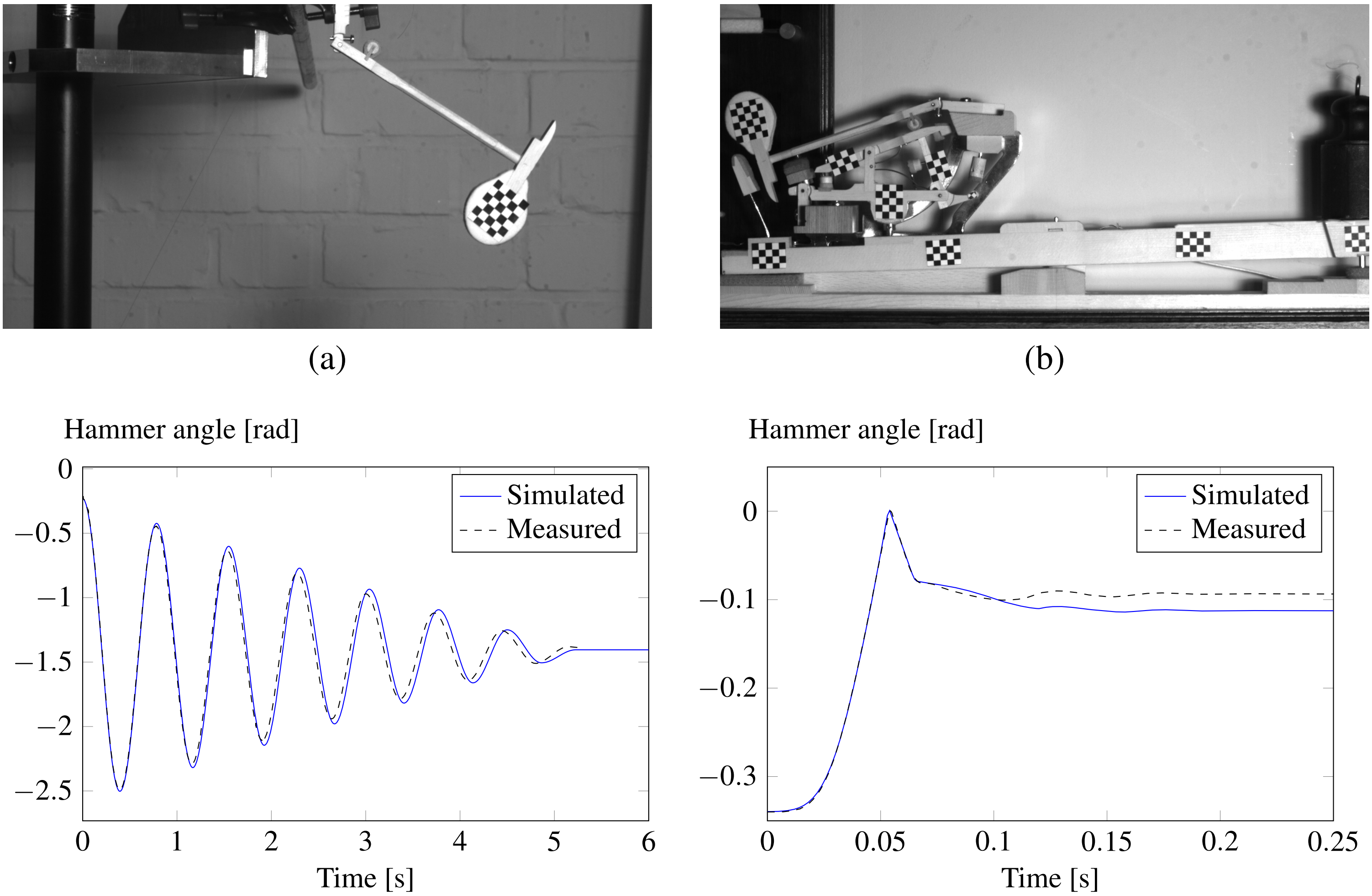

$\boldsymbol{\theta}^h$
$\boldsymbol{\theta}^r$
$\boldsymbol{\theta}^w$
$\boldsymbol{\theta}^j$
$\boldsymbol{\theta}^k$

