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A standardised pendulum to impact ice hockey boards



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Contents

I.	Abstract / Zusammenfassung / Résumé	6
1.	A standardised pendulum to impact ice hockey boards	6
2.	Pendel für Eishockeybandentests	7
3.	Hockey sur glace: pendule standardisé pour les essais d'impact sur les systèmes de bandes	8
II.	Introduction and aim	9
III.	Design of a new impactor	11
IV.	Proof of concept	13
1.	Pre-tests	13
2.	Comparison of old vs. new impactor	13
V.	Conclusions	17
VI.	Appendix	18
1.	Recorded measurements	18
2.	Derived measurements	19
3.	Pendulum acceleration data	20
	References	22

I. Abstract / Zusammenfassung / Résumé

1. A standardised pendulum to impact ice hockey boards

The following report summarizes the work conducted within the project «Development of a standardised pendulum to impact ice hockey boards». The project was commissioned by bfu in November 2017 and completed by March 2018.

A new impactor suitable for pendulum impact tests against ice hockey boards and shielding was developed. The aim of the design was to overcome some of the disadvantages of the sand-filled punching bag impactor used in the first series of tests performed in 2016. In particular, the new impactor is built of a steel tube covered with neoprene foam and filled with rigidly mounted steel ballast discs. Thus, the new device can be precisely specified for e. g. a standardized ice hockey board test procedure.

The new impactor was validated in tests using a commercially available board / shielding system. The tests showed that the reproducibility is much better than with the punching bag. In particular, the disadvantages associated with the fact that the sand in the punching bag changes its shape at each impact, is completely overcome. In consequence, also the measured accelerations and deformations assume different values.

In view of future homologation procedure, facilitating impactor tests appears most promising. The (inter-lab) repeatability of such tests is high and the cost are moderate such that good acceptance for

this kind of methodology may be expected. Dummy experiments, in contrast, have shown their strength in determining biomechanical measures related to injury risk using certain threshold or reference values. However, the method is difficult to standardise. A combined approach in which dummy experiments are used to determine a board design that is regarded as acceptable (i. e. to establish a reference) and corresponding pendulum impacts could be performed. This would allow the definition of reference values for pendulum impact tests such that for future homologation these reference values could be used in standardized pendulum impact tests. The impactor that was developed in this project offers the possibility to be used as a tool in such a procedure.

2. Pendel für Eishockeybandentests

Diese Grundlage fasst die Arbeiten im Rahmen des Projekts «Entwicklung eines standardisierten Pendels für Eishockeybanden» zusammen. Das Projekt wurde von der bfu – Beratungsstelle für Unfallverhütung im November 2017 in Auftrag gegeben und im März 2018 abgeschlossen.

Das neue Pendel wurde für Schlagtests an Eishockeybanden und Schutzscheiben entwickelt. Ziel der Konstruktion war es, einige der Mängel des mit Sand gefüllten Boxsack-Pendels aus der ersten Versuchsreihe im Jahr 2016 zu beheben. Das neue Pendel besteht aus einem Stahlrohr, das mit Neoprenschaum ummantelt und mit starr gelagerten Stahl-Ballastscheiben gefüllt ist. So kann das neue Gerät z. B. für ein standardisiertes Eishockeybanden-Testverfahren exakt eingestellt werden.

Das neue Pendel wurde in Tests mit einem handelsüblichen Banden-/Schutzscheibensystem validiert. Die Tests haben gezeigt, dass die Reproduzierbarkeit viel besser ist als beim Boxsack. Vorher hat der Sand im Boxsack bei jedem Aufprall seine Form verändert; diese Schwäche wurde behoben. Mit dem neuen Pendel nehmen die gemessenen Beschleunigungen und Verformungen unterschiedliche Werte an als in früheren Versuchen mit dem Boxsack.

Im Hinblick auf ein zukünftiges Normenverfahren ist es wichtig, Pendelschlagversuche möglichst einfach zu gestalten. Die Wiederholbarkeit der hier vorgeschlagenen Tests ist gegeben und die Kosten sind moderat, sodass eine gute Akzeptanz erwartet werden kann. Dummy-Experimente hingegen haben ihre Stärke bei der Bestimmung biomechanischer Messwerte im Zusammenhang mit dem Verlet-

zungsrisiko anhand bestimmter Schwellen- oder Referenzwerte gezeigt. Die Methode ist jedoch schwer zu standardisieren. Alternativ könnte ein kombinierter Ansatz angewandt werden, bei dem mit Hilfe von Dummy-Experimenten ein akzeptiertes Banden-Design (d. h. eine Referenz) und entsprechende Pendelschläge ermittelt werden. Dies würde die Definition von Referenzwerten für Pendelschlagversuche ermöglichen, sodass diese Referenzwerte für zukünftige Normenverfahren in standardisierten Pendelschlagversuchen verwendet werden könnten. Das in diesem Projekt entwickelte Pendel kann als Werkzeug in einem solchen Verfahren eingesetzt werden.

