

Research report - Department of Mechanics and Maritime Sciences 2018:02

Handball shot on goalkeeper's head – How detrimental is it?

Project in Applied Mechanics 2018

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Preface

The work in the present report was carried out as a part of the course TME131 Project in Applied Mechanics, which is a mandatory course within the Applied Mechanics Masters programme at Chalmers. The course was carried out during spring semester 2018.

We would like to thank our supervisors Anders Ekberg and Johan Davidsson for their support and help during this project. We also want to thank the players from Redbergslids IK who took their time to answer the questions in our survey. We would like to express special thanks to the players Oliver Wigmark, Simon Örtelind, Jonathan Carlsbogård, Anton Gustafsson, Kristian Zetterlund and the coaches Jasmin Zuta, Magnus Wislander and Daniel Westerberg for helping us with preparation, implementation and protection of equipment during the test with the crash test dummy.

During the testing in Rosendalshallen where Redbergslid IK practices Oliver Wigmark, Simon Örtelind, Jonathan Carlsbogård and Anton Gustafsson helped out by throwing balls at the dummy. Kristian Zetterlund helped by protecting the camera. Jasmin Zuta and Magnus Wislander helped us with the distances that the players were supposed to throw from. We would like to thank them for their help.

Abstract

The aim of the project was to evaluate the nature of the forces and accelerations affecting the head of a goalkeeper in handball when getting hit by a ball in the head. A ball hitting of the head might lead to a concussion, which is a general problem in the sport world. To get a better understanding of how common it is to get hit by a ball in the head as a handball player, a survey was sent out to the players of Swedish first league handball club Redberglids IK.

In order to find a correlation between the pressure, the velocity and the ball size drop tests were performed. During the drop tests the impact force time history and the ball velocity were measured.

Concussions can be linked to large linear and rotational acceleration of the head. To be able to measure the linear and the rotational acceleration of the head during actual match situations, a test with a crash test dummy was created. The test featured players shooting on a (Hybrid III) crash test dummy's head.

The results from the drop tests were not sufficient enough to draw general conclusions on how the impulse is affected by pressure. In order to draw firm conclusions on how the ball pressure, ball size and velocity of the ball affects the impulse and force, more tests need to be performed.

The dummy test showed that the parameter with the most effect on the head accelerations was the point of impact. The test resulted in linear acceleration of 41.7 ± 14.1 g and rotational acceleration of 1566.7 ± 505.4 rad/s² in the dummy's head. These numbers were in the same range for getting concussions as in other sports, e.g. baseball. Since there have not been enough research about concussions in handball it is currently not possible to state exactly when the hit is detrimental.

Sammanfattning

Syftet med projektet var att undersöka de krafter och de accelerationer som huvudet utsätts för då en handbollsmålsvakt träffas av en boll i ansiktet. Speciellt undersöktes inverkan av bollstorlek och hastighet. Studien motiverades av att det är ett generellt problem i sportvärlden att vissa slag i huvudet kan leda till hjärnskakning.

För att få en ökad förståelse för hur vanligt detta är i handboll genomfördes en enkätstudie bland junior- och seniorspelare i Redberglids IK. Fallprov med handbollar mot en stel lastmätande träffyta genomfördes för att studera eventuella korrelationer mellan hastighet, tryck och bollstorlek gentemot krafthistoria.

Under mer realistiska matchförhållanden genomfördes ytterligare ett test där spelare från Redberglid IKs elitlag kastade handbollar på en krockdocka. I detta test mättes linjär och roterande acceleration av krockdockans huvud.

Från fallprovet gick det inte att dra några slutgiltiga slutsatser angående hur impulsen påverkas av bolltrycket. Detta på grund av att resultaten inte var tillräckligt omfattande. För att kunna ge en definitiv beskrivning av hur bolltrycket, bollstorleken och hastigheten påverkar impuls och kraft skulle fler test behövas.

Test med krockdocka visade att den parametern som hade mest påverkan på huvudets acceleration var vilken del av huvudet som blev träffad. Den linjära acceleration på huvudet fick ett utslag på 41.7 ± 14.1 g och vinkelaccelerationen på huvudet visade 1566.7 ± 505.4 rad/s². Dessa siffror låg i samma intervall som för att få en hjärnskakning inom andra sporter, till exempel baseball. Eftersom att det inte finns tillräckligt mycket forskning om hjärnskakningar inom handbollen, var det inte möjligt att dra någon slutsats om hur skadligt det är att få en boll i huvudet.

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1 Introduction

A handball can reach a speed of over 100 km/h [1]. If it hits the goalkeeper's head it may cause head injuries, especially concussions. This is a common problem in several sports.

1.1 Background

In many team sports there is a risk of contracting head injuries. This applies among other things to ice hockey, American football and handball. One common head injury in sports is concussion. Concussions are caused by a direct blow to the head causing the brain to strike against the skull [2]. In sports this can occur for instance when getting hit by a ball or during a tackle [3]. This might lead to players having to quit playing since several concussions can lead to permanent brain damage [4].

In handball, when the shooter is trying to score, the shooter is usually 3 to 9 meters away from the goalkeeper. From this distance a handball shot can reach a speed of over 100 km/h. If the goalkeeper gets hit in the head there is a significant risk for concussion. Due to this there is a discussion on tightening the regulations. To base this discussion on facts, there is a need of investigating how detrimental a handball shot to the head can be. As for now there are no established injury measures for the injury determination in handball head impacts and this study is a step towards establishing some [5].

1.2 Problem statement

The aim of the project was to investigate the detrimental impact of the ball when it hits the goalkeeper in the head from a mechanical perspective. This was done by considering different parameters such as ball size, ball pressure, acceleration, point of impact and the impact velocity of the ball. It was also determined which parameters that have the most influence on the linear and rotational acceleration of the head.

2 Theory

When the goalkeeper gets hit in the head by a handball there is a substantial risk of developing a concussion. Good knowledge of the symptomatology of concussions is key to recognizing affected goalkeepers and to get them off the field quickly and out of play for as long as necessary. Should the player contract a new concussion before fully recovered it could have a severe impact and cause more damage to the brain [6].

2.1 Concussion

Concussions are common in sports and are a concern for different sports around the world. Concussions occurs through a hard blow to the head that causes a rotation of the head and sets the brain in motion [7]. Linear acceleration–deceleration and rotational acceleration–deceleration of the head are the two major reasons for why concussions occur. Linear acceleration causes injuries that occurs in a specific area while rotational acceleration causes both injuries in a specific area and in a widespread area. Rotational accelerations contributes more to concussions compared to linear accelerations [6].

Different injuries occurring in handball are mostly muscle and ligament sprains and contusions [5], but of all different types of injuries 30% are head and neck injuries. The high amount of head and neck injuries are related to the fact that handball is a relatively unprotected contact sport [8].

Concussion is an injury that is hard to diagnose and recognize since it cannot be tested by laboratory measures, but only by the symptoms presented by the affected. Common symptoms for concussion are headache, nausea, dizziness, memory problems and unconsciousness [8]. However, a study from Sahlgrenska academy states that a blood sample can be used as a prognostic marker for concussions in order to predict the rehabilitation time for the affected [9]. This is not only a great progress in order to assess the severity of concussions, but also a major indicator of new bio markers to serve in the diagnostics of concussions.

