# THE DESIGN OF THE PRODON DATA JAVELIN

## Providing performance feedback for indoor javelin throwing

TU Delft

APPENDICES

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# APPENDICES

# TABLE OF APPENDICES





Glenn Morris-USA during the 1936 Olympics in Berlin

# A.1 INTERVIEW

A user interview is conducted to get a better understanding of the users wants and needs. The main focus of this interview is to understand what information in most useful for the users during indoor training. Because this can differ between the athlete and the coach they will be interviewed separately.  All the interviewees are Dutch so the questions will be in Dutch and later translated

## Questions

- What does a javelin training look like?
  - Any difference between indoor and outdoor?
  - Any difference throughout the season
  - Where do you train?
- What do you look for in a throw?
- How do you determine what a good throw is?
- Is there a difference to the distance you throw throughout the season
- If yes, where does that difference come from
  - Physical
  - Mental
- How do you analyze your throws
- What doe you look for when analyzing
- How do you feel about the use of technology during training

## Quotes

Training buildup

- Mobility /warming up
- Warm-up run
- Training drills
- Short throws with focus on both throwing high and having a sweep
- Throw form approach
-
- Throwing on grass is different than on the approach (timing)
- It is all about the feeling there is little aiming involved
- You can get much feedback from the flight of the javelin
- I can also feel a lot from the throw itself. I know if I hit the javelin well or not. If the energy was going through the point. But not how high the throw was, I have no idea about that.
- A couple of people in my group have no idea what direction their javelin is aiming to during the approach
- Maybe live feedback for a javelin during the approach could be helpful.
- Indoors we throw with a ball at the beginning of the winter
- We do not have the opportunity to throw javelins inside with is a shame.
- Throwing a ball is way different from throwing a javelin. no feedback at your eye, you can use a different technique that does not work with a javelin
- In the winter we train a lot on the basics
- We want to throw javelin as much as we can
- Everybody struggles with the translation form ball to javelin.
- The transition from ball to javelin throwing is fluent.

Most information is collected in informal conversations with coach and athletes with the same questions in mind. I was also a member of the javelin klankbord groep whatsappgroup with the top athletes and coaches of the netherlands, which allowed me to get fast feedback from the users.