3. Hockey sur glace: pendule standardisé pour les essais d'impact sur les systèmes de bandes

Le présent texte résume les travaux réalisés dans le cadre du projet «Mise au point d'un pendule standardisé pour les essais d'impact sur les systèmes de bandes de hockey sur glace», commandité par le bpa – Bureau de prévention des accidents en novembre 2017 et achevé en mars 2018.

Un nouveau pendule convenant aux essais d'impact sur les systèmes de bandes de hockey sur glace (bandes et vitres de protection) a été mis au point. L'objectif était de supprimer certains inconvénients présentés par l'impacteur utilisé lors de la première série d'essais réalisés en 2016 et constitué d'un sac de boxe rempli de sable. Le nouveau pendule est ainsi fait d'un tube en acier recouvert de mousse de néoprène et rempli d'une structure rigide de poids (disques) en acier. De cette manière, le pendule peut être défini avec précision, p. ex. pour une procédure d'essai standardisée sur des systèmes de bandes.

Le nouveau pendule a été validé au cours d'essais réalisés sur un système de bande usuel. Les essais ont montré que la reproductibilité est bien meilleure que pour le sac de boxe. En particulier, les inconvénients liés au fait que le sable dans le sac de boxe change de forme à chaque impact ont complètement disparu. Avec le nouveau pendule, les valeurs des accélérations et déformations mesurées sont différentes de celles obtenues avec le sac de boxe.

Dans l'optique d'une future procédure d'homologation, il est important de rendre les essais d'impact plus aisés. La répétabilité de ces essais (entre différents laboratoires) est grande et leur coût est raisonnable, si bien que l'on peut s'attendre à une bonne

acceptation de ce type de méthode. L'avantage des essais à l'aide de mannequins, quant à eux, réside dans la détermination de valeurs biomécaniques relatives au risque de blessure, en faisant intervenir un certain seuil ou des valeurs de référence. Cette méthode s'avère toutefois difficile à standardiser. Il est donc envisageable d'adopter une approche combinant deux éléments: des essais à l'aide de mannequins permettant de déterminer une configuration acceptable pour les systèmes de bandes (afin de définir une référence) et des essais d'impact à l'aide d'un pendule. Cela permettrait de définir des valeurs de référence pour les essais d'impact au moyen du pendule, valeurs qui pourraient être utilisées pour une future homologation des systèmes de bandes dans le cadre d'essais d'impact standardisés à l'aide d'un pendule. Le pendule mis au point dans le cadre du projet dont il est question ici pourrait être utilisé pour une telle procédure.

II. Introduction and aim

In a previous collaboration (bfu-Swiss council for accident prevention and AGU Zurich) a procedure was developed to assess the biomechanical loading that an ice hockey player may experience when impacting the ice hockey board. Such impacts bear a certain risk of injury and are thus subject to research. New board designs claim to reduce the impact load which was the motivation to develop a test procedure that allows assessing the performance of a board.

The test procedure previously developed and implemented makes use of two components:

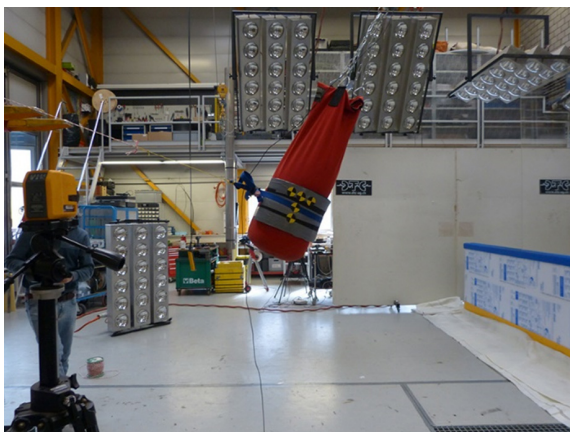
- a) impact tests utilizing a pendulum and
- b) impact tests with a crash test dummy.