The impact of a concussion can be seen within 24 hours and can last up to several weeks after the injury. After a concussion, within 7–10 days the risk of a subsequent concussion is increased [6]. For those players who lose consciousness it is a sixfold increase of the risk of getting a subsequent concussion compared with players who do not lose consciousness. One concussion is usually not harmful but repeated concussions can lead to serious consequences. It can lead to depression, prolonged recovery time, mild cognitive impairment and the chronic disease "chronic traumatic encephalopathy" (CTE) [6]. The symptoms for this injury are memory loss, confusion, impaired judgment, aggression, depression, anxiety, impulse control issues and sometimes suicidal behavior [10].

Before returning to the sport, the player must be free from any symptoms both at rest and during exercise [6]. As long as the player has symptoms, the player should for example abstain watching TV and playing computer games until the symptoms are gone. When the player rehabilitates the training should increase gradually until full exercise [8]. Concussions differ from each other and it is important to treat each concussion individually [6].

2.1.1 Sports

Two common sports that have problems with concussions are ice hockey and American football. The main problem in these sports for causing concussions is the contact between the players. In contrast to handball, the players in both ice hockey and American football, use helmets. In these sports, helmets have some protective effect regarding concussion. Test with helmets, compared with test without helmets, show a reduction in linear acceleration but an increase in rotational acceleration [6].

One test has been performed comparing two different liner in helmets for ice hockey. The test represented what may happen during a game. Both linear and rotational accelerations were investigated. The two liners were a vinyl nitrile liner and an expanded polypropylene liner. When measuring linear and rotational acceleration in a helmet with vinyl nitrile liner the peak linear acceleration became 113.6 ± 12.9 g and rotational acceleration became 5614 ± 863 rad/s². For the expanded polypropylene liner the peak linear acceleration became 105.1 ± 20.2 g and the rotational acceleration became 5910 ± 1233 rad/s². These values correspond to when the helmet was hit in the front [11].

When measuring the concussive impact forces in American football in National Football league (NFL), laboratory reconstruction of concussive impacts was used measuring linear and rotational acceleration of the helmet as well as the impact duration. The linear acceleration became 98.0 ± 28.0 g when looking at the struck player. The rotational acceleration for this case became 6432 ± 1813 rad/s² and the impact duration was 9.3 ± 1.9 ms. When looking at the striking player both linear and rotational acceleration decreases. The linear acceleration became 58.5 ± 21.4 g and the rotational acceleration became 4225 ± 1405 rad/s² [6].

When looking at test created in a laboratory causing non-concussive impact forces in NFL the linear acceleration decreased. For the struck player the linear acceleration became 59.7 ± 23.9 g and for the striking player the linear acceleration became 56.2 ± 22.2 g. The rotational acceleration for the struck player became 4234.7 ± 1716.3 rad/s² and for the striking player the value was 3982 ± 1402 rad/s². The impact duration for the struck player became 7.1 ± 2.6 ms and for the striking player the impact duration was 9.3 ± 1.9 ms. When comparing to a game situation for the struck player the linear acceleration became 67.8 ± 14.7 , the rotational acceleration became 4847.6 ± 929.8 rad/s² and the impact duration was 7.9 ± 1.9 ms [6].

Two other sports besides ice hockey and American football that have been investigated are soccer and baseball. These sports were investigated to see what the impact forces were when concussions occurred. For soccer the head-to-head situation is the most harmful situation and when reconstructing a FIFA soccer game the average of the highest linear acceleration became 87 g and the rotational acceleration became 7033 rad/s² in the head. For baseball the concussive events occur when striking the masks of catchers and umpires. In this case, the linear acceleration in the head varied from 26 to 42 g and the rotational acceleration in the head varied from 1974 to 5266 rad/s² [12].

3 Methodology

Since concussions are a problem in other sports than handball it was investigated how often concussions occurs in handball by getting hit in the head with a ball. This was done by sending out a survey, that will be explained in detail in Section 3.1.

The drop test that was made in order to find a correlation between ball parameters and impact forces and the full-scale test with a crash test dummy are described in detail in Section 3.2 and 3.3.

3.1 Survey

To investigate how common it is to be hit in the head by a ball during a handball season, a survey was made for the players. The questions in the survey were:

- Are you a field player or a goalkeeper?
- How many times per season do you get hit hard in the head by a handball on average?
- Where in the head did you most often get hit?
- How many times have you had a concussion caused by a ball in the head?
- Where in the head did you get hit when you got the concussion?
- How long did it take for you to recover and be able to play again after the concussion?

This survey was sent out to junior and senior players, male and female in Redberglids IK. The reason for sending out the survey was to get a better understanding of how common concussions are when playing handball. It was beneficial to know where in the head the players got hit when they got a concussion in order to have background investigation information for the following investigations.

3.2 Tests

Two series of tests have been conducted. One of the tests was performed using a load cell to analyze how ball pressure, ball size and impact velocity changes the impact force. The other test was with handball players throwing balls at the head of a crash test dummy to determine linear and rotational acceleration of the head of the dummy.

3.2.1 Preparation of the tests

In order to prepare for the tests it was crucial to establish that all equipment was at hand and that it was working properly. This was done by trying the two setups in advance without collecting any data. The equipment that was used for the drop test and the dummy test is presented in Table 1.

Table 1: Equipment needed for the tests

Equipment	Drop test	Dummy test
3 accelerometers		x
A/D - converter	x	x
Basic mechanic tools		x
Ball pump	x	x
Computer	x	x
Crash test markers		x
Duct tape	x	x
Dummy - Hybrid III		x
Extension cables	x	x
GoPro and stand	x	x
Gyroscope		x
Handballs	x	x
Lasersizer	x	x
Lights	x	x
Load cell	x	
Multiplug	x	x
Signal amplifier	x	x
Pressure gauge	x	x
Projector screen		x
Straps		x
Yardstick/Tape measure	x	x

A trial setup with the dummy and all of the equipment was carried out. The dummy's head was removed from the torso and the back of the head was unmounted to be able to put in three accelerometers and gyroscope. The accelerometers were mounted in a way that enabled measuring of the acceleration in the x -, y - and z -direction, see Figure 1. The accelerometers and the gyroscope were all mounted to a piece metal plate, that was positioned in the center of gravity of the head. When the head was mounted back on the dummy, two rubber blocks were attached between the neck of the dummy and the head. These were added in order to make the dummy correspond to a fully alert person. The head was only able to rotate in the frontal direction, around the y -axis, see Figure 1.

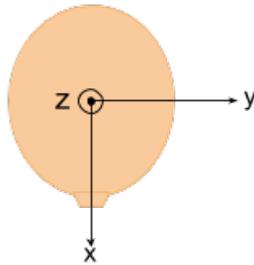


Figure 1: Top view of the dummy head with the coordinate system.