Figure 4



(a) (b)

(c) (d)

Figure 5

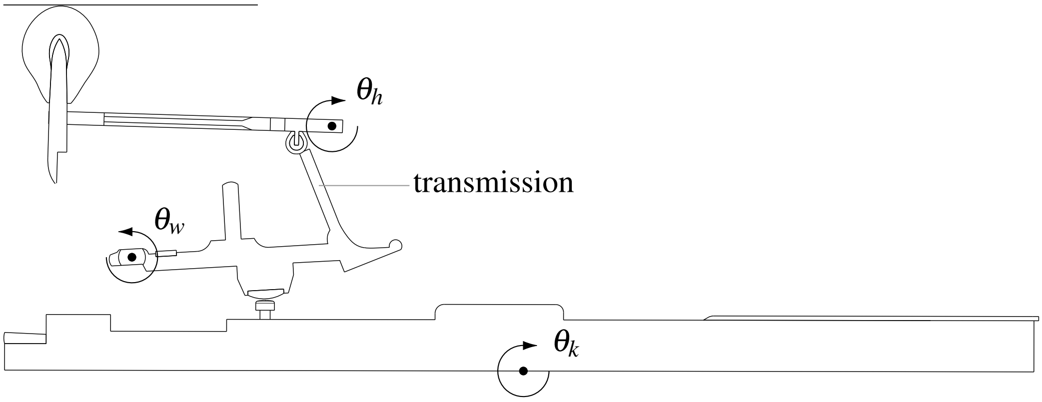
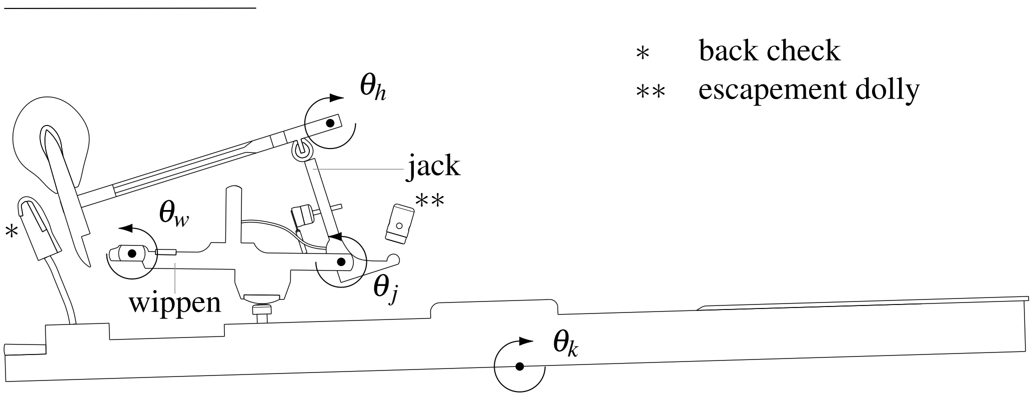
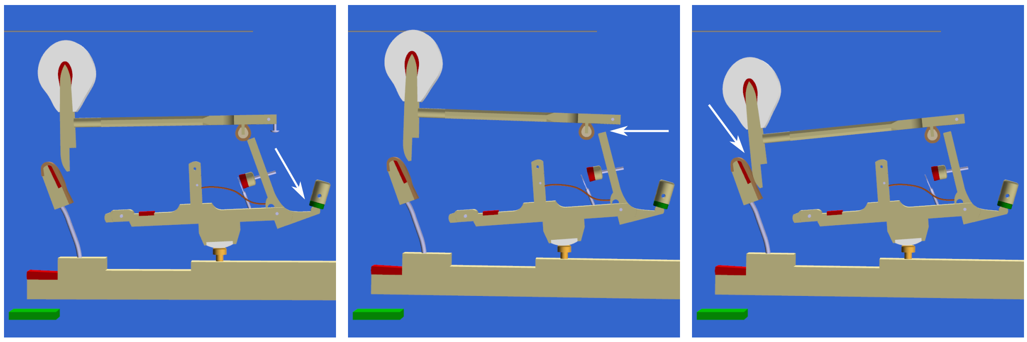