The pendulum used so far was based on a study by Poutiainen et al (2014) [1]. This impactor consists of a punching bag filled with sand (Figure 1); its mass is 60 kg. The punching bag was instrumented by an accelerometer placed as close as possible to the centre of gravity, i. e. it was positioned inside the sand. While a punching bag pendulum is easy to use and

its components are widely available and inexpensive, it comes with several disadvantages:

- Sand is compressible and can move inside the bag. This results in overall deformation of the pendulum when impacting the board. Consequently, not all of the impact energy is transferred to the board, but some is used to deform the punching bag.
- The position of the accelerometer inside the bag is hard to control. The sensor can move at impact, changing its orientation. This holds particularly true as the sand deforms. Therefore a tri-axial sensor is needed (while theoretically one axis would be sufficient) to determine the resulting acceleration which is used for evaluation.
- The design of the bag is not standardised. While the overall mass can easily be adjusted, the other dimensions / features of a punching bag are not clearly specified as it would be required if such tests were introduced in a test standard or standardised test procedure, respectively.

Figure 1
Punching bag impactor



These disadvantages of the punching bag result in uncertainties when interpreting the measurements. Therefore, it was the **aim of this project to develop a new impactor** that can be used in place of the punching bag. The new pendulum should be suitable for a standardised procedure.

III. Design of a new impactor

In a first step **the specifications for an impactor** used to test ice hockey boards were developed. Starting point was the previously used punching bag which in principle worked well for this application in the sense that:

- a mass of 60 kg seems appropriate. This mass was suggested by Poutiainen et al (2014) [1] based on an evaluation of real-world impacts. Additionally, the previous research project has shown that an impact using the 60 kg punching bag and an impact utilising a crash test dummy results in a similar displacement of the board, i. e. the mass effective at impact seems similar for both impactors. To ensure good comparability of the punching bag and the new impactor, a total mass of 60 kg was therefore defined.
- a cylindrical shape is preferred. The impactor should be symmetric with regard to rotation around the vertical axis, and the contact area at impact should not be concentrated in one point (as e. g. with a spherical shape) but be larger and along a vertical line (to closer represent the impact of a player).
- the instrumentation was basically reasonable, i. e. an accelerometer should be positioned at the centre of gravity of the impactor. However, it must be ensured that the sensor stays in position during impact.
- the new impactor should be resistant with respect to varying temperature and humidity (as experienced in an ice rink) and (material) aging.
- the mass of the impactor should be adjustable to also have the opportunity to simulate impacts of players of different body weight (e. g. juvenile players).
- the device must be portable such that it allows testing in different places including an ice hockey arena. Therefore, the impactor should be suspended at one rope or string only (in contrast to other pendulum designs that require two or more suspension strings such as a battering ram).
- the cost of the impactor should be reasonably low.

Additionally, the following requirements were defined:

- the impactor must be suitable for a standardised test procedure, i. e. its components and dimensions must be clearly specified such that the device can easily be reproduced by others.

In a second step **a new impactor was designed and produced** based on these requirements. In an iterative process involving several brainstorming sessions, the technical design of different options, discussions with material suppliers and the manufacturing workshop the final design was derived.

The new impactor consists of a steel tube with a wall thickness of 10 mm and an outer diameter of 245 mm approximately, that defines the outer shape of the device. In order to reduce impact forces and acceleration peaks in impacts against hard surfaces, the tube is covered by three layers of neoprene foam with a thickness of 20 mm each. In contrast to the sand used in the punching bag for this purpose, neoprene is elastic and thus the pendulum always returns to its original shape after an impact.

Inside the tube, up to four steel ballast discs are mounted, adding up to the desired mass of the impactor. One disc is mounted with its lower surface about 10 mm above the geometrical centre of the impactor and its circumference is welded to the steel tube. An accelerometer mounted on the lower surface of this disc sits therefore in the centre of gravity of the assembly, since the other three discs are arranged symmetrically around the geometrical (and mass) centre of the assembly. These other discs are connected to the first disc by threaded rods. All discs feature cut-outs at the rear side of the impactor, to allow mounting / unmounting without disconnecting the suspending rope. The first (welded) disc also features a supporting structure, where the suspending rope is connected.

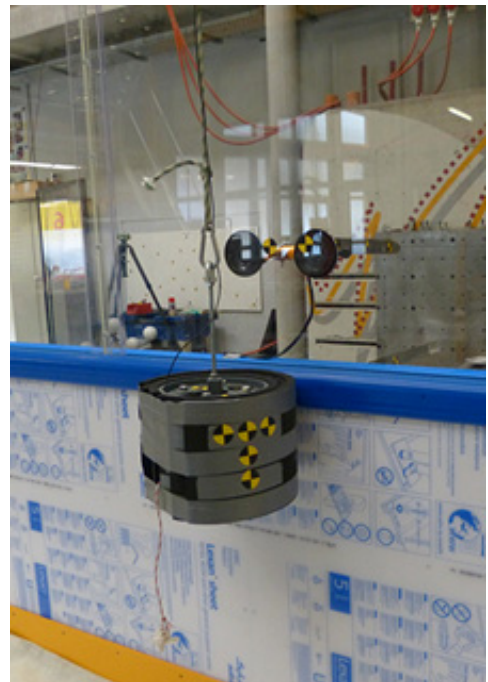
Finally, a vertical slot at the rear side of the outer tube offers the possibility to connect a piece of string or steel cable to a location near the centre of

gravity; thus, it is ensured that the pendulum is always extended by a pulling force acting on the centre of gravity and the pendulum will swing without twisting or wobbling.