3.2.2 Drop test

The drop test was done to be able to compare force histories of the ball for different ball pressures, sizes and velocities. This correlation was used to estimate the expected impulses in the dummy test.

The drop test was performed by dropping three handballs with different sizes from three different heights and with three different ball pressures, on a load cell. The balls were pumped and the pressure was measured with a pressure gauge. The heights that were used were 3.72, 5.00 and 6.55 meters and the ball pressures were 0.1, 0.2 and 0.5 bars. The heights were measured using a laser sizer and a tape measure to make sure that the laser sizer was accurate.

When producing handballs and testing them the pressure of the ball is 0.5 bar, therefore the maximum pressure was chosen accordingly [13]. However when the dummy test was made, Redberglids IK's own balls were used. These had a lower pressure than 0.5 bar and therefore the lower pressures were investigated as well.

The different ball sizes that were used are presented in Table 2. The circumference and the weight of the balls depends to some extent on the pressure. Since three different pressures were used when performing the tests the circumference and the weight of the handballs will vary within the values presented in Table 2.

Table 2: Ball sizes according to the Swedish association of handball [14].

Size	Circumference	Weight
size 1	50-52 cm	275-325 gr
size 2	54-56 cm	325-400 gr
size 3	58-60 cm	425-475 gr

The drop tests were split into two parts to investigate different correlations. The correlations that were sought for were the following:

1. Velocity–impact force–pressure
2. Ball size–impact force

The correlation between the velocity, the force and the pressure was investigated by throwing a size 3 ball from all three heights with varying pressure. For each height and pressure, at least three measurements were performed in order to capture the variation in impact force. This test would later result in a velocity–force graph for all different pressures for the size 3 ball.

The size 3 ball was used during the dummy test, therefore only the correlation for this ball was of interest. This correlation was necessary to be able to estimate how large the impact force would be in the test with the dummy, by knowing the velocity and the pressure of the ball.

The correlation between the ball sizes and the impact force was investigated by dropping all three ball sizes from the same height (3.72 m) with the same pressure (0.2 bar). For each ball size at least three measurements were performed. This analysis was carried out in order to investigate which ball size gives the highest impact force characteristics depending on the ball size and how big of a difference there was in impact force between the three sizes.



Figure 2: Setup for the drop test.

When performing the drop test, the setup was arranged according to Figure 2. The load cell was mounted on the ground below an open staircase using duct tape in order to prevent the load cell from moving and giving inaccurate results. The balls were then released from three different floors above the load cell.

The load cell was divided into three zones to be able to rate the hits and to know where the ball landed. The zones were defined according to how the ball bounced after it hit the load cell. Zone 3 represented a bounce with an angle larger than 60 degrees, Zone 2 represented a bounce with an angle between 30 and 60 degrees and Zone 1 represented a bounce with an angle less than 30 degrees. The angles were measured from a vertical line through the center of gravity of the load cell.

The impact force history when the ball hits the load cell was measured, stored and analyzed using a computer with LabVIEW software [15]. The collected data and the recorded video was checked between each drop to ensure that the ball landed in the right zone and that the load cell gave a result. If the data or the video for a drop did not fulfill the requirements for the analysis, that specific drop was neglected. Only the hits in Zone 1 were used later on in the analysis. This was done in order to obtain the peak values. If there were more than one hit in Zone 1 for one height and pressure, these were compared and the hit with the highest peak force was chosen.

The impact was video recorded using a GoPro on a stand that was placed next to the load cell, see Figure 2. The impact velocity was computed using video analysis. In order to ensure that the video was bright enough for the video analysis a 500W lamp was used. It was also necessary to have a reference distance to be able to evaluate the velocity in m/s in the video analysis, therefore two crash test markers were placed in the background.

3.2.3 Test with players and dummy

The test with the players was carried out in Rosendalshallen in Gothenburg which is the training arena of Redberglids IK. The dummy was placed on a gymnastics plinth against the goalpost, where the head was 1.90 meters above the ground, see Figure 3. Straps were used to make the torso of the dummy as rigid as possible in order to simulate an alert goalkeeper. To prevent the head from hitting the goalpost and thereby affecting the results during the test, mattresses were placed between the dummy and the goalpost. Furthermore a crash test marker was attached to the side of the dummy's head to be able to follow the movement of the head when doing the video analysis. The linear acceleration was measured in three directions, x -, y - and z -direction and the rotational acceleration was measured around the y -axis, see Figure 1.

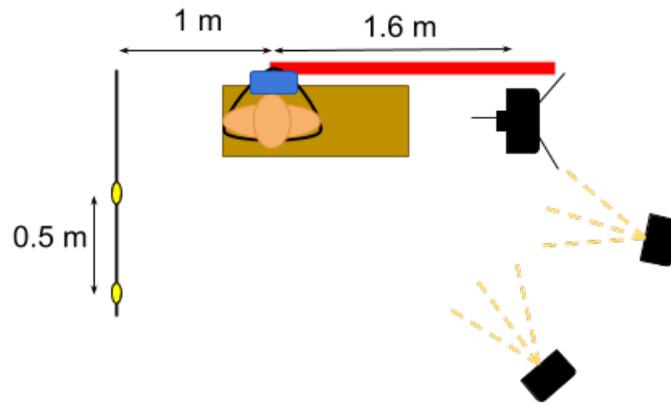


Figure 3: The setup for the dummy test.

A black background was placed parallel to the direction of the ball, one meter away from the center of gravity of the dummy's head. The black background was needed in order prevent shadowing and to facilitate the tracking of the ball later on in the video analysis. On the black screen, two crash test markers were added with a distance of 50cm from each other, see Figure 4. These were later used as reference in the video analysis.

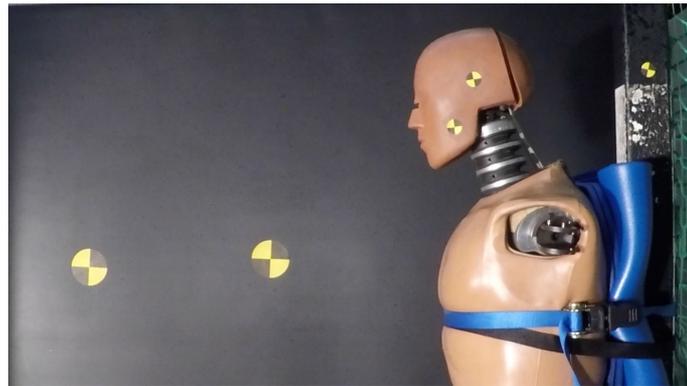


Figure 4: The dummy setup from the view of the GoPro.

To ensure that there was enough light intensity to obtain a video that was good enough for the analysis, two lamps were used when filming. One of the lamps had a power of 1000W and the other of 500W. The lamps were placed with different angles to prevent shadowing, see Figure 3.

The GoPro was placed on the same height as the dummy's head and perpendicular to the direction of the ball in order to capture the impact of the ball when it hits the dummy along with the movement of the dummy's head. The GoPro was placed 1.6 meters away from the dummy. The full setup can be seen in Figure 3.