Figure 6

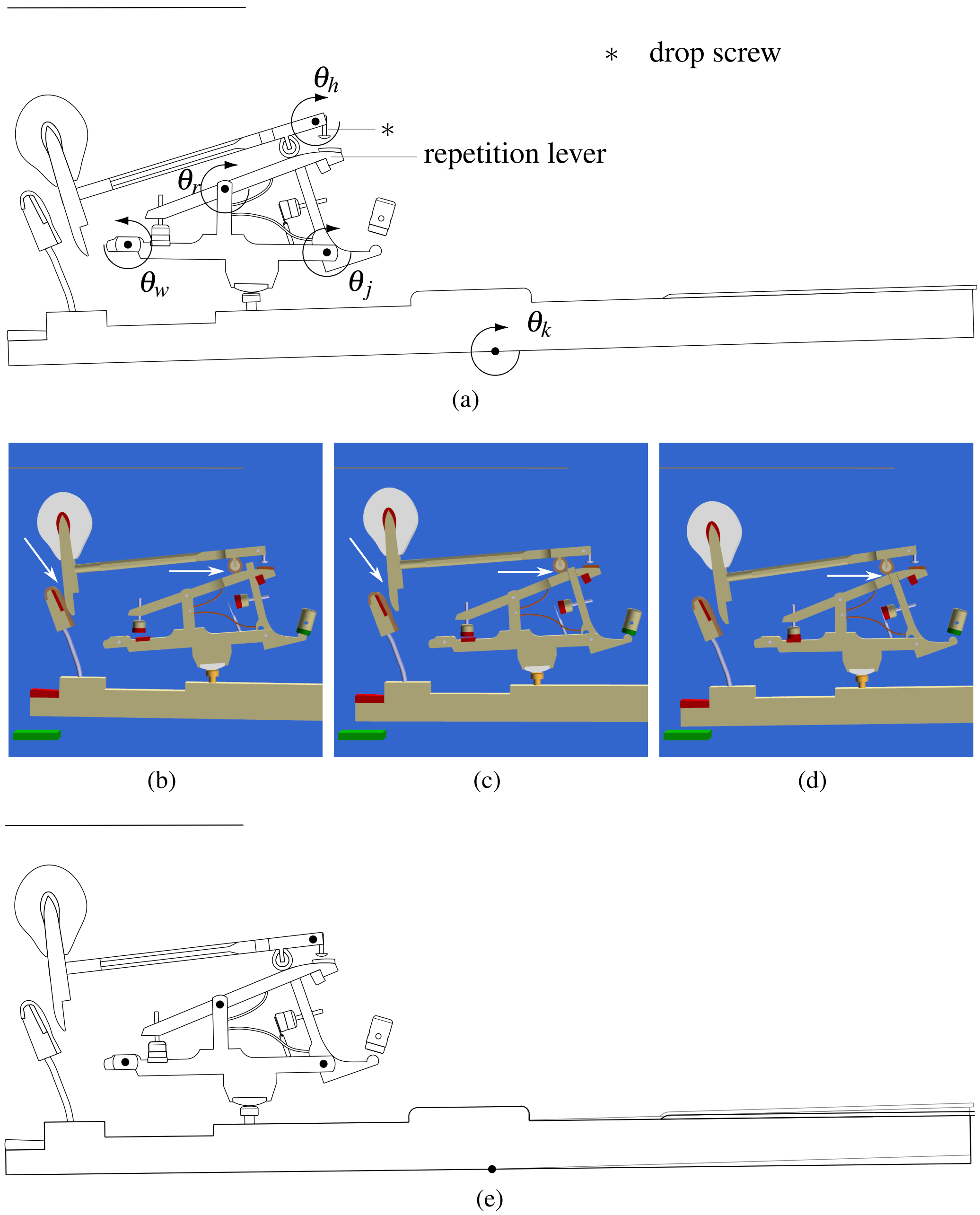


(a)



