Designing a mass-spring system drop test, for quantifying force attenuation properties of athletic footwear, using force-time curves from human locomotion

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Abstract

ASTM F1976 is a standard designed to test shoe cushioning. A limitation to the standard is the missing option to reproduce any force-time curve from sport specific impacts, as the ASTM F1976 only reproduces walking, running and jump landings. Therefore, the purpose of the present study was to design, construct and validate an adjustable impact device (AID), for testing force attenuation of shoes. The drop height, mass and spring stiffness were made adjustable, to be able to reproduce sports specific impacts. A badminton lunge was used as a sports specific impact, and the AID was fitted to the force-time curve with a precision of 2.24 %.

It was tested if three badminton shoes would exhibit a crossover in ability to attenuate peak impact forces, when impacted with three different impact profiles. The shoe attenuating the most force at the lowest impact forces was also found to attenuate the least force at the highest impact. The opposite result was found for the shoe attenuating the most force at the highest impact.

An AID was created and validated, and was used to find a cross-over effect in force attenuation at different loading scenarios. Furthermore it was partially confirmed that equal peak forces obtained with different loading rates will produce differences in force attenuation.

Keywords: Force attenuation | Shoe cushioning test | Impact drop test | Force reduction

Introduction

Sporting activities produce heel strike impact forces ranging from around 1.1 x BW, during walking, (Keller et al., 1996; Von Porat et al., 2006) up to 9.0 x BW, in basketball (McClay et al., 1994). In order to overcome these impacts, athletes use sport-specific footwear, in which the midsole is responsible for attenuating impact forces. Midsoles are generally made from polymers (Silva et al., 2009), and the force attenuation of these polymers are decided by the viscoelastic properties they possess (Silva et al., 2009).

When an athlete impacts the ground the momentum is given by the integral of the force-time curve. The force attenuation of a shoe is not supposed to change the integral, but alter the shape of the force-time curve, ideally lowering the peak impact force. One way of achieving this is to increase the thickness of the sole. However, this can be impactful on performance i.e. because of weight and size. Therefore, the material composition of the sole in regards to force attenuation is crucial, as a compliant midsole, impacted with high forces, may be compressed to a point where it can no longer attenuate forces effectively. On the other hand, at low impact forces, a stiff midsole does not lower the peak force of the momentum to the same extent as a compliant midsole. Materials of different viscoelastic composition react differently to different loading rates, allowing shoe manufacturers to design shoes suitable for different sports. In this study, the term force attenuation refers to a percentagewise reduction of peak impact force compared to the same impact on concrete, which is considered as infinitely stiff.

In the field of sports engineering, mechanical testing is commonly used to determine the viscoelastic properties of athletic footwear (Odenwald, 2006; Hennig, 2011). The current standard for evaluating force attenuation of athletic footwear is the ASTM F1976, a mechanical drop test. The test is conducted by dropping an 8.5 kg missile onto a shoe from a height of 3-7 cm, depending on the desired impact, while measuring impact forces with a force transducer. The method is intended for producing force-time curves comparable to heel and forefoot impacts observed during walking, running and jumping. The force attenuation of the test specimen is evaluated by calculating peak-acceleration, peak compression and time to peak of the force-time curves produced by the test, as well as energy return/loss due to hysteresis (ASTM F1976). A limitation of the current standard is the lack of control of contact time and loading rate of the impact. This could be solved by adding a spring to the missile, as well as making the mass adjustable. In running biomechanics, the leg is commonly described as a spring, as a result of the human ability to alter the stiffness of the leg (Nigg & Wakeling, 2001; van der Krogt et al., 2009; Reeve et al., 2013). The consequence of this is that heel impact force-time curves can take many different shapes. Testing of athletic footwear should ideally simulate actual loading scenarios from different sporting events, where the contact time, peak impact and loading rate can all vary.

This would enable shoe manufactures to test and thus improve their shoes specifically to the intended sport and user. Today most commercially available shoes are sorted only in shoe size. However, it is possible for two people of the same shoe size to have completely different impact profiles, due to i.e. differences in body weight. As the 3D-printing technology is rapidly advancing, it should be possible to make soles with force attenuation properties matching the impact profile of a specific athlete or sport. In example, Nike patented their 3D-printed shoe technology in 2015. Furthermore, in May 2016 Nike partnered up with Jet Fusion 3D to continue the work on 3D-printing footwear (3ders.org).

The purpose of the current study is: To design, construct and validate a method of quantifying force attenuation of athletic footwear using force-time curves generated from actual movements.

The study aims to test the following hypotheses:

1. It is possible to recreate the force-time curves for actual sporting events using a mass-spring system.

2. Shoes show a crossover effect in force attenuation at different loading scenarios.

3. Shoes impacted with equal peak forces, obtained with different loading rates will exhibit differences in force attenuation.

Method

Preface

To accommodate the purpose of the current study, an adjustable impact device (AID) was built. The AID was built on the principles of the advanced artificial athlete (AAA), which is a mass-spring system drop test for testing floors, utilizing accelerations to calculate, amongst other things, force attenuation (EN14904). As previously stated the limitations of the ASTM F1976 can be solved by adding a spring to and making the mass of the missile adjustable. In addition it would be advantageous to remove the limitation to the drop height. When implementing these changes, it is possible to recreate any given parabola (See Figure 1).