Figure 2 shows the new impactor. Engineering drawings of the device and material specifications can be provided as individual (CAD) files on request¹.

Figure 2

Left: CAD rendering of the new impactor without Neoprene coating. Right: impact test against the board system used for the validation of the new impactor.



¹ E-mail address for request: forschung@bfu.ch

IV. Proof of concept

1. Pre-tests

A series of pre-tests was conducted with the new pendulum. In these tests the design and handling of the pendulum was checked for the first time. The device was instrumented as planned and a number of impacts onto a massive concrete block were conducted (Figure 3). Additionally, impacts on a slightly deformable wooden board were carried out. All data was recorded and briefly analysed (e. g. with respect to reproducibility). For comparison, some experiments utilising the punching bag were conducted under the same conditions. Following the tests, minor changes were introduced to optimise the design of the new impactor. Since the number of layers of neoprene had to be increased from one to three during the pre-tests, holes were drilled in the upper- and lowermost ballast discs to compensate for the additional mass of the neoprene. As a result of those pre-tests the final design as described

above was derived and the pendulum was ready for use.

2. Comparison of old vs. new impactor

A test series was conducted to gain experience with the new impactor and to compare its performance with the punching bag pendulum. A set of impacts was carried out under the same conditions as in previous tests (e. g. described in Schmitt et al. 2017/2018 [2,3]). All tests were performed on 20./21.02.2018 at the Dynamic Test Center (DTC) in Vauffelin (Figure 4, p. 14). A commercial ice hockey board was mounted in the lab consisting of three board elements (board height: 1,1 m; transparent shielding: synthetics, 1,9 m).

All instrumentation and test conditions were the same as in previous studies mentioned above:

- accelerometer inside the pendulum

Figure 3

Pre-testing using the new impactor. In this test, a wooden board was mounted to a concrete block with an intermediate layer of damping foam (left, blue) in order to simulate a deforming hockey board



- accelerometer mounted to the back of the board (at 1,0 m above ground)
- displacement sensors mounted at the back of the board (at 1,0 m) and at the shielding (at 1,4 m)
- the system was impacted in the board area (at 1 m) and in the shielding area (at 1,4 m)
- intended pendulum speeds were 3,37 m/s and 4,76 m/s. The impact speed of 3,37 m/s was derived by Poutiainen et al (2014) [1] whereas higher velocity represent impacts double the impact energy.
- for all impact conditions two tests were conducted to check for repeatability.

The detailed results of this test series are presented in the appendix VI.1 and VI.2. The results can generally be separated into measures that were recorded (like pendulum acceleration, board acceleration, board displacement, rebound velocity) and measures that were derived from these recordings (i. e. results that are calculated based on the original measurements such as the kinetic energy, energy absorption, effective mass and the stiffness). Generally, the new pendulum leads to a much better repeatability, especially with respect to the acceleration recorded inside the impactor.

Regarding the measures recorded with the two impactors, the following was found:

- **rebound velocity:** the new impactor results in a slightly higher rebound velocity which can be attributed to its design in the sense that less energy is dissipated in the device itself (e. g. the damping of the sand in the punching bag is eliminated).
- **board acceleration:** at a lower impact velocity there is hardly any difference between the two impacts (difference of approx. 0,5 g). A difference of about 10,0 g was, however, recorded at higher impact velocities where the new pendulum results in a higher acceleration of the board. This is again explained by the fact that the new pendulum shows no permanent deformation.

As an improvement of this test series over the previously performed, an additional accelerometer was attached to the impact area at the shielding. Thus, the stiffness of the shielding can be assessed separately from the stiffness of the board itself.

- **board displacement:** in line with the findings above, the new impactor leads to larger displacements. Less energy is absorbed in the impactor itself, resulting in more displacement of the board system. The board is displaced approx.

Figure 4
New impactor used to test an ice hockey board



10 mm more at high impact velocities and impacts to the shielding.