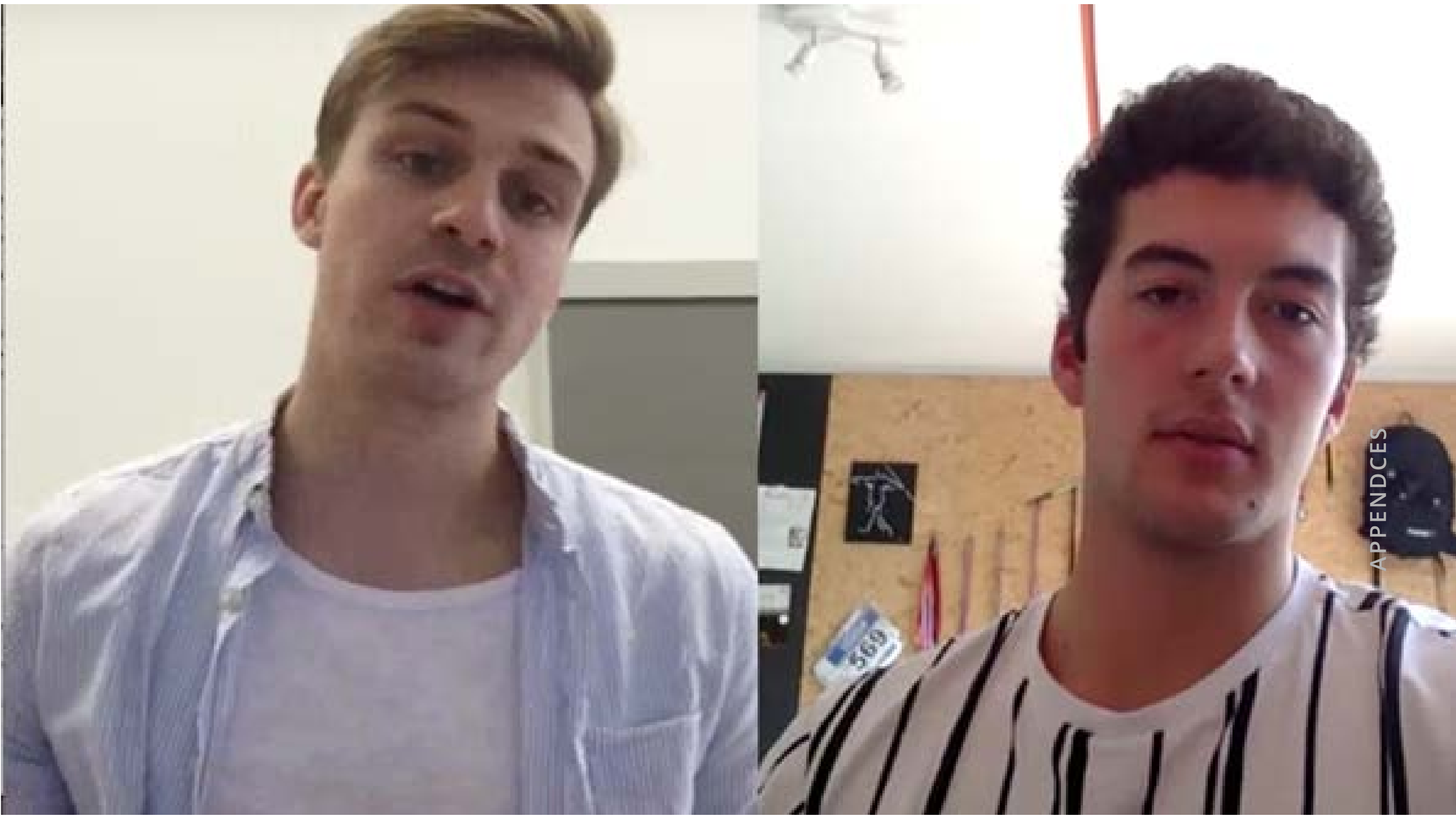


Figure 1: Image of the Skype interview with Erik Huijing Cartero (6th at javlin nationals 2019)

# A.2 JAVELIN THROWING TECHNIQUE

## Throwing phases

Javelin throwing starts with a front-facing approach at the back of the approach lane.

- Cyclic phase of the approach
- Acyclic phase of the approach
- Delivery

### Cyclic phase of the approach

The purpose of the cyclic part of the approach is to achieve a base velocity in the run-up. This is done by smoothly accelerating to the desired velocity. The thrower starts by standing face forward, gripping the javelin at the corded grip and lifting it close to the head with the tip of the javelin pointing forward, as shown in Figure 2 10-12 upright running steps are made wherein world-class athletes achieve a velocity between 5,5 m and 7.6 m/sec.

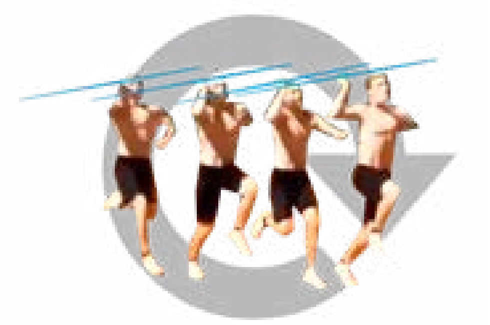


Figure 2: Showing the cyclic phase of the approach

### Acyclic phase of the approach

The acyclic phase in the approach consists of four to seven strides. The start of the withdrawal marks the beginning of this phase. The acrylic phase can be divided into four sub-phases:

- Withdrawal
- Intermediate stride
- Impulse stride
- Pre-delivery stride

#### *Withdrawal*

During the withdrawal, the athlete moves the javelin back in an almost straight line from the starting position close to the head until the throwing arm is extended and the hand in slightly higher than the shoulder. This is done in either one quasi impulse. stride or two more fluent strides.

Figure 3: Showing the withdrawal

### *Intermediate step*

The intermediate strides are used to connect the withdrawal to the impulse stride while maintaining the velocity generated in the cyclic phase. Few athletes are able to accelerate in this sub-phase. Most athletes use either one or three strides in their intermediate strides. In a particular type of withdrawal, two strides are added to this sub-phase, and the intermediate strides are left out altogether, linking the withdrawal directly to the impulse step.

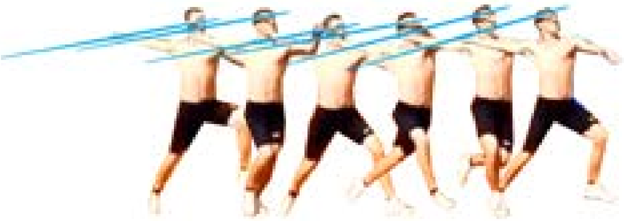


Figure 4: Showing the intermediate step

### *Impulse stride*

The impulse stride is characterized by its flight time. During the flight, the athlete leans back from the throwing direction, bringing the shoulders in line with the throwing direction. The back foot (for right-handed athletes the right foot) should be placed ahead of the center of gravity of the body pointing perpendicular to the throwing direction. The knee of the right leg is slightly bent, creating a sitting posture. The front foot (for right-handed athletes the left foot) is moved forward in an elevated position.