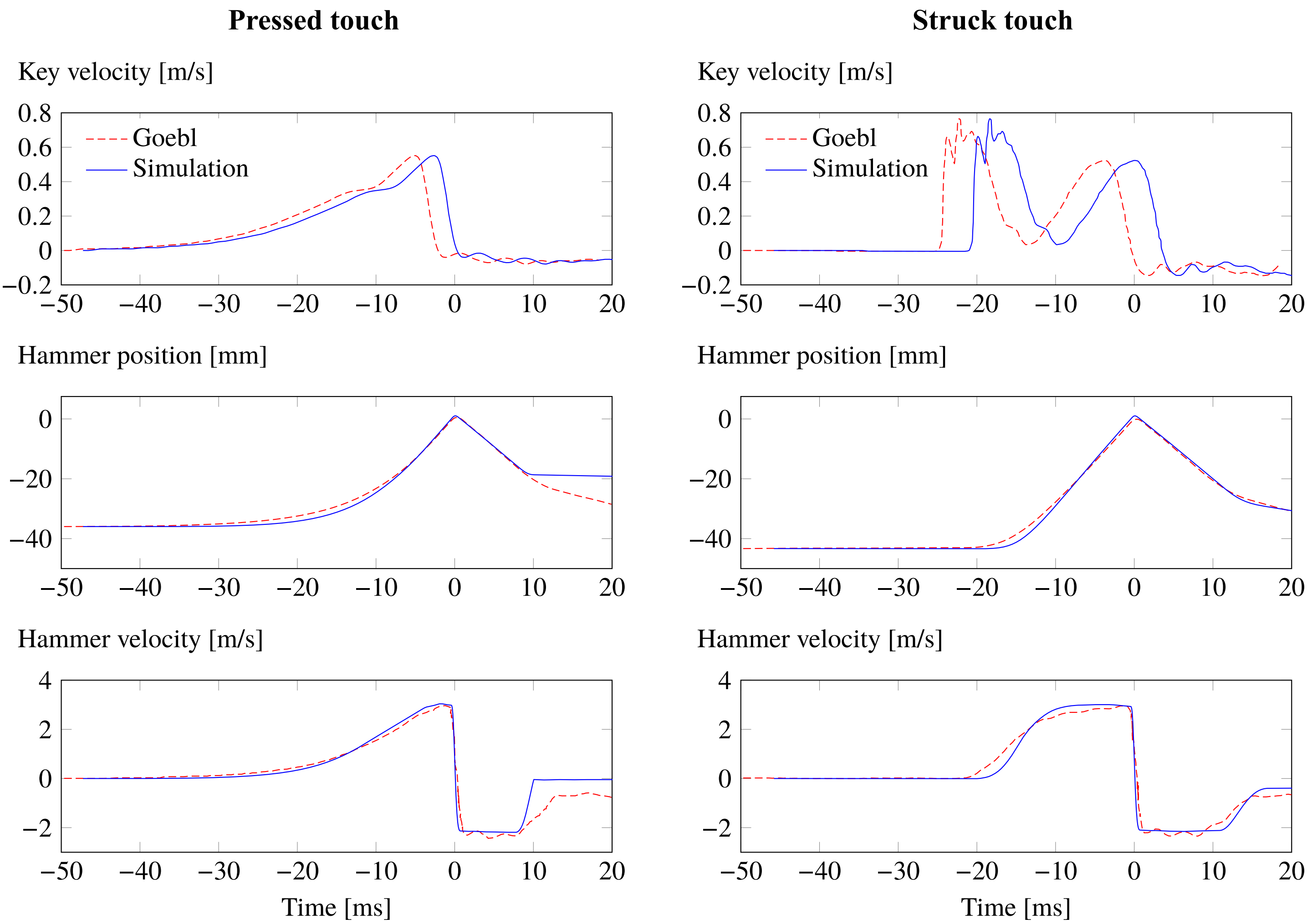
(b) (c) (d)

Figure 7



θ_h
*
repetition lever
* drop screw
θ_r
θ_w
θ_j
θ_k
(a)
(b)
(c)
(d)
(e)

Figure 8



Pressed touch
Struck touch
Key velocity [m/s]
Goebl
Simulation
Hammer position [mm]
Hammer velocity [m/s]
Time [ms]