As seen in Figure 1a force-time curves resulting from a mass-spring system, dropped onto a hard surface, will take the form of a parabola. As seen in Figure 1b the impact from an actual badminton lunge does not look like a parabola. However, as 1c illustrates, the heel strike force of the badminton lunge clearly resembles a parabola. Figure 1d illustrates a quadratic fit of the heel strike of the badminton lunge. The quadratic fit is applied to the points between the first point of the heel strike and the first point after peak impact. Notice that the amplitude of the peak in 1d matches the amplitude of the peak in 1c. To calculate weight, drop height and spring stiffness, from here on referred to as configuration, the AID-model was created. The AID-model calculates the configurations by utilizing numerical solution to replicate the quadratic fit.

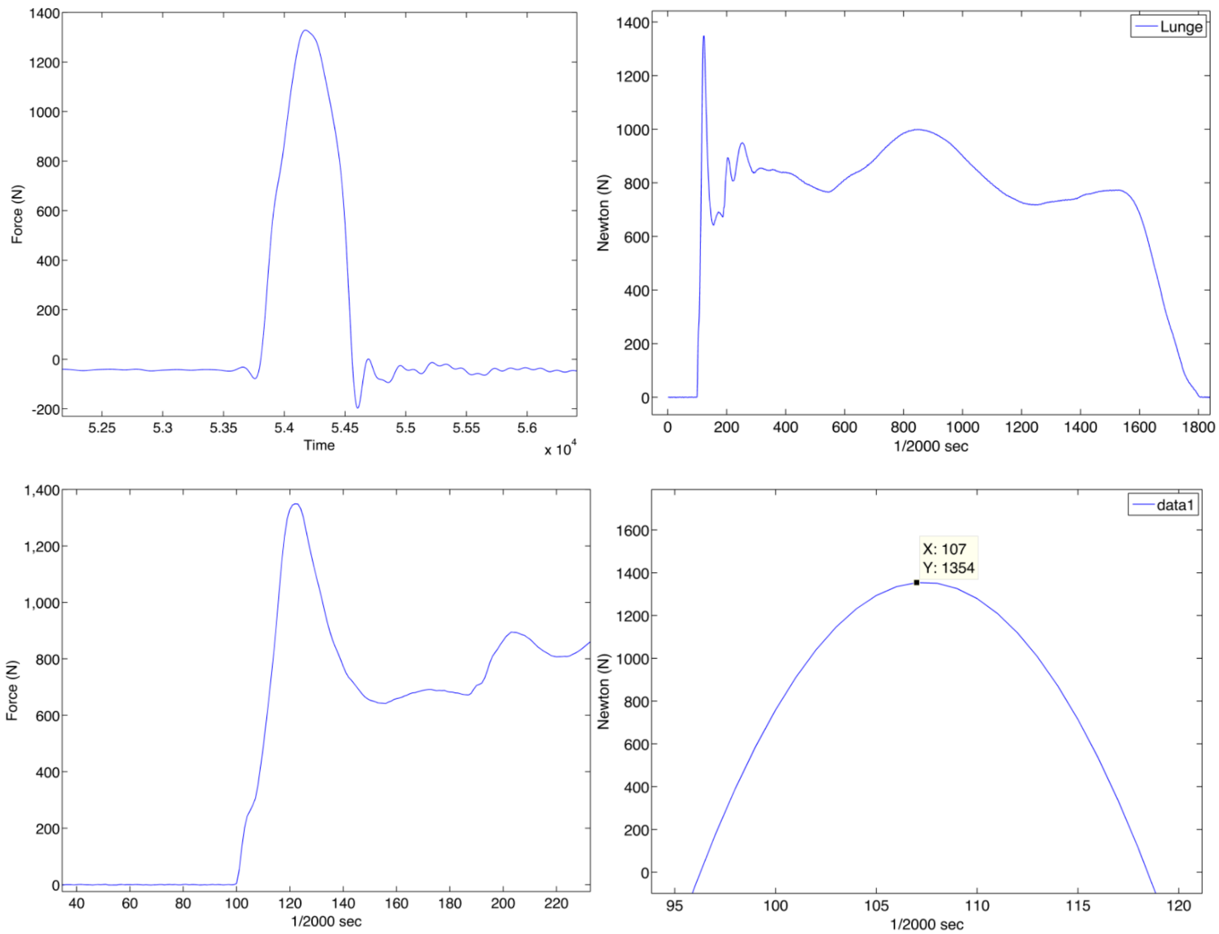

Figure 1: *Top left (1a): Impact with AID. Top right (1b): Badminton lunge impact performed by a player. Bottom left (1c): Heel strike part of the badminton lunge force-time curve. Bottom right (1d): Quadratic fit of the impact peak from the badminton lunge.*

The AID-Model

The model describes two masses, two springs and one damper (Figure 2). For the shoes tests, a third mass and spring could be added to the model. However, when testing the shoes on concrete, which can be considered very heavy and infinitely stiff, the stiffness of the floor and shoe becomes the same and therefore a third mass and spring is not necessary.

The AID-model was created with the assumption of constant acceleration in small time-steps. This assumption allowed for the use of numerical modelling and thus the use of the dynamic equilibrium equation:

$$F_s - mg = \ddot{x}_0 \leftrightarrow -kx - mg = ma \qquad (1)$$

Where F_s is the spring force, m is the mass dropped, g is the gravity constant, $\ddot{x}$ is the acceleration, k is the spring constant and x is the displacement.