- **pendulum acceleration:** the repeatability of the results with the new pendulum was very high. This is a significant improvement compared to the punching bag. In absolute values the peak acceleration of the pendulum is approx. 10,0 g lower for impacts at 1,0 m and comparable for impacts at 1,4 m. It is not obvious why the punching bag results in higher peak accelerations given its larger deformation. However, the acceleration curves show that the characteristics of the new impactor are as expected whereas the punching bag often features a curve with two peaks close to each other. It is assumed that this phenomenon is related to some movement of the accelerometer inside the punching bag. Such effects are no longer possible with the new impactor as the accelerometer is rigidly fixed to the centre of gravity of the pendulum (see section VI.3). Therefore, the measurements recorded with the new device are much more reliable and repeatable.

The results derived from the measurements reflect the influence of the new impactor whereas the excellent repeatability of the new device is apparent again (Table 1, p. 16). The **kinetic energy** of the rebound increases with the new pendulum due to the reduced amount of deformation in the pendulum itself. This leads to a reduction of the **energy absorption** attributed to the board system, because the energy absorption is calculated from the difference in kinetic energy based on the impact velocity and rebound velocity. Less deformation of the pendulum results in a higher rebound velocity and thus a smaller energy absorption value. This again highlights a shortcoming of using a punching bag: with the method applied (in line with Poutiainen et al. [1]) the value «energy absorption» quantifies the

absorption of the entire system of board and bag and it is not possible to specifically determine the absorption of the board only. The new device therefore represents an improvement as the impactor itself does not dissipate energy, i. e. the energy absorption is better linked to the characteristics of the board system. Likewise, the values obtained for **effective mass** become clearly lower when using the new impactor as also this measure is influenced by the pendulum acceleration. The same holds true for the **stiffness** which is calculated by the pendulum acceleration multiplied by the pendulum mass, divided by the displacements (at 1,0 m or 1,4 m, respectively). It should be pointed out that the additional accelerometer placed on the shielding level now allows calculating the effective mass specifically for the shielding. This is a further improvement of the overall test procedure. As expected, it was found that the effective mass of the board elements (at 1,0 m) is much higher than the effective mass at the shielding (at 1,4 m). Using this set-up, the effect of different shielding material can be analysed in more detail.

In summary, using the new impactor results in a slightly reduced energy absorption and clearly lower effective mass of the board and clearly lower stiffness values.

Table 1
Test series comparing punching bag vs. new impactor: derived measurements

impact height = 1 m	punching bag		new impactor		punching bag		new impactor	
Test No.	1	2	11	12	3	4	13	14
impact velocity [m/s]	3.37				4.76			
energy absorption [-]	0.90	0.91	0.87	0.87	0.95	0.95	0.92	0.92
board effective mass	119.36	145.53	84.00	83.77	156.88	127.68	67.95	66.83
stiffness, 1 m, [kN/m]	541.57	644.17	259.05	259.97	626.85	503.08	334.00	344.61
stiffness, 1.4 m, [kN/m]	451.31	528.22	228.90	226.86	522.62	422.35	297.67	307.19

impact height = 1.4 m	punching bag		new impactor		punching bag		new impactor	
Test No.	5	6	17	18	7	8	19	20
impact velocity [m/s]	3.37				4.76			
energy absorption [-]	0.92	0.94	0.92	0.92	0.95	0.95	0.95	0.95
board effective mass	*	*	21.70	21.82	*	*	27.84	28.12
stiffness, 1 m, [kN/m]	259.95	299.09	208.92	208.80	350.40	254.36	263.95	264.22
stiffness, 1.4 m, [kN/m]	136.31	153.47	114.15	114.75	185.97	135.73	150.92	151.46

Top: impact at 1.0 m; bottom: impact at 1.4 m.

*: Note that the shielding acceleration measurement at 1.4 m was only introduced with the new impactor, thus the corresponding values for the punching bag are left open

V. Conclusions

- The new impactor represents a significant improvement compared the punching bag pendulum. The new device is suitable for use in a standardised procedure. Its mass can easily be adjusted to also consider impacts of lighter / heavier athletes. Measurements taken with the new impactor show an excellent repeatability. A major improvement of the new impactor over the punching bag is the fact that there is practically no energy absorbed through deformation of the impactor, only the neoprene layers slightly damp the impact which is necessary to obtain reasonable measurements.
- The comparison of the results obtained by the new impactor vs. the punching bag reflects the design changes. As the new impactor dissipates only a minimum amount of energy, the board displacement measures with the new device are larger. Additionally, the rebound velocity is higher. Consequently, parameters derived from these measurements change. Most notably the stiffness values and the values for effective mass of the board are reduced when using the new impactor.
- Adding a further accelerometer to the test set-up proved to be valuable in the sense that the effective mass can now be determined for the actual board area and the shielding area separately.