The players threw at the dummy from two distances, approximately 3.7 and 7.6 meters. These distances were chosen with help of the players and the coaches, to make the test as realistic and representative as possible. The players threw the balls both from a standing position at 7.6 meters and by jumping at 3.7 meters. The shorter distance, 3.7 meters, represented a shot during a counter attack and the 7.6 meters distance represented a shot through a standing defense.

3.3 Analysis of the tests

All the measuring equipment used in the tests (load cell, accelerometer and gyroscope) delivered a small electrical signal [mV]. The signal was sent through an amplifier before it passed through an

A/D-converter which digitized the signal and delivered it to the computer where the signal was recorded and saved using the software LabVIEW [15].

The linear accelerations and rotational velocities from the dummy test, and the impact forces from the drop test, were evaluated in MATLAB [16] using the formulas presented in equations (1), (2) and (3). Here the input was the signal delivered to the computer. The amplification factors can be found in Table 3 and the sensitivities in Table 4. The excitation is equal to 10V, the capacity of the load cell is 5000lbs (2268.0kg) and g is the gravitational acceleration ($9.81m/s^2$).

$$F = input \cdot \frac{1}{amplification} \cdot \frac{capacity}{excitation \cdot sensitivity} \cdot g - F_{offset} \quad (1)$$

$$a = input \cdot \frac{1}{amplification \cdot sensitivity} - a_{offset} \quad (2)$$

$$\omega = input \cdot \frac{1}{amplification \cdot sensitivity} - \omega_{offset} \quad (3)$$

Sensor	Amplification
Accelerometers	500
Gyroscope	50
Load cell	500

Table 3: Amplification factor of the different sensors.

Sensor	Sensitivity
Accelerometer 1	0.1307 $\frac{mV}{g}$
Accelerometer 2	0.1452 $\frac{mV}{g}$
Accelerometer 3	0.1324 $\frac{mV}{g}$
Gyroscope	0.09473 $\frac{mV}{deg/s}$
Load cell	4.362 $\frac{mV}{V}$ at max capacity (2267.96kg)

Table 4: Sensitivities of the different sensors.

3.3.1 Drop test

The impact velocities in the drop tests were estimated using energy conservation assuming that the ball falls without air resistance. These velocities were compared to the ones obtained from the video analysis to make sure that the velocity from the video analysis was lower than the theoretical one (due to the influence of the air resistance). The equation that was used to calculate the velocity was derived using the equations for kinetic (E_k) and potential (E_p) energy.

$$E_k = \frac{1}{2}mv^2 \quad (4)$$

$$E_p = mgh \quad (5)$$

Equation (4) was set equal to equation (5) and the velocity could be computed as,

$$\frac{1}{2}mv^2 = mgh \rightarrow v = \sqrt{2gh} \quad (6)$$

where m is the mass of the ball, h is the height which the ball is dropped from, v is the impact velocity of the ball and g is the gravitational acceleration. From equation (6) the unit of the velocity was in m/s and was transformed to km/h by multiplying by 3.6.

When analyzing the drop test, the impulse was calculated for the size 3 ball for all pressures from all different heights. This was done since both the duration time of the hit and the impact force affects the severity of the hit. Since the duration time can vary a lot for each load case, a hard impact force doesn't necessarily have to be the worst case scenario if the duration time is very small. Therefore, by

calculating the impulse for each hit it was possible to get a better picture of what load case is the worst. The impulse was calculated by integrating the force evolution when the ball hits the load cell as,

$$\mathbf{J} = \int_{t_1}^{t_2} \mathbf{F} dt \quad (7)$$

where impact time is between t_1 and t_2 .

3.3.2 Test with dummy

The variables that were interesting when analyzing the dummy test concerning concussions were the linear acceleration, rotational acceleration and the impact time. The impact velocity was calculated using video analysis in LabView [15].

The directional accelerations (a_x , a_y and a_z), measured with the accelerometers, were not as relevant as the resultant (total) acceleration. In the results the focus is on the acceleration resultant (a_{tot}) which was computed using Equation (8).

$$a_{tot} = \sqrt{a_x^2 + a_y^2 + a_z^2} \quad (8)$$

Since acceleration is related to force, and it is the ball that exposes the head to a force, the time the ball is in contact with the head should be the same as the time where there is a positive linear acceleration. The impact time was therefore estimated as the time where the acceleration (a) was larger than the background noise. Since the noise had an amplitude of around 6 g, this was achieved by implementing Equation (9).

$$T_{\text{impact}} = t(a < 6)_{\text{decreasing}} - t(a > 6)_{\text{increasing}} \quad (9)$$

Since the signals were noisy with high-frequency fluctuations, the angular velocity (ω) measured with the gyroscope, had to be filtered in MATLAB to be able to calculate the rotational acceleration. The angular velocity was filtered using the cubic interpolation function `pchip.m` in MATLAB and the acceleration was then calculated numerically according to Equation (10).

$$\alpha(t) = \frac{\omega(t + \Delta t) - \omega(t - \Delta t)}{2\Delta t}, \quad \Delta t = 0.005s \quad (10)$$

4 Results

The data from the survey that was sent out to the players was collected and analyzed. From the drop test and the dummy test, data was collected, compiled and analyzed.

4.1 Survey to players

There were 24 players that answered the survey. Of these, 14 players had got hit hard in the head at least once during the latest season. Six of these players got hit more than three times, whereof five of these were goalkeepers.

Out of all the players that answered there were six persons that got a concussion at least one time during the latest season due to getting hit hard in the head by the ball. The cases of concussion that required the longest rehabilitation time were for the goalkeepers who could be away from playing for more than a month. From the survey it could also be concluded that the most common cause for concussion was getting hit in the forehead. This was the case for both goalkeepers and field players. A summary of the survey is presented in Appendix A.

4.2 Drop test

Table 5 gives theoretical speeds corresponding to the the heights which the ball was dropped from. Table 5 shows how large the force and the velocity was for each combination of pressure and height. It is evident that the theoretical and actual velocities are similar although some the actual velocities are slightly bigger than the theoretical ones.

Table 5: Velocity computed using the energy conservation, equation 6.

Height	Theoretical velocity
3.72 m	30.76 km/h
5 m	35.66 km/h
6.55 m	40.81 km/h

The maximum forces that are shown in Table 6 can also be seen in Figure 5 with the time history of the force. Note that for the pressure 0.1 bar, the velocities for the two first heights are larger than for the other two pressures on the same heights.

Table 6: Maximum force for different pressures and heights, velocities evaluated from video analysis.

	Height = 3.72 m	Height = 5 m	Height = 6.55 m
Pressure = 0.1 bar	791 N / 31.26 km/h	969 N / 37.05 km/h	1057 N / 40.38 km/h
Pressure = 0.2 bar	910 N / 29.36 km/h	886 N / 34.92 km/h	1278 N / 39.75 km/h
Pressure = 0.5 bar	894 N / 29.90 km/h	1056 N / 34.93 km/h	1279 N / 39.12 km/h

Figure 5 shows the impact force of the ball for different combinations of pressure and the heights. It can be observed that the average force (in the exposure time) is higher for higher pressures. It can also be seen that when the pressure increases, the time that the ball is in contact with the load cell decreases.