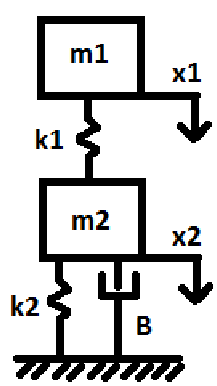

Figure 2: *A free body diagram of the AID-model. m1 and m2 are the masses of the missile and floor/shoe. x1 and x2 are the displacements of the missile and floor/shoe, respectively. the displacement of the shoe. k1 and k2 are the spring constants of the missile and floor/shoe, respectively. B is the dampening coefficient.*

Because acceleration is the second derivative of displacement (x), Equation 1 can be rewritten and the acceleration can be isolated:

$$\text{For the top mass (AID)} \qquad (2a)$$
$$m_1 g - k_1(x_1(t) - x_2(t)) - m_1\ddot{x}_1(t) = 0$$
$$\Rightarrow m_1\ddot{x}_1(t) = m_1 g - k_1(x_1(t) - x_2(t)$$
$$\Rightarrow \ddot{x}_1(t) = g - \frac{k_1}{m_1}(x_1(t) - x_2(t))$$

$$\text{For the bottom mass (Floor/Shoe)} \qquad (2b)$$
$$m_2 g - k_1(x_1(t) - x_2(t)) - m_2\ddot{x}_2(t) - k_2 x_2 - B\dot{x}_2 = 0$$
$$\Rightarrow m_2\ddot{x}_2(t) = m_2 g - k_1(x_1(t) - x_2(t) - k_2 x_2 - B\dot{x}_2$$
$$\Rightarrow \ddot{x}_2(t) = g - \frac{k_1}{m_2}(x_1(t) - x_2(t)) - \frac{k_2}{m_2}x_2 - \frac{B}{m_2}\dot{x}_2$$

Where m_1 is the weight of the AID, m_2 is the weight of the floor, $\dot{x}$ is velocity, t is time, B is dampening and x_1 and x_2 are the displacements of the missile and floor/shoe, respectively.

From the assumption of constant acceleration in a small time interval, Δt, follows linear velocity ($\dot{x}$), as velocity is the first derivative of displacement. This means that when the acceleration, and thus velocity, is known at x_0, the velocity for the next time step can be calculated by adding the change in acceleration, $\ddot{x}\Delta t$, to the current velocity:

$$\dot{x}(t) = \dot{x}_0 + \ddot{x}\Delta t \qquad (3)$$

Where $\dot{x}_0$ is the velocity Δt earlier and t is the time. From linear velocity follows quadratic displacement, which can be calculated with the following:

$$x(t) = x_0 + \dot{x}\Delta t + \frac{1}{2}\ddot{x}\Delta t^2 \qquad (4)$$

Where x_0 is the displacement Δt earlier. When the displacement is known, the spring force (F) can be calculated by multiplying with the spring constant, k:

$$F(t) = -kx(t) \qquad (5)$$

With Equations 1-5 it was possible to calculate the theoretical force-time curve for any given combination of mass, spring stiffness and drop height.

The best configuration was then found by optimizing drop height, mass and spring stiffness, in order to minimize the integral residual impact force (ΔF) between the AID-model and the fitted quadratic equation from the desired movement. For practical purposes the spring stiffness and mass were set in intervals. The intervals represented the different commercially available springs and the possible weight plate plus AID combinations:

$$\Delta F = \sum_{i=1}^{t}(F_{(t)Quadraticfit} - F_{(t)AID-Model})^2 \qquad (6)$$

Where t is the number of time steps for the impact. The impact force of the AID model was considered applicable if a difference less than 5 percentage between the AID-model and the quadratic fit was found (See Figure 3 for an example).

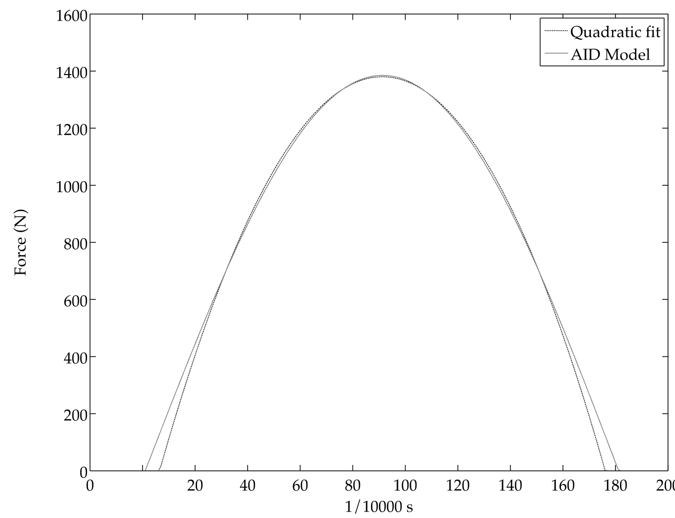

Figure 3: *A comparison between the AID-model and the quadratic fit made from the badminton lunge. The configuration illustrated is the badminton configuration found in table 2.*

Calculations

In order to calculate forces, and thus force attenuation, from the data from the accelerometer, Newton's second law of locomotion can be utilized:

$$F_{max} = m * \ddot{x}_{max} \qquad (7)$$

Where F_{max} is peak force, m is the mass of the missile and $\ddot{x}_{max}$ is the maximal acceleration. When the peak impact force has been calculated, the force attenuation can be calculated:

$$FA = (1 - \frac{F_{max}}{F_{maxConcrete}}) * 100 \qquad (8)$$

$F_{maxConcrete}$ is the mean maximal peak force from the impacts on concrete from the measured AID configuration.

From the force-time curve the loading rate can be calculated using the following formula:

$$Loading\ rate = \frac{F_{max}\ (N)}{Time\ to\ peak\ (ms)} \qquad (9)$$

Construction of the AID

As previously stated, the AID is a mass-spring system drop test, similar to the AAA, but is designed to be able to recreate force-time curves ranging from walking to jump landings in i.e. basketball. This was done by making height, mass and spring stiffness adjustable (See Figure 4 & 5).