Overall, we believe that the new impactor represents a major advancement over the punching bag. Adding an accelerometer further improves the quality of the tests and allows analysing the board and shielding in more detail.

With respect to homologation of new ice hockey boards the new impactor has the potential to be used as a standardised tool. It is easy to handle and features a simple, reasonable and inexpensive design. For homologation, testing in a laboratory is mandatory since new designs and/or design not yet installed in an arena are to be tested. The controlled laboratory setting therefore allows for standardised tests to determine the performance of the boards, and to compare different products.

For a future perspective, a homologation procedure facilitating impactor tests appears most promising. The (inter-laboratory) repeatability of such tests is high and the cost are moderate such that good acceptance for this kind of methodology may be expected. Dummy experiments, in contrast, have shown their strength in determining biomechanical measures related to injury risk using certain threshold or reference values. However, the method is rather complex and thus more difficult to standardise. A combined approach in which dummy experiments are used to determine a board design that is regarded as acceptable (i. e. to establish a reference) and corresponding pendulum impacts could be performed. This would allow the definition of reference values for pendulum impact tests such that for future homologation these reference values could be used in standardized pendulum impact tests. The impactor that was developed in this project offers the possibility to be used as a tool in such a procedure.

VI. Appendix

1. Recorded measurements

The tables below present the measurements of the test series comparing the punching bag vs. the new impactor. All tests were performed using the same board system. The upper table shows impacts at

1,0 m above ground (board area); the lower table presents results from impacts at 1,4 m above ground (shielding area). Repeatability of the impacts can be assessed by the difference between two measurements under same conditions (column «difference»). It can be seen that the new impactor particularly improves the repeatability of the acceleration measurements of the pendulum.

Table 2
Test series comparing punching bag vs. new impactor: recorded measurements

	punching bag		difference	new impactor		difference	punching bag		difference	new impactor		difference
No.	1	2		11	12		3	4		13	14	
impact height [m]	1.00	1.00		1.00	1.00		1.00	1.00		1.00	1.00	
mass [kg]	60.5	60.5		60.0	60.0		60.5	60.5		60.0	60.0	
impact velocity [m/s]	3.37	3.37		3.37	3.37		4.76	4.76		4.76	4.76	
rebound velocity [m/s]	1.03	0.98	0.05	1.18	1.19	0.01	1.01	1.05	0.05	1.37	1.36	0.01
board acceleration												
peak (+), 1.0 m, [g]	11.1	11.1	0.0	10.5	10.6	0.1	14.5	14.5	0.0	23.4	24.6	1.2
peak (+), 1.4 m, [g]	*	*		10.5	10.6	0.1	*	*		19.9	20.8	0.9
board displacement												
h = 1.0 m, [mm]	24.0	24.6	0.6	33.4	33.9	0.5	35.6	36.1	0.5	46.7	46.8	0.1
h = 1.4 m, [mm]	28.8	30.0	1.2	37.8	38.4	0.6	42.7	43.0	0.3	52.4	52.5	0.1
pendulum acceleration												
peak (+) [g]	21.9	26.7	4.8	14.7	14.8	0.1	37.6	30.6	7.0	26.5	27.4	0.9

	punching bag		difference	new impactor		difference	punching bag		difference	new impactor		difference
No.	5	6		17	18		7	8		19	20	
impact height [m]	1.40	1.40		1.40	1.40		1.40	1.40		1.40	1.40	
mass [kg]	60.5	60.5		60.0	60.0		60.5	60.5		60.0	60.0	
impact velocity [m/s]	3.37	3.37		3.37	3.37		4.76	4.76		4.76	4.76	
rebound velocity [m/s]	0.92	0.79	0.13	0.95	0.94	0.01	1.00	0.98	0.02	1.09	1.07	0.02
board acceleration												
peak (+), 1.0 m, [g]	5.9	6.3	0.4	6.3	6.3	0.0	13.2	10.6	2.6	12.4	12.7	0.3
peak (+), 1.4 m, [g]	*	*		31.8	31.9	0.1	*	*		43.1	43.1	0.0
board displacement												
h = 1.0 m, [mm]	25.8	25.4	0.4	32.4	32.7	0.3	35.4	35.7	0.3	44.6	45.0	0.4
h = 1.4 m, [mm]	49.2	49.0	0.3	59.3	59.5	0.2	66.7	66.9	0.2	78.0	78.5	0.5
pendulum acceleration												
peak (+) [g]	11.3	12.8	1.5	11.5	11.6	0.1	20.9	15.3	5.6	20.0	20.2	0.2

*Note that the shielding acceleration measurement at 1.4 m was only introduced with the new impactor, thus the corresponding values for the punching bag are left open

2. Derived measurements

The parameters that were calculated based on the measurements are summarized here. Note that the effective mass was determined using the board acceleration at 1,00 m and 1,40 m.