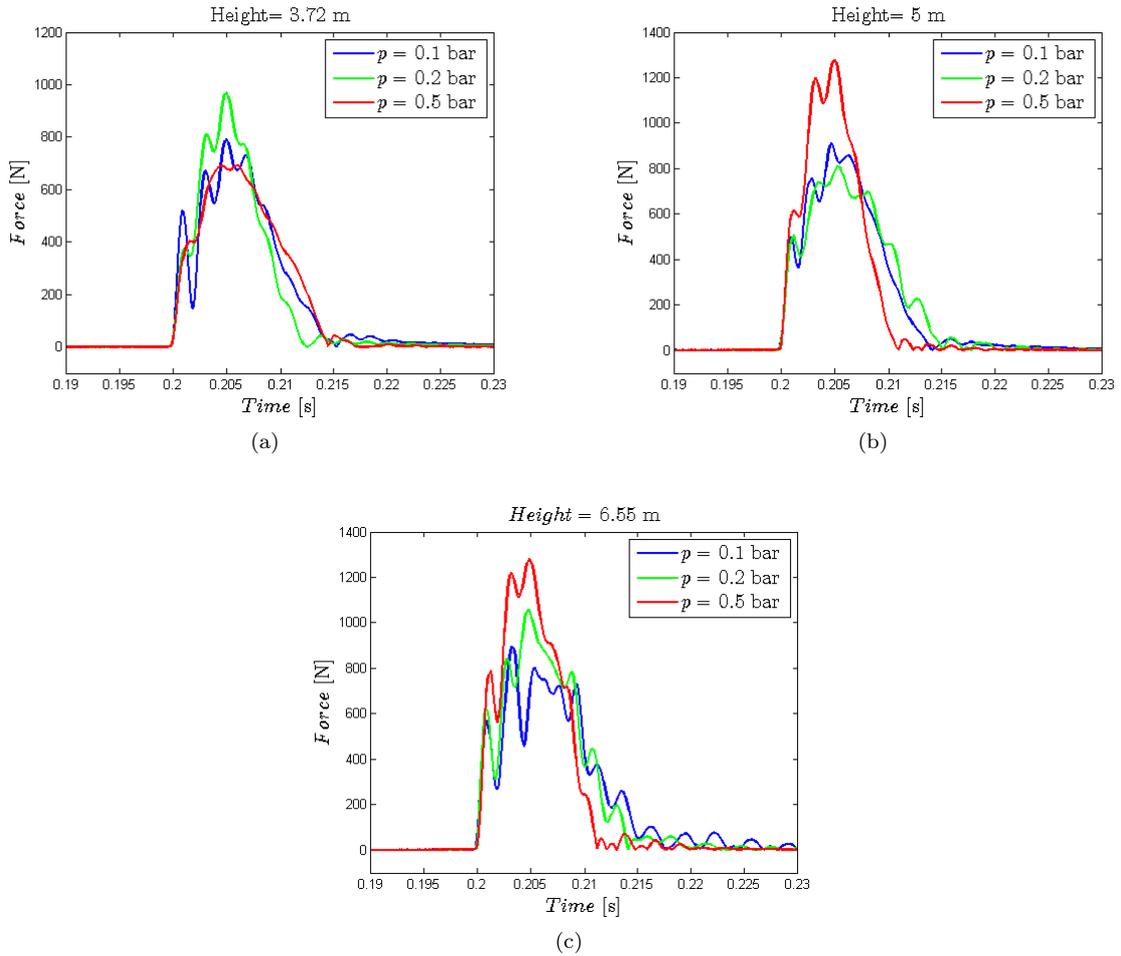


Figure 5: Impact force histories for different ball pressures and drop heights for a ball size 3. a) Height=3.72m, b) Height=5 m and c) Height=6.55m

From Figure 6 it can be seen that when the height increases the impulse (calculated by eq. 7) increases. Further, an increased pressure is found to correspond to a higher impulse for the cases studied.

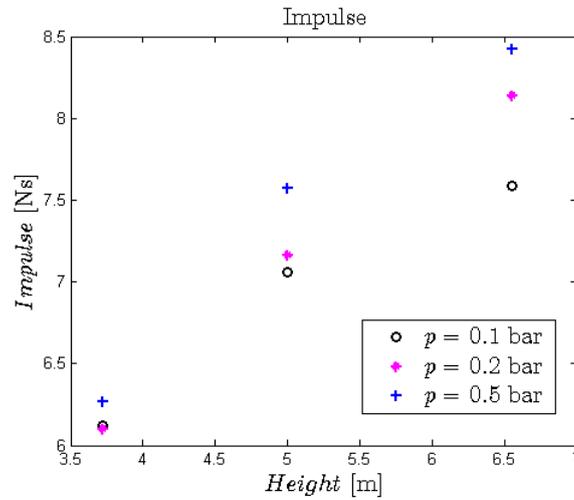


Figure 6: Impulse for the different pressures at the three different heights.

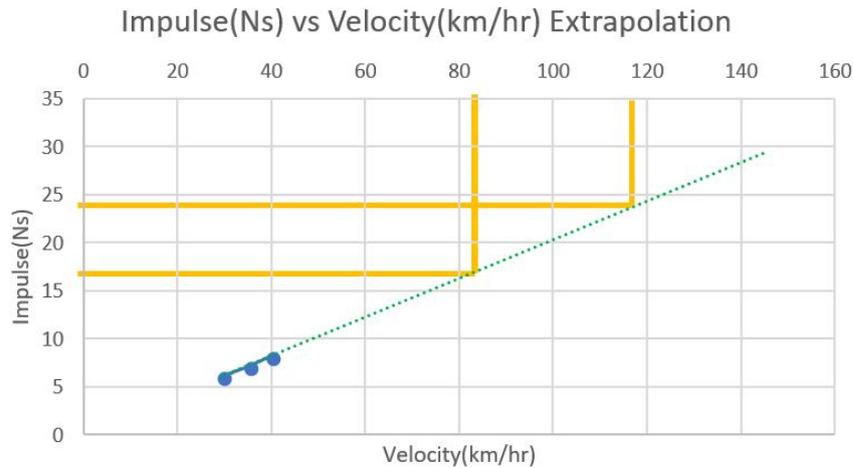


Figure 7: Extrapolation of drop test impulse corresponding to velocities in dummy test for 0.2bar pressure

The drop test impulse results were extrapolated in Figure 7 for estimating the impulse experienced by the dummy's head (from the ball impact). The impulse-velocity corridor corresponds to impulse ranges between 16Ns and 24Ns for a range of throws (83 km/h to 115 km/h) found in the dummy experiment.

In Figure 8 the velocity profile for a ball dropped, with negligible air resistance, at different heights is shown. The black dots mark the range from where the ball was dropped during the drop tests and the red dots represents the velocities of the thrown handballs in the dummy test. It is found that the dummy test conditions correspond to a drop test from approximately 50 m.