Figure 4 & 5 show the complete AID test setup. The missile holder is made as a tripod for stability. The missile is held in place by an electromagnet. The slider controls the drop height and is freely adjustable from 0-50 cm when measured from the foot of the missile to the point of impact. The slider is held in place by two bolts. The tube prevents the missile from tipping over after impact which could potentially damage the accelerometer. Figure 3 shows the missile, which has a base weight of 1.763 or 1.853 kg with a 156.3 and 709 N/mm spring, respectively. These are the two springs used in the this study, but the design allows for selecting any spring with a minimum inner diameter of 0.025 cm and a maximum outer diameter of 0.05 cm. The foot holder can move freely upwards into the rod and thus allows the springs to compress. The foot is rounded to a radius of 5m to mimic a human heel (EN 14904). In addition the foot should not weigh more than 0.2 kg (ASTM F1976).
Accelerations were recorded with a uniaxial ADXL193 accelerometer and a National Instruments 6009 14 bit AD-converter at a rate of 48 kHz. Data were digitally filtered with a 4th order 250 Hz Butterworth filter.

Validation

To test if it is possible to recreate the force-time curves for actual sporting events using a mass-spring system (Hypothesis 1), the AID was validated by deploying it onto concrete five times at three different locations. This was done to avoid potential irregularities in the concrete influencing the results. The AID was set to badminton lunge configurations (Table2). A percentagewise comparison of force-time curves between AID-drop test and AID-model values was conducted. If the simulated force-time curve was less than 5% different from the measured values, the AID was considered accurate.

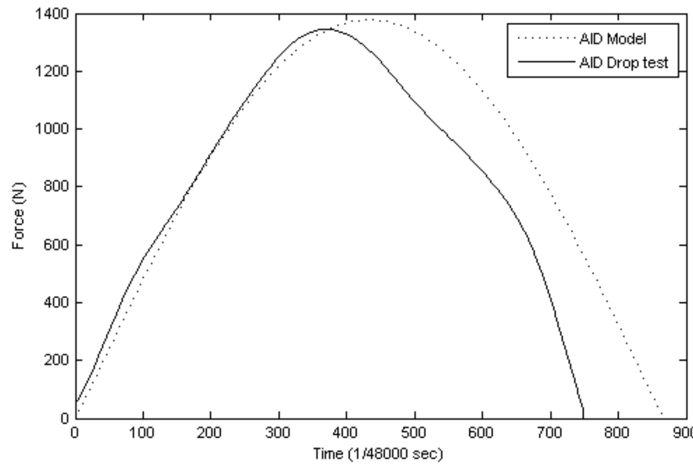

Figure 6: *Force-time curves of the AID-model (theoretical) and mean of 15 AID-drop tests for the badminton lunge configuration.*

Theoretically no energy is dissipated, but in reality this is not the case. This means that the AID force-time curve is not an exact parabola. In this study only the loading phase of the impact i.e. the force-time curve up until the peak force is of interest. For this reason, the percentage comparison was only made for this part. The validation test protocol showed a 2.24 % difference, when comparing the AID-drop test force-time curve to the AID-model force-time curve. (See Figure 6)

Protocol

In addition to the validation test, this study contains three tests, which are presented below.

The AID-model was used to calculate AID configurations for the tests. Configurations can be found in Table 2. A concrete floor as well as three unused shoes (Table 1) on top of concrete were tested with all configurations.