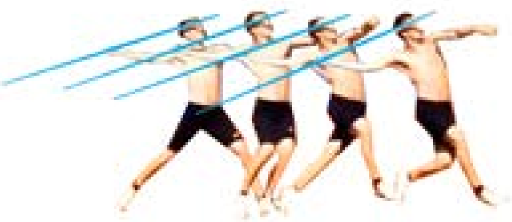


Figure 5: Showing the pulse stride

### *Pre-delivery stride*

This stride takes place just before the delivery of the javelin. The front foot (for right-handed athletes the left foot) moves forward while the hips and shoulders move in the throwing direction.

Figure 6: Showing the pre-delivery stride

## Delivery

Once the front foot hits the ground, the throwing position is established. The hand holding the javelin creates an arc of tension all the way down to the foot of the back leg. This arc lets the whole body contribute with the throw instead of just the arms like most people think. The front leg is kept straight and is used to transfer the forces from the run-up to the throwing arm. The athlete throws the javelin with a whipping motion of the throwing arm ending at the highest point above the head.

After the throw is done, the recovery makes sure the athletes keep his whole body behind the throwing line, making it a valid throw. The recovery is done in various ways

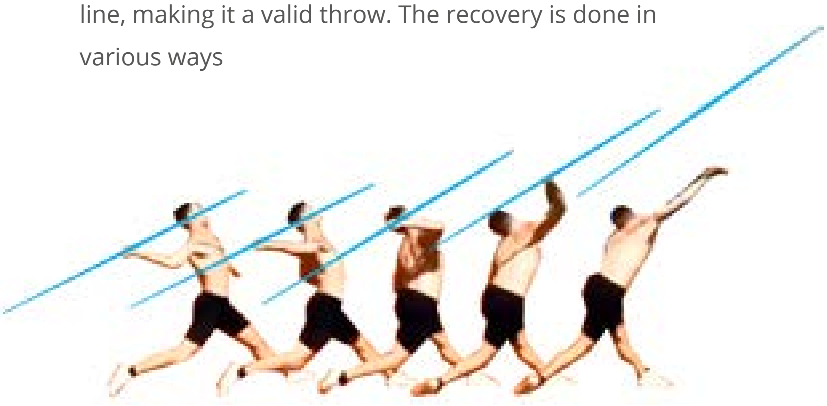


Figure 7: Showing the delivery

# A.3 RULES & REGULATIONS

## Javelin rules

In 1986 the javelin rules were changed because the sport became too dangerous. A world record of 104,80 throw by Uwe Hohn in 1984 (IAAF.org) meant that the stadiums were no longer big enough to host this event. The tendency of the old rules javelin to land flat on its belly and slide over the grass is another dangerous part of this event, which can harm the field officials.

In the new rules javelin, the center of gravity is moved 4 cm forward (IAAF.org). Furthermore, the surface area in front of the center of gravity is reduced while the surface area behind the center of mass is increased. The effect of these measures is that the javelin is more stable in the air turning into the relative wind, much like the flight of an arrow.

The relative wind is mostly coming from the flight path, so the new rules javelin is no longer able to create sustained lift forces since the lift becomes higher with a greater angle of attack. This reduced the throwing distance of the javelin by 10% according to (Les Hatton, 2005).

Another effect of this measure is that the tip of the javelin will point to ground when the relative wind comes from underneath in the second half of the flight curve.

The measurements of the new rules javelin can be found in Table 1 & Table 2 and Figure 8

| | | Min | Max |
|---|---|---|---|
| **D0** | Before corded grip | - | - |
| **D1** | Behind corded grip | D0 | D0 - 0,25 mm |
| **D2** | 150 mm from tip | 0,8 D0 | - |
| **D3** | Rear end tip | - | - |
| **D4** | Right after metal tip | - | D3 - 2,5 mm |
| **D5** | Halfway tip to Cm | 0,90 D0 | - |
| **D6** | Corded grip | D0 +8 mm | - |
| **D7** | Halfway rear end to Cm | - | 0,9 D0 |
| **D8** | 150 mm from rear end | - | 0,4 D0 |
| **D9** | Rear end | - | 3,5 mm |