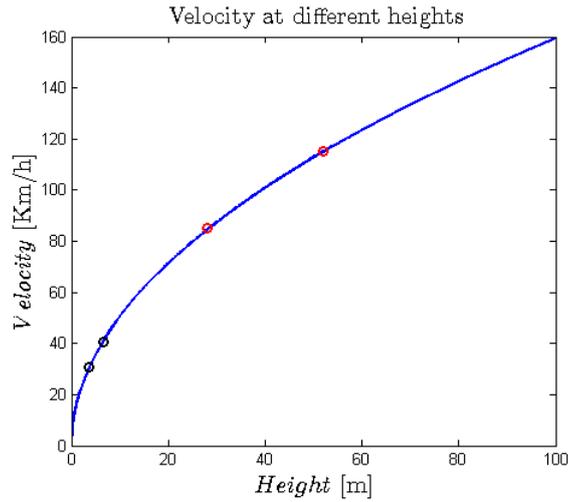


Figure 8: Theoretical drop-test velocities for different heights. Velocities for performed drop-tests indicated by black circles and red circles for dummy tests.

Figure 9 shows how the impact forces differ with different ball size. Note that for ball size 1 and ball size 2 a second peak appear. This may occur due to movement of the load cell, that can be seen in the film analysis.

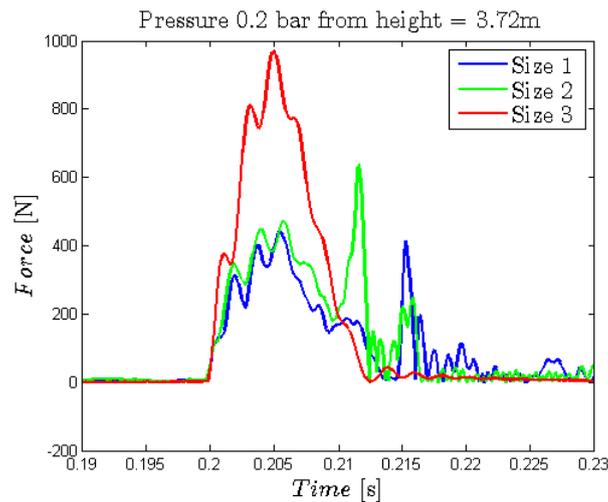


Figure 9: Influences of ball sizes on impact force.

Table 7: Max force for the different sizes of handballs plotted in Figure 9.

	Max force
Ball size 1	441 N
Ball size 2	638 N
Ball size 3	969 N

Figure 9 and Table 7 show that if the size of the ball increases, higher peak forces will be obtained in drop tests from the same height.

4.3 Test with dummy

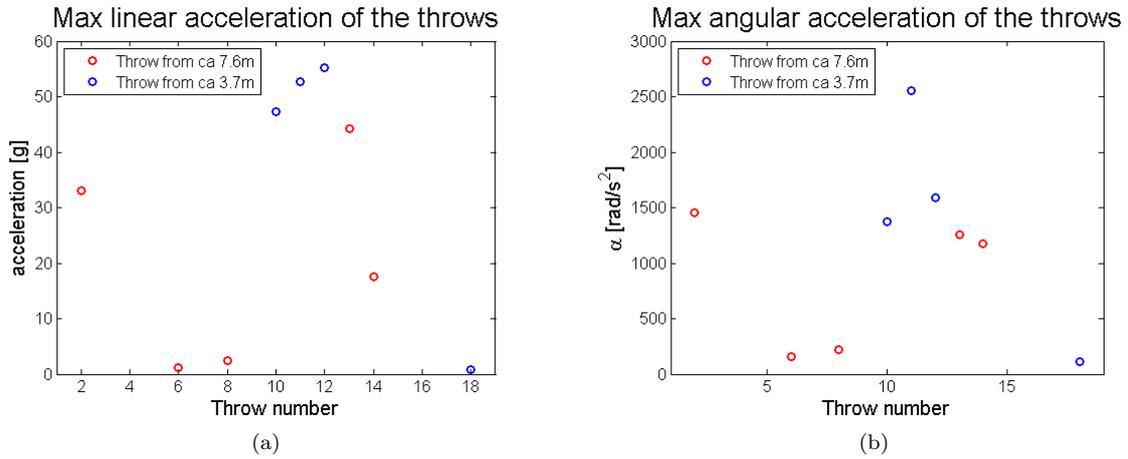


Figure 10: a) Linear and b) rotational acceleration for the center of gravity of the dummy head.

In Figure 10 the maximum linear and rotational acceleration of the dummy's head for each hit is shown. The highest linear acceleration recorded is 55.2 g from throw number 12 and the highest rotational acceleration is 2555.1 rad/s^2 recorded from throw number 11.

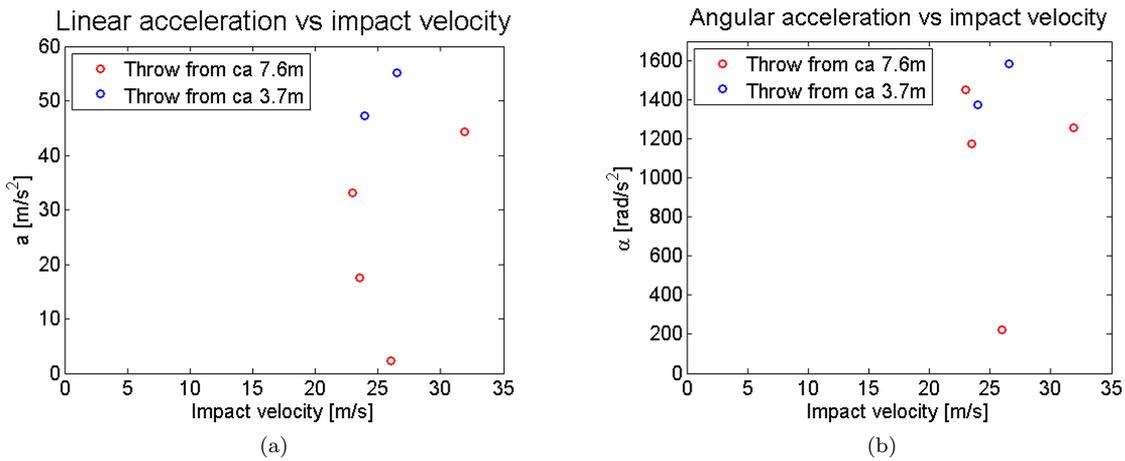
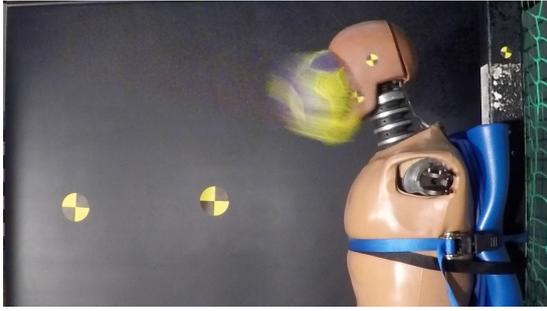


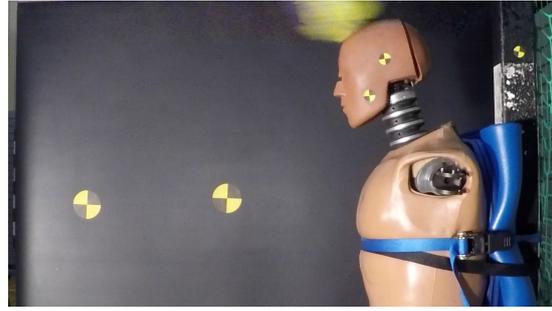
Figure 11: a) Linear and b) rotational acceleration for the center of gravity of the dummy head plotted against impact velocity.