Table 3
Derived measurements

	punching bag		difference	new impactor		difference	punching bag		difference	new impactor		difference
No.	1	2		11	12		3	4		13	14	
impact height [m]	1.00	1.00		1.00	1.00		1.00	1.00		1.00	1.00	
mass [kg]	60.5	60.5		60.0	60.0		60.0	60.5		60.0	60.0	
impact velocity [m/s]	3.37	3.37		3.37	3.38		4.76	4.76		4.76	4.76	
kinetic energy impact [J]	329.42	329.42	0.00	326.70	326.70	0.00	640.09	668.22	28.13	662.70	662.70	0.00
kinetic energy rebound [J]	31.84	28.93	2.91	41.64	42.17	0.53	30.68	33.58	2.90	56.21	55.20	1.01
energy absorption [-]	0.90	0.91	0.01	0.87	0.87	0.00	0.95	0.95	0.00	0.92	0.92	0.00
board effective mass [kg]	119.36	145.53	26.16	84.00	83.77	0.23	156.88	127.68	29.21	67.95	66.83	1.12
stiffness, 1.0 m, [kN/m]	541.57	644.17	102.60	259.05	256.97	2.08	626.85	503.08	123.77	334.00	344.61	10.61
stiffness, 1.4 m, [kN/m]	451.31	528.22	76.91	228.90	226.86	2.04	522.62	422.35	100.26	297.67	307.19	9.52

	punching bag		difference	new impactor		difference	punching bag		difference	new impactor		difference
No.	5	6		17	18		7	8		19	20	
impact height [m]	1.40	1.40		1.40	1.40		1.40	1.40		1.40	1.40	
mass [kg]	60.5	60.5		60.0	60.0		60.5	60.5		60.0	60.0	
impact velocity [m/s]	3.37	3.37		3.37	3.37		4.76	4.76		4.76	4.76	
kinetic energy impact [J]	329.42	329.42	0.00	326.70	326.70	0.00	640.09	640.09	0.00	662.70	662.70	0.00
kinetic energy rebound [J]	25.45	18.96	6.49	27.03	26.74	0.29	30.31	29.06	1.26	35.55	34.32	1.22
energy absorption [-]	0.92	0.94	0.02	0.92	0.92	0.00	0.95	0.95	0.00	0.95	0.95	0.00
board effective mass [kg]	*	*		21.70	21.82	0.12	*	*		27.84	28.12	0.28
stiffness, 1. m, [kN/m]	259.95	299.09	39.14	208.92	208.80	0.12	350.40	254.36	96.04	263.95	264.22	0.27
stiffness, 1.4 m, [kN/m]	136.31	153.47	17.16	114.15	114.75	0.61	185.97	135.73	50.24	150.92	151.46	0.54

*Note that the shielding acceleration measurement at 1.4 m was only introduced with the new impactor, thus the corresponding values for the punching bag are left open

3. Pendulum acceleration data

Figure 5 and Figure 6 (p. 21) illustrate two examples of acceleration measurements. As mentioned in section IV.2nd the punching bag did in some cases result in an acceleration pattern featuring two peaks. The second peak cannot be explained; it might be related to motion of the accelerometer inside the sand. The new impactor in contrast did not exhibit such phenomena. The diagrams refer to tests no. 1 (punching bag, $h = 1\text{m}$, v_1) and no. 11 (new impactor, same conditions); both data set were processed and filtered in the same way (filter CFC 180).