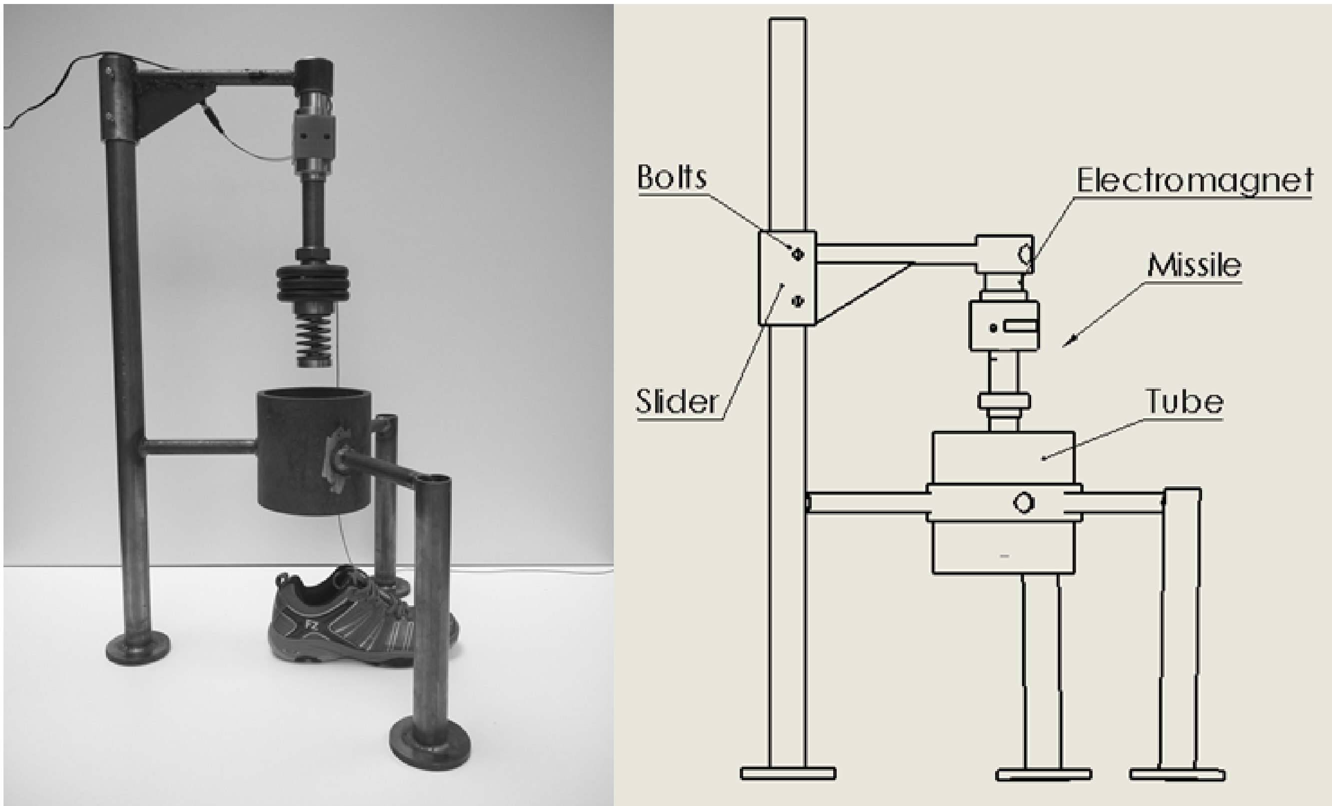

Figure 4: *The test setup. The missile is held by an electromagnet. Acceleration is recorded upon release of the missile. After impact, the missile is contained by the surrounding tube.*

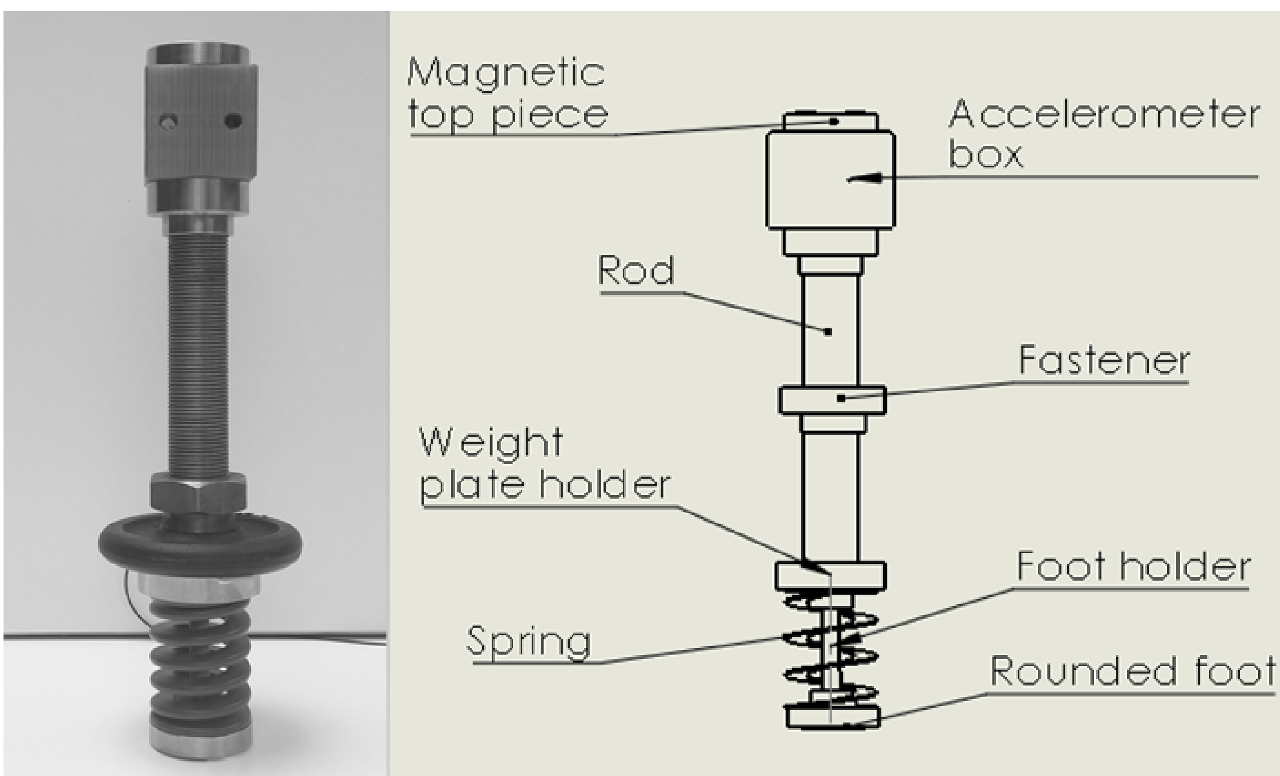

Figure 5: *Left: The missile of the AID. Right: Labelled technical overview of the AID. The overview is without added weight plate(s).*

Force attenuation test

To test if shoes show a crossover effect in force attenuation at different loading scenarios (Hypothesis 2), three badminton shoes (Table 1) were impacted five times, on concrete, with low- medium and high impacts. A low impact was recreated by modelling data from a subject walking on a force plate. Impacts from a badminton lunge and the AAA were used as medium and high impacts, respectively. The configurations to recreate walking, badminton lunge and AAA can be seen in Table 2.