In Figure 11 the maximum linear and rotational acceleration is plotted against the impact velocity. The impact velocity could not be calculated for throw 6, 11 and 18 since the ball wasn't visible in the frame. Therefore they are not included in the figure. It can be seen that the linear acceleration in Figure 11 (a) has no correlation to the impact velocity. Excluding one throw that hardly hit the head and therefore resulted in a low rotational acceleration, all throws in Figure 11 (b) have a similar rotational acceleration. For both the linear and rotational acceleration the throws from 3.5 m results in a slightly higher acceleration than the throws from 8 m.

In Figure 12 the point of impact for throws 12 and 2 are shown. It can be seen that in throw number 12, which resulted in the highest linear acceleration (55.2 g), the ball hit in the lower part of the face slightly to the left. Throw number 2, which gave a lower linear acceleration (33.1 g), hit very high up on the head. The two throws had similar rotational acceleration with 1586.5 rad/s^2 for throw number 12 and 1452.9 rad/s^2 for throw 2.



(a)



(b)

Figure 12: Point of impact for throw number a) 12 and b) 2.

In Figure 13, point of impact for throw number 11 is shown and the throw hit on the left side of the forehead. The highest rotational acceleration occur for throw 11 and Figure 10(b) shows that the highest rotational acceleration has a maximum value of 2555.1 rad/s^2 . Throw 11 has also the second highest value for linear acceleration with a maximum value of 52.8 g .

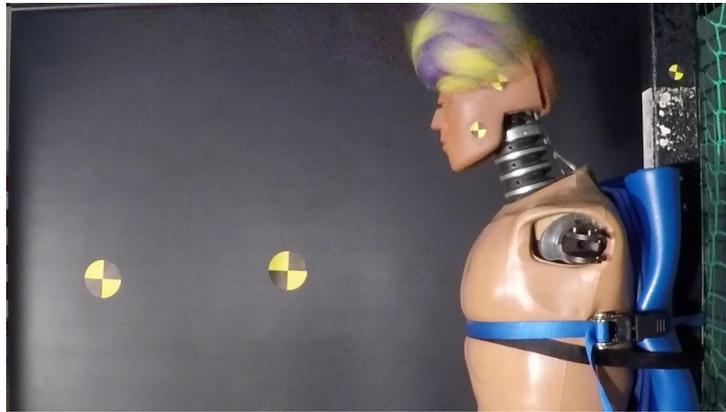


Figure 13: Point of impact for throw number 11.

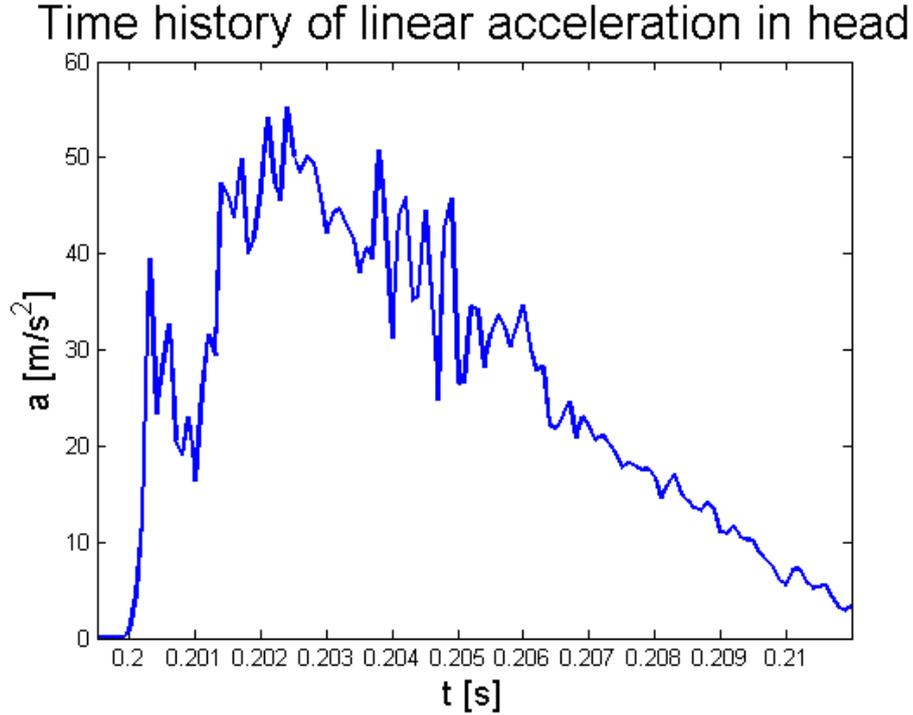


Figure 14: Time history of the linear acceleration for throw number 12.

The time history of linear acceleration in the head of the dummy is presented in Figure 14. As can be seen the signal for the linear acceleration is very noisy but a general form of the time history can be distinguished.

In Table 8 the impact times of the dummy’s head for the different shots is presented. A large variation of the impact time for the backwards motion of the head can be seen.

Table 8: Impact time of the head for six shots.

Throw number	2	10	11	12	13	14
Impact time [ms]	8.6	11.7	18.5	10.6	16.0	7.6

The mean and standard deviation for the maximum linear and rotational acceleration as well as the impact time for each throw has been calculated and presented in Table 9. Throws 6, 8 and 18 are omitted since these hits essentially missed the head.

Table 9: Mean results and standard deviations for six shots on the dummy head.

Impact results	Mean \pm SD
Linear acceleration	41.7 ± 14.1 g
Rotational acceleration	1566.7 ± 505.4 rad/s ²
Impact time	12.2 ± 4.3 ms

5 Discussion

The time evolution in graph (c) in Figure 5 essentially looks as expected following basic laws of physics: high pressure gives a high maximum force but a shorter impact time, while lower pressure gives lower maximum force but longer impact time. However in graphs (a) and (b), contact time and force did not fully trend as anticipated. The reason for this could be that the height was low and any small changes gave a larger influence on the force compared to results from larger heights. Another cause for the variation could be that the load cell registered the hits differently depending on how the ball hit the

load cell.

The odd behaviour in graphs (a) and (b) can also be seen in Table 6 where the velocities for low heights vary a lot with the pressure even though the ball is thrown from the same height. One cause of this could be that there was a small variation of the height and drop conditions (e.g different person dropping the ball) each time the ball was dropped. When comparing Table 5 to Table 6 the velocities for the various heights are quite similar apart from the velocities for pressure 0.1 bar for the two first heights. Since these velocities are larger than the velocities computed using energy conservation, this indicates that the ball wasn't free falling. Probably the person dropping the ball gave it some extra acceleration when it was dropped.