Figure 9

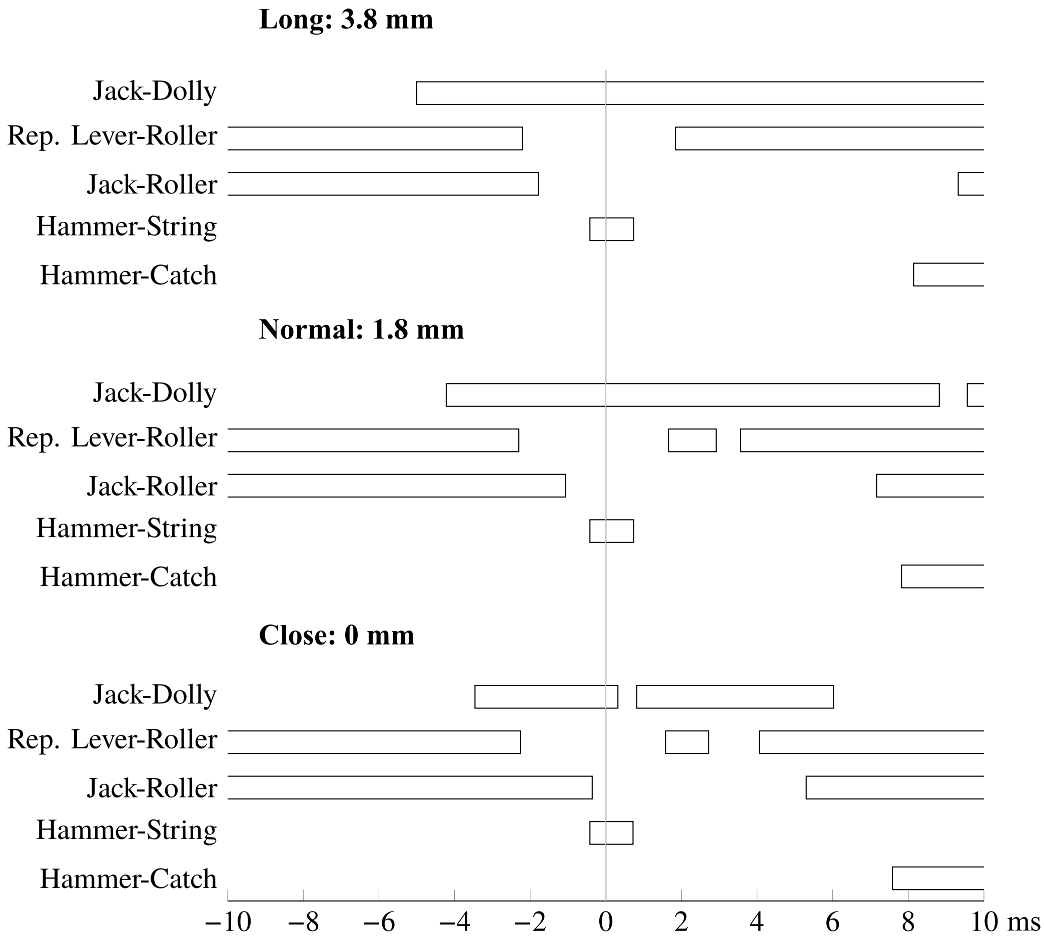

Long: 3.8 mm
Jack-Dolly
Rep. Lever-Roller
Jack-Roller
Hammer-String
Hammer-Catch
Normal: 1.8 mm
Jack-Dolly
Rep. Lever-Roller
Jack-Roller
Hammer-String
Hammer-Catch
Close: 0 mm
Jack-Dolly
Rep. Lever-Roller
Jack-Roller
Hammer-String
Hammer-Catch
−10
−8
−6
−4
−2
0
2
4
6
8
10 ms