Table 2: Explaining the dimension numbers

| | | 500 g | 600 g | 700 g | 800 g |
|---|---|---|---|---|---|
| **L0** | Total length | 2000 - 2100 mm | 2200 - 2300 mm | 2300 - 2400 mm | 2600 - 2700 mm |
| **L1** | Distance tip to Cm | 780 - 880 mm | 800 - 920 mm | 860 - 1000 mm | 900 - 1060 mm |
| **L2** | Distance back-end to Cm | 1120 - 1320 mm | 1280 - 1500 mm | 1300 - 1540 mm | 1540 - 1800 mm |
| **L3** | Length of metal tip | 220 - 270 mm | 250 - 330 mm | 250 - 330 mm | 250 - 330 mm |
| **L4** | Length of corded grip | 135 - 145 mm | 140 - 150 mm | 150 - 160 mm | 150 - 160 mm |
| **D0** | Diameter thickest point of shaft | 20 - 24 mm | 20 - 25 mm | 23 - 28 mm | 25 - 30 mm |

Table 1: Showing the dimensions for a competition javelin

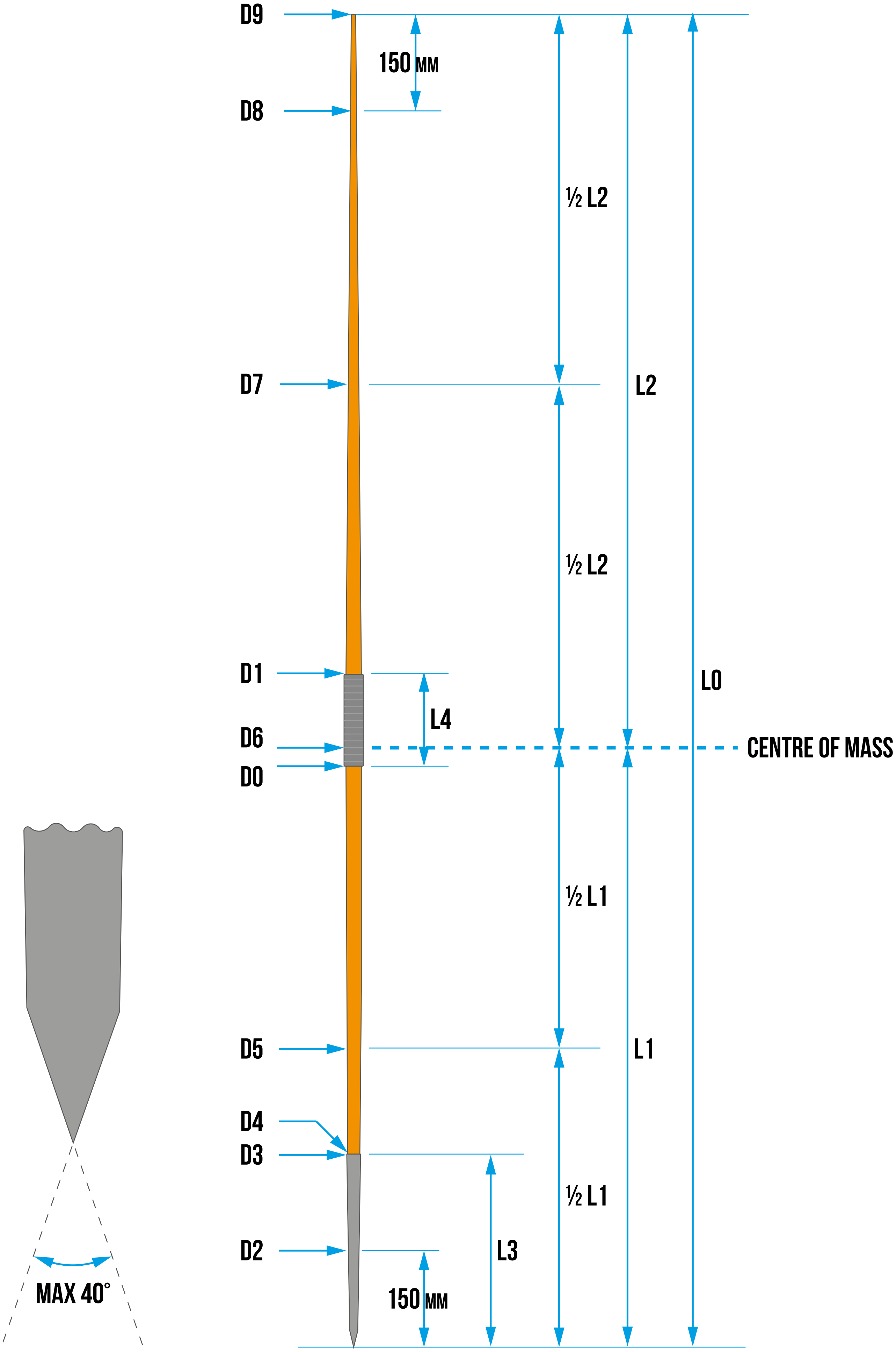



Figure 8: Showing the dimension regulations for a competition javelin

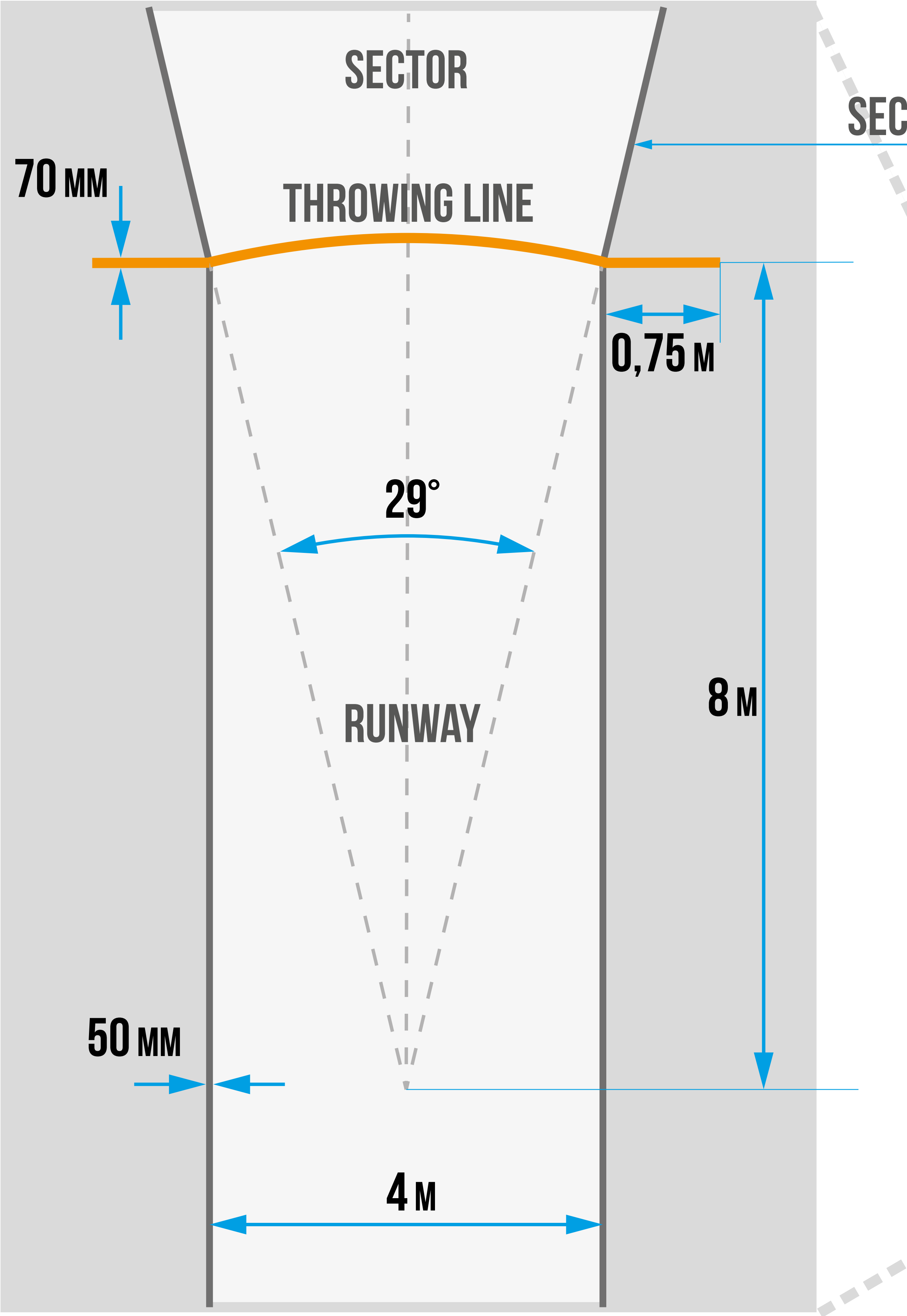