Figure 6 shows that increased pressure and height leads to higher impulses. With increased height the difference in impulse gets larger between pressure 0.1 bar and 0.5 bar. The ball with pressure 0.2 bar acts differently. For the lower height it has an impulse value close to the ball with 0.1 bar and with increased height it is getting closer to the impulse value of the ball with pressure 0.5. The impulses are calculated from the results presented in Figure 5 for which accuracy has been discussed above. Due to these uncertainties it's not possible to establish any firm conclusions regarding how the pressure and velocity affects the impulse. To investigate trends, a larger number of tests would be required.

The dummy test was conducted during 30 minutes including the setup time. Only 18 shots were recorded out of which nine shots hit the head. Therefore there are few shots to draw any definite conclusions from in the tests. With more time, more shots could have been thrown and calibration could have been done between each test to ensure less errors and higher precision. However, overall conclusions will still be discussed.

In Figure 10 the highest linear and rotational accelerations were for the throws from 3.7 m. Since the players were asked to aim for the head, the reason for the stronger reactions could be that the players have easier to aim for the forehead from the shorter distance, which probably led to cleaner hits.

For the throws where the velocity was able to be calculated, the impact velocity varied from 23 – 32 m/s. Despite similar impact velocities for all the recorded shots, the linear acceleration (seen in Figure 11 (a)), with the lowest values excluded, varies from 17.6 to 55.2 g. The rotational acceleration (seen in Figure 11 (b)) on the other hand has more concentrated values (if very low value are excluded) varying from 1175.6 to 1586.5 rad/s². For the throw that resulted in the highest rotational acceleration (throw 11) the impact velocity could not be calculated and it is therefore not shown in Figure 11. Both for the linear and the rotational acceleration there seems likely to be no, or only a small, correlation between impact velocity and the head acceleration. More throws would have been needed to analyze a possible correlation between impact velocity and head acceleration.

Comparing the point of impact for throw 12 (shown in Figure 12 (a)) with the point of impact for throw 11 (shown in Figure 13) it can be seen that the ball hits the forehead for throw 11 while for throw 12 the ball hit the middle of the face. Throw 11 generated a higher rotational acceleration since the lever between the hit and center of gravity of the head became longer. From this and the fact that there seems to be no correlation between impact velocity and the accelerations, it seems like the factor that has the most effect on the accelerations is the point of impact.

When testing conditions likely to result in concussions for different sports the range of acceleration magnitudes is large. The linear acceleration values differ from approximately 26 to 113 g while the rotational acceleration differ from 1974 to 7033 rad/s². The linear acceleration from the handball test lies in the range from different sports and has a value of approximately 41.7 ± 14.1 g, with the highest test result being 55.2 g. The rotational acceleration from the handball is approximately 1566.6 ± 505.4 rad/s² which is low compared to the sports referred to in Section 2.1.1. However the highest rotational acceleration recorded during the throwing test was 2555.1 rad/s² which is within the range of the other sports.

The impact duration for the tests conducted regarding American football was approximately 9.3 ± 1.9 ms. Comparing this with the impact time measured in the head of the crash test dummy during the handball test, 12.2 ± 4.3 ms, it can be noted that the impact time in the handball test is slightly longer

than the impact duration in the American football test.

American football, ice hockey, soccer and baseball differ to handball regarding equipment, rules and contact in the game. Since no tests have been done for handball related to concussions earlier, it is hard to tell in what range of acceleration values are susceptible to the risk of concussion in handball.

6 Concluding remarks

From the drop test it is concluded that the heights that were used are too low to be able to relate the results to the results from the dummy test. It is also seen that more fully tests need to be performed at each height for quantification. To be able to see trends for relations between pressure, heights and impact force clearly more measuring points from higher heights would be needed.

The test with the hybrid III 50th and the handball players showed that the parameter with the most effect on the head accelerations was the point of impact. A hit to the forehead leads to higher rotational acceleration than a hit in the middle or the lower part of the face. A ball that hits on top of the head results in a high rotational but lower linear acceleration. From the survey it is stated that a hit in the forehead was the most common reason for concussion.

Due to the low number of hits on the dummy's head, the conclusions drawn are unreliable. Therefore, a study with more test throws would be necessary to confirm the results from this report.

The literature survey showed that biomechanics of distinct sports are different and the range of acceleration magnitudes for concussions vary in sports. The values that were obtained from the tests with the dummy were in the range to obtain concussions for the sports mentioned in the literature study. There have not been much research on concussions in handball and therefore there are not any range of values of linear and angular accelerations defined for concussion in handball. This means that it cannot be stated exactly how detrimental a handball's throw to the head is.

7 Future work

From the literature study values for when concussions occur are available for different sports. The head accelerations for handball recorded in this study are comparable to sports like American football and ice hockey. In order to know whether or not the values that are obtained from this study are detrimental more tests need to be done. When measuring linear and rotational accelerations in other sports, accelerometers and gyroscopes have been mounted in the players helmets. This might be possible to apply in handball using for example a headband. Since the values obtained are comparable from other sports a discussion about changing the handball regulations allowing head protection or increased punishment for shooting the goalkeeper in the head should be held. A player that, as a result of a hit to the head, needs medical attention should as a safety measure be removed from the game.

It would be interesting to correlate the test with the Hybrid III dummy to simulations of the head response in similar conditions. Additionally, the Human Body Model (HBM) can be used to determine the risk of head injuries with more accuracy. It is also cheaper to evaluate possible countermeasures in simulations compared to doing physical tests. HBM can also predict the possible muscle injuries and tissue ruptures which can't be tested with a dummy. This can be simulated in various explicit finite element solvers like LS-DYNA, Pam-Crash, Abaqus explicit etc.

Force-time history for different impact velocities, ball weight and pressure can be incorporated in simulations to simulate ball hits to the head. It would be desirable to use validated finite element model of the handball with a dummy. The range of linear and rotational acceleration measured in this study can be used to verify that the simulations are reasonable and correlated well with the test. Since tests should not be conducted on humans, simulations are an ideal tool for determining risk of injury for different ball sizes, pressures, velocities and points of impact.

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Appendix

A Summary of survey to players

Table 10: Questions to and answers from players in survey

Question	Answer	Goalkeeper(s)	Field player(s)
Goalkeeper or field player?		5	19
How many times did the players get hit in the head?	None	0	10
	1 time	0	3
	2 times	0	4
	≥ 3 times	5	2
Where did the players get hit?	Forehead	5	7
	Side of head	2	1
	Back of head	1	2
How many times did the player get a concussion caused by a ball?	None	2	5
	1 time	1	3
	≥ 2 times	1	1
Where did the player get hit when the concussion occurred?	Side of head	1	1
	Back of head	0	1
	Forehead	1	2
For how long was the player not able to play after the concussion?	4-5 days	0	1
	1 week	0	1
	3 weeks	0	1
	1 month	2	0