Figure 5
Punchbag acceleration

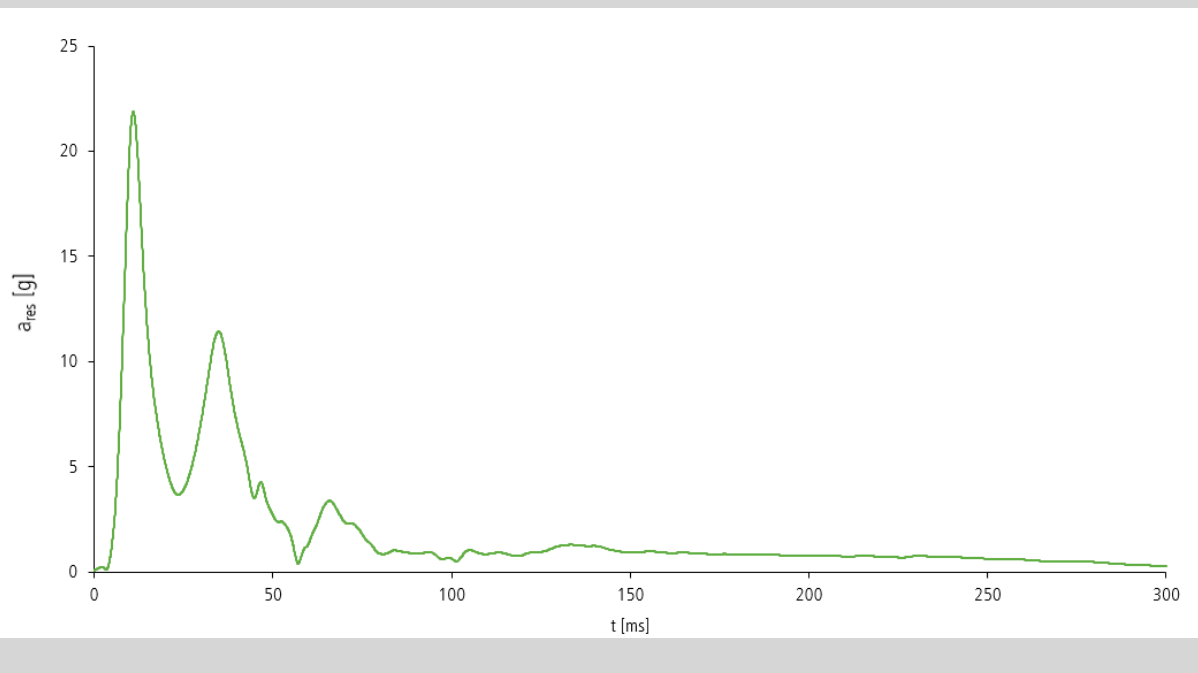
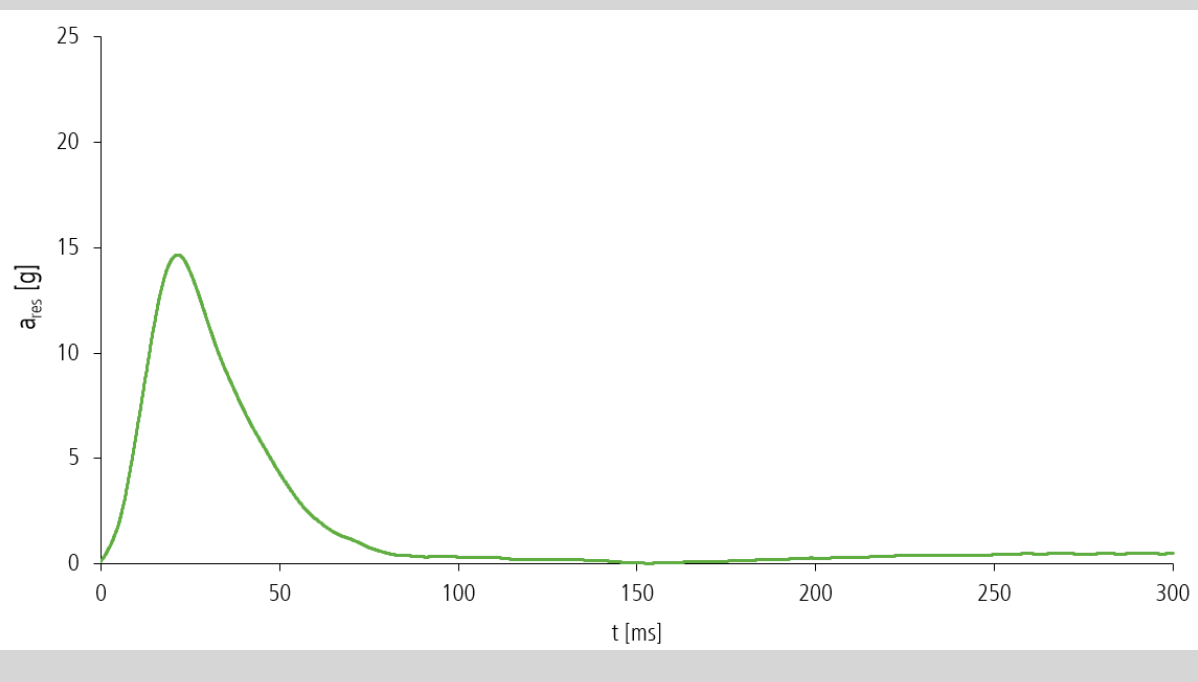


Figure 6
Pendulum acceleration



References

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