Table 2: *Badminton shoes tested in the present study*

	Brand	Model	Size (EU)
Shoe1	Asics	Gel Blade 4	40.5
Shoe2	Victor	SH-LYD-G	40
Shoe3	Forza	Leander	40

Loading rate test

To test if shoes impacted with equal peak forces, obtained with different loading rates will exhibit differences in force attenuation. (Hypothesis 3), the three shoes were tested with configurations resulting in different loading rates, but the same peak impact force of 1377.3 N $\pm$ 2 %. The configurations are referred to as Loading Rate 1-4 (Table 2). Five drops were conducted onto the concrete floor and each of the three shoes resulting in a total of 20 impacts for each mass – spring combination.

Statistical analysis

IBM SPSS 22 was used for the statistical analysis. An analysis of variances (ANOVA) was used to investigate if there were any significant differences between impact forces on concrete across the loading rate configurations. Paired t-tests were used to investigate if there were any significant differences between the three shoes in regards to force attenuation and loading rate.

The level of significance was set at $p \leq 0.05$, but the listed p-values are the actual p-values.

Results

Table 3 shows the mean peak impact forces for all configurations used in this study. For all configurations the peak impact force was significantly lower on Shoe1-3 than on concrete ($p<0.001$). In the force attenuation test, at walking configuration, Shoe2 had significantly lower peak impact forces than Shoe1 and Shoe3 ($p<0.001$) and Shoe1 had significantly lower impact than Shoe3 ($p<0.001$). With badminton configuration, Shoe1 had significantly lower impact force than Shoe2 and Shoe3 ($p\leq0.031$) and Shoe2 significantly lower than Shoe3 ($p<0.002$). With AAA configuration, Shoe3 had significantly lower peak impact force than Shoe1 and Shoe2 ($p<0.001$) and Shoe1 significantly lower than Shoe2 ($p<0.006$). In the loading rate test peak impact forces were significantly different between all configurations on concrete ($p<0.001$), and therefore significance between shoes in configurations are only tested as percentage force attenuation (Table 4).

Table 2: *Shows the mass, drop height and spring combinations used in the study and their respective estimated peak force. Note that the loading rate configurations are all within 2% of 1377.3 N in estimate peak force.*

	Drop Height (cm)	Mass (kg)	Spring stiffness (N)	Estimated Peak Force (N)
Walking	3.1	3.338	156.3	621.6
Badminton Lunge	11.7	4.913	156.3	1404.6
AAA	47.4	6.918	709.0	6913.7
Loading rate 1	10	5.438	156.3	1373.7
Loading rate 2	15	3.863	156.3	1381.1
Loading rate 3	20	2.813	156.3	1354.6
Loading rate 4	25	2.288	156.3	1351.8

In Table 4 the mean force attenuation percentage of two tests is shown. For the force attenuation test difference between Shoe1-3 in all configurations are significant (p<0.004). At walking configuration Shoe1-3 attenuated 39.1, 50.0 and 20.8 % of the force respectively. At badminton configuration Shoe1-3 attenuated 31.6, 30.6 and 28.1 % respectively. At AAA configuration Shoe1-3 attenuated 17.5, 14.3 and 26.7 % respectively. It is noteworthy that a different shoe attenuates most force at each configuration, as well as the difference between shoes being the least at the badminton configuration. A graphical illustration of the force attenuation percentages from the force attenua-

Table 3: *Mean peak impact force (N) ± SD for concrete and Shoe1-3 for the force attenuation and loading rate tests. Significant differences between all impacts in a configuration is marked with * at the configuration name. Significant difference from all other reference values is marked with * in the concrete column.*

	Concrete	Shoe1	Shoe2	Shoe3
Walking	580.9 ± 7.2*	354.0 ± 2.7	290.6 ± 1.2	460.3 ± 2.5
Badminton Lunge	1344.3 ± 19.2*	919.4 ± 4.2	933.0 ± 12.0	965.9 ± 11.6
AAA	6588.3 ± 135.1*	5436.3 ± 115.6	5647.3 ± 69.8	4828.3 ± 109.8
Loading rate 1	1316.6 ± 17.6*	890.7 ± 15.6	915.3 ± 9.0	951.9 ± 8.5
Loading rate 2	1383.2 ± 5.9*	972.0 ± 6.9	980.7 ± 7.1	943.0 ± 6.9
Loading rate 3	1372.8 ± 3.3*	934.6 ± 3.6	965.8 ± 3.6	959.6 ± 18.1
Loading rate 4	1405.8 ± 3.1*	923.3 ± 7.8	954.4 ± 3.2	1022.5 ± 9.8

Table 4: *Mean force attenuation percentage ± SD of Shoe1-3 for the force attenuation and loading rate tests. Insignificant differences between shoes for configurations are marked by ø.*

	Shoe1	Shoe2	Shoe3
Walking	39.1 ± 0.5	50.0 ± 0.2	20.8 ± 0.4
Badminton Lunge	31.6 ± 0.3	30.6 ± 0.9	28.1 ± 0.9
AAA	17.5 ± 1.8	14.3 ± 1.1	26.7 ± 1.7
Loading rate 1	32.3 ± 1.2	30.5 ± 0.7	27.7 ± 0.6
Loading rate 2	29.7 ± 0.5	29.1 ± 0.5	31.8 ± 0.5
Loading rate 3	31.9 ± 0.3	29.6 ± 0.3 ø	30.1 ± 1.3 ø
Loading rate 4	34.3 ± 0.6	32.1 ± 0.2	27.3 ± 0.7