Figure 10

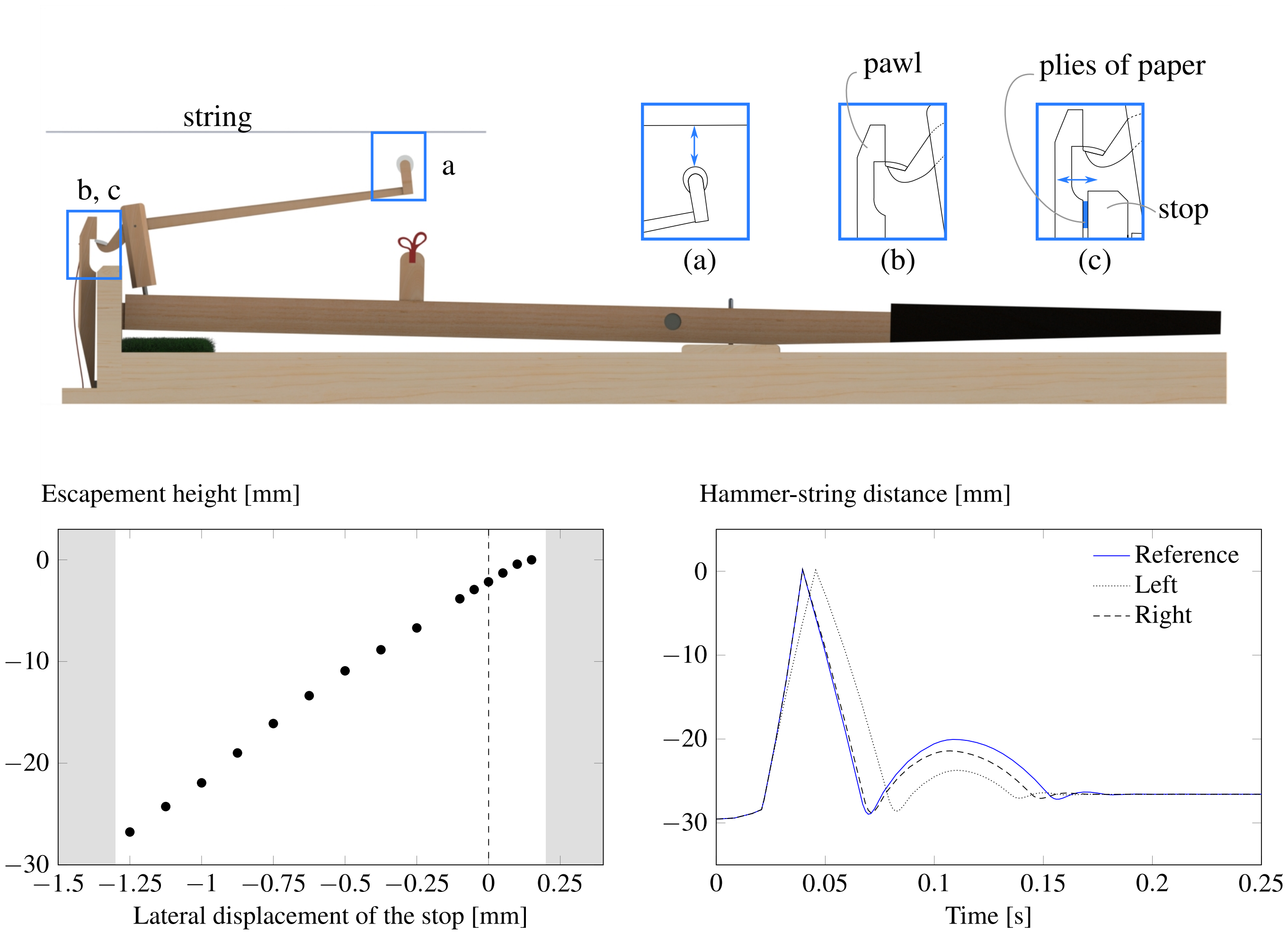
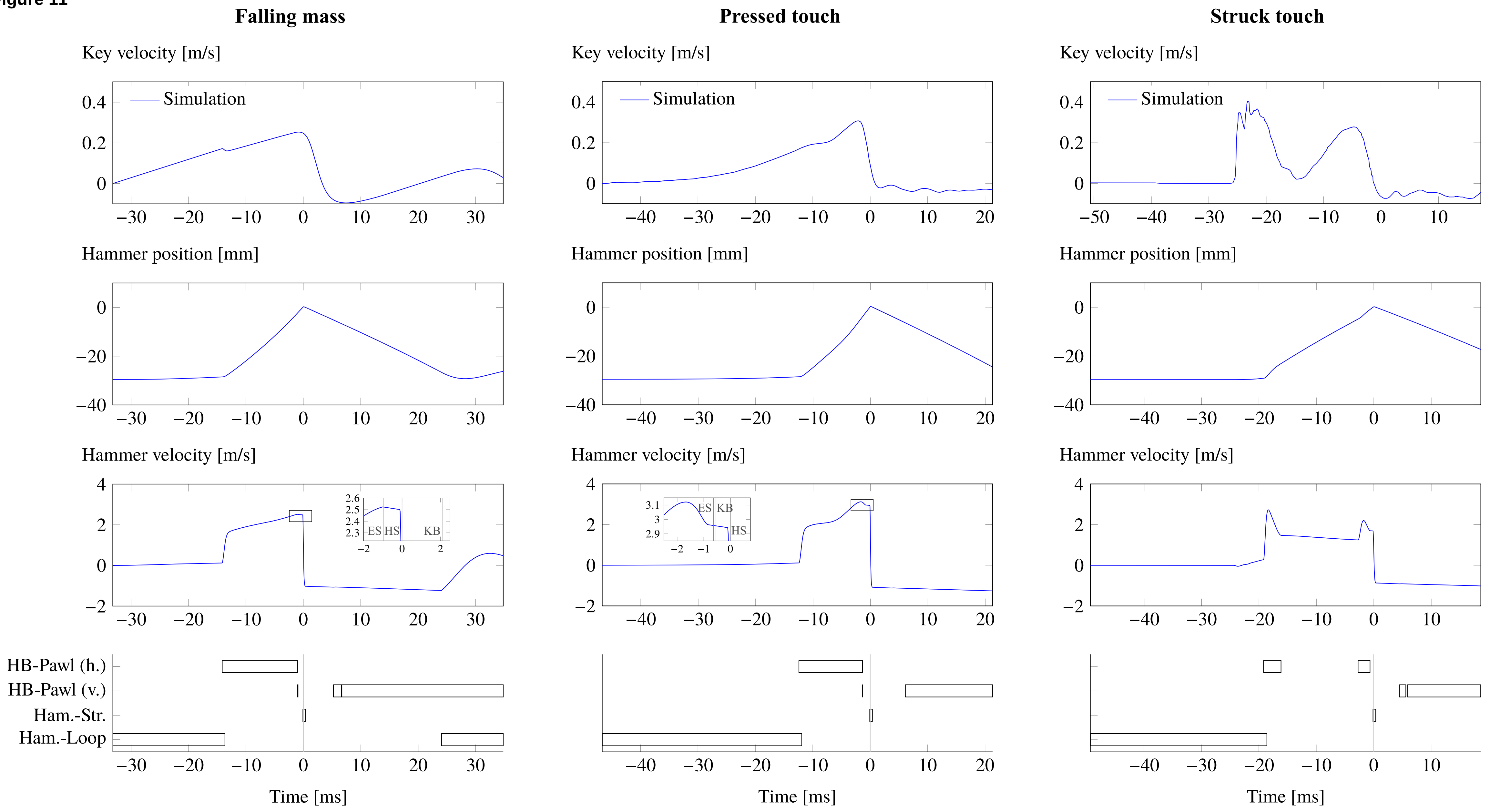

string
a
b, c
pawl
plies of paper
stop
(a)
(b)
(c)
Escapement height [mm]
0
−10
−20
−30
−1.5
−1.25
−1
−0.75
−0.5
−0.25
0
0.25
Lateral displacement of the stop [mm]
Hammer-string distance [mm]
Reference
Left
Right
0
−10
−20
−30
0
0.05
0.1
0.15
0.2
0.25
Time [s]

Figure 11



Falling mass
Pressed touch
Struck touch
Key velocity [m/s]
Simulation
Hammer position [mm]
Hammer velocity [m/s]
ES
HS
KB
HB-Pawl (h.)
HB-Pawl (v.)
Ham.-Str.
Ham.-Loop
Time [ms]

Video 1

Click here to download e-component: Video1.mp4

Video 2

Click here to download e-component: Video2.mp4

Video 3

Click here to download e-component: Video3.mp4