Table 5: *Mean loading rate (N/ms) ± SD for concrete and Shoe1-3 for the force attenuation and loading rate tests. Insignificant differences between shoes for configurations are marked by ø and øø.*

	Concrete	Shoe1	Shoe2	Shoe3
Walking	86.6 ± 3.0	29.6 ± 0.5	19.3 ± 0.3	54.1 ± 0.8
Badminton Lunge	170.3 ± 10.9	84.6 ± 0.8	84.6 ± 0.8	94.3 ± 1.8
AAA	1131.5 ± 42.3	633.4 ± 14.2	676.3 ± 9.9	550.6 ± 19.3
Loading rate 1	159.7 ± 15.2	86.0 ± 2.5 ø	86.0 ± 2.5	86.0 ± 2.5 ø
Loading rate 2	194.4 ± 1.7	86.7 ± 1.2 ø	81.4 ± 1.3	92.4 ± 1.1 ø
Loading rate 3	228.4 ± 4.5	87.1 ± 0.5 ø	85.5 ± 0.8	177.2 ± 10.0 øø
Loading rate 4	274.9 ± 1.6	139.2 ± 2.2	88.6 ± 0.4	173.1 ± 4.5 øø

tion test can be found in Figure 7.
For all configurations in the loading rate test the force attenuation percentages were all significantly different ($p<0.048$), except for the difference between Shoe2 and Shoe3 at loading rate 3 configuration ($p=0.2225$). It is noteworthy that the force attenuation percentages for all configurations and shoes are between 27.3 and 34.3, and that Shoe1 attenuates the most force at loading rate configurations 1,3 and 4. A graphical illustration of the force attenuation percentages from the loading rate test can be found in Figure 8.

Table 5 shows the mean loading rate for all configurations used in the study. For the force attenuation test it is noteworthy that the order of lowest loading rate follows the order of highest force attenuation percentage, except for the badminton configuration, where Shoe1 and Shoe2 has swapped positions. For the loading rate test all loading rate configurations resulted in significantly different loading rates on concrete, as well as Shoe2 ($p<0.05$). For Shoe1 only loading rate configuration 4 resulted in loading rates that differed from loading rate configuration 1-3 ($p<0.001$). For Shoe3, loading rate configuration 1-2 produced loading rates differing from those of configuration 3-4 ($p<0.01$).

Discussion

The validation protocol served to investigate if the AID drop test is valid in regards to replicating the AID-model correctly. The comparison, illustrated in figure #, was based only on the loading phase of the impact, from initial ground contact to peak impact of the AID-model. The comparison resulted in a 2.24% difference. However, the part of the force-time curve of the AID drop test from shortly before the peak, does not match the AID-model's. Factors that can cause this are hysteresis, which is not accounted for in the AID-model, the spring not being pre-stressed and thereby not having a linear spring constant at initial compression, as well as the fact that accelerations were measured with a uni-axial accelerometer. Hysteresis and non-spring linearity could be the explanation for the difference in peak impact force. The uni-axial accelerometer could explain the difference in integral during the decompression of the spring. If the missile does not impact the, often uneven, surface of the shoe perpendicularly, the missile will not return from the impact in a straight line. Possible improvements to the setup could be pre-stressing the spring and measuring accelerations with a tri-axial accelerometer and calculating the resultant accelerations.

The AID is considered reliable due to the small standard deviations found during the tests.

Figure 5 shows the findings from the force attenuation test and that the three shoes attenuate forces differently. More interestingly it shows a cross-over in force attenuation in regards to impact type. This is seen by Shoe1 and Shoe2 attenuating less force with increasing impact force (39.1-31.6-17.5% and 50.0-30.6-14.3%, respectively.), whereas Shoe3 attenuates more force at badminton than walking configuration, and almost retains the force attenuation from badminton to AAA (20.8-28.1-26.7%).
A possible explanation for the shoes' different force attenuation capabilities is that when examining the shoes, Shoe3 feels considerably more stiff than Shoe1 and Shoe2, which confirms the suspicion that a more compliant midsole will get compressed to a point where the material becomes hard and thus bad at attenuating forces during high impacts. Furthermore, it confirms that a stiffer midsole will not lower the peak of the momentum to the same extent as a compliant midsole, at lower impact forces. The findings from the force attenuation test, show that shoes react differently depending on the loading scenario. This suggests that shoes should be tested and manufactured in regards to the sport they are intended for. It is also noteworthy that the three shoes, that are all badminton shoes, performed very similar in force attenuation when tested with a badminton specific loading scenario. This can, however, be due to the cross-over effect randomly crossing at this peak force magnitude or that the three different manufactures having wanted to attenuate forces specifically in this region of peak impact forces.

If the third hypothesis of this study "Shoes impacted with equal peak forces obtained with different loading rates, will exhibit differences in force attenuation", is true, it indicates that impacts should be reproduced by

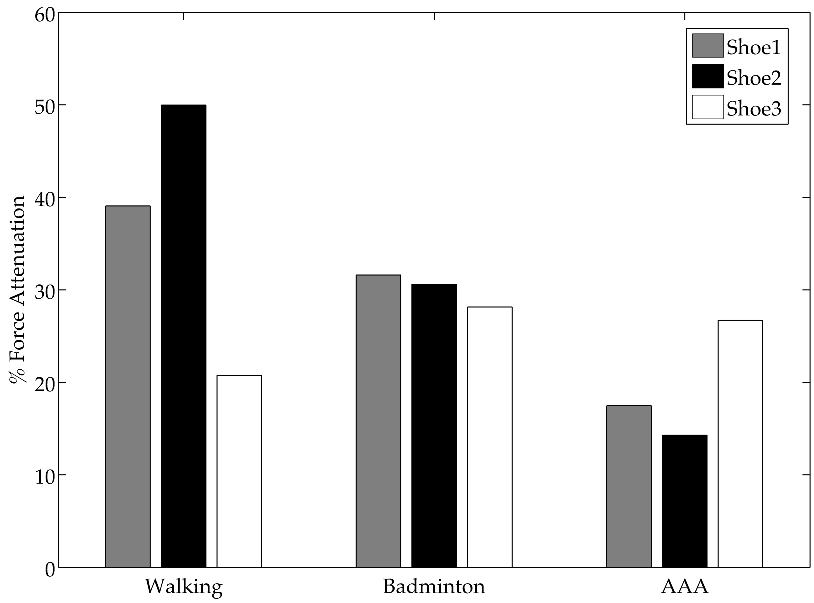

Figure 7: *Mean percentagewise force attenuation of Shoe1, Shoe2 and Shoe3 from the force attenuation test.*

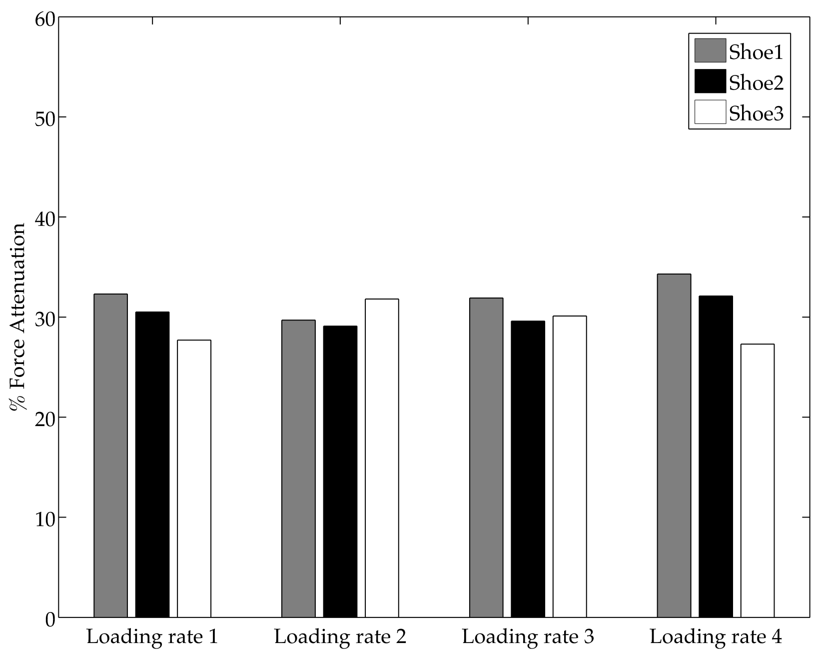

Figure 8: *Mean percentagewise force attenuation of Shoe1, Shoe2 and Shoe3 from the loading rate test.*

recreating the force-time curve of the impact peak instead of only the peak impact force, when trying to quantify shoe-cushioning. Table 5# shows that when shoes are impacted with force-time curves with the same peak impact force, obtained with different loading rates, they show differences in how they attenuate the momentum. Shoe1 attenuates the momentum of loading rate configuration 1-3 at the same rate, but at configuration 4, the loading rate suddenly increases. Shoe2 attenuates the momentum of loading rate configuration 1-4 at slowly increasing loading rates. Shoe3 attenuates the momentum of loading rate configuration 1-2 at higher loading rates than Shoe2 does loading rate configuration 4, which otherwise has the highest loading rate. Shoe3 has the highest loading rates of all the shoes at configurations 3-4, indicating a more viscoelastic midsole, as the stiffness increases with loading rate.

In addition to confirming hypothesis 3, because the four different loading rate configurations results in, although significantly different, similar peak impact forces, but with very different loading rates and thus force-time curves, this shows that shoes attenuate momentums at different loading rates depending on midsole characteristics.

Since the shoes react significantly different to momentums, in terms of both percentagewise force attenuation and loading rate, athletic footwear midsoles should be manufactured not only with sporting events in mind, but also with the weight of the athlete, as this directly alters the impact momentum. With the rapid advances in 3D printing, it should soon be possible to customize shoes without major costs from shutting down production . This could potentially result in shoes with midsoles that are specifically made for the intended user, i.e. a more compliant midsole in the smaller shoe sizes as the users for these normally weigh less. In addition a shoe of a certain size could be made with two different midsoles for light and heavy users.

Future work on this topic should be to determine the stiffness and dampening of the shoes tested. This could be done with numerical solution, solving for the spring stiffness and dampening of the floor/shoe, in this study referred to as k2 and B.

Conclusion

The present study successfully designed, constructed and validated the AID-drop test. The AID was found to be a reliable method for recreating impacts matching actual impacts from sporting events. Any force-time curve can be approximated in the AID-model by creating a quadratic fit of the peak impact of the given force-time curve, thus confirming hypothesis 1.

The results showed that the three shoes did exhibit a crossover effect in force attenuation at different impact magnitudes, confirming hypothesis 2. This is believed to be due to the midsoles having different stiffness and dampening coefficients, however these could not be determined by the current method.

The four loading rate configurations resulted in peak impact forces within the expected range of 1377.3N $\pm$ 2%, however, they were significantly different ($p<0.001$) due to small standard deviations. This means that hypothesis 3 is partly confirmed, as peak impacts for the four loading rate configurations were within the desired range and had statistically different loading rates ($p<0.001$) and thus force-time curves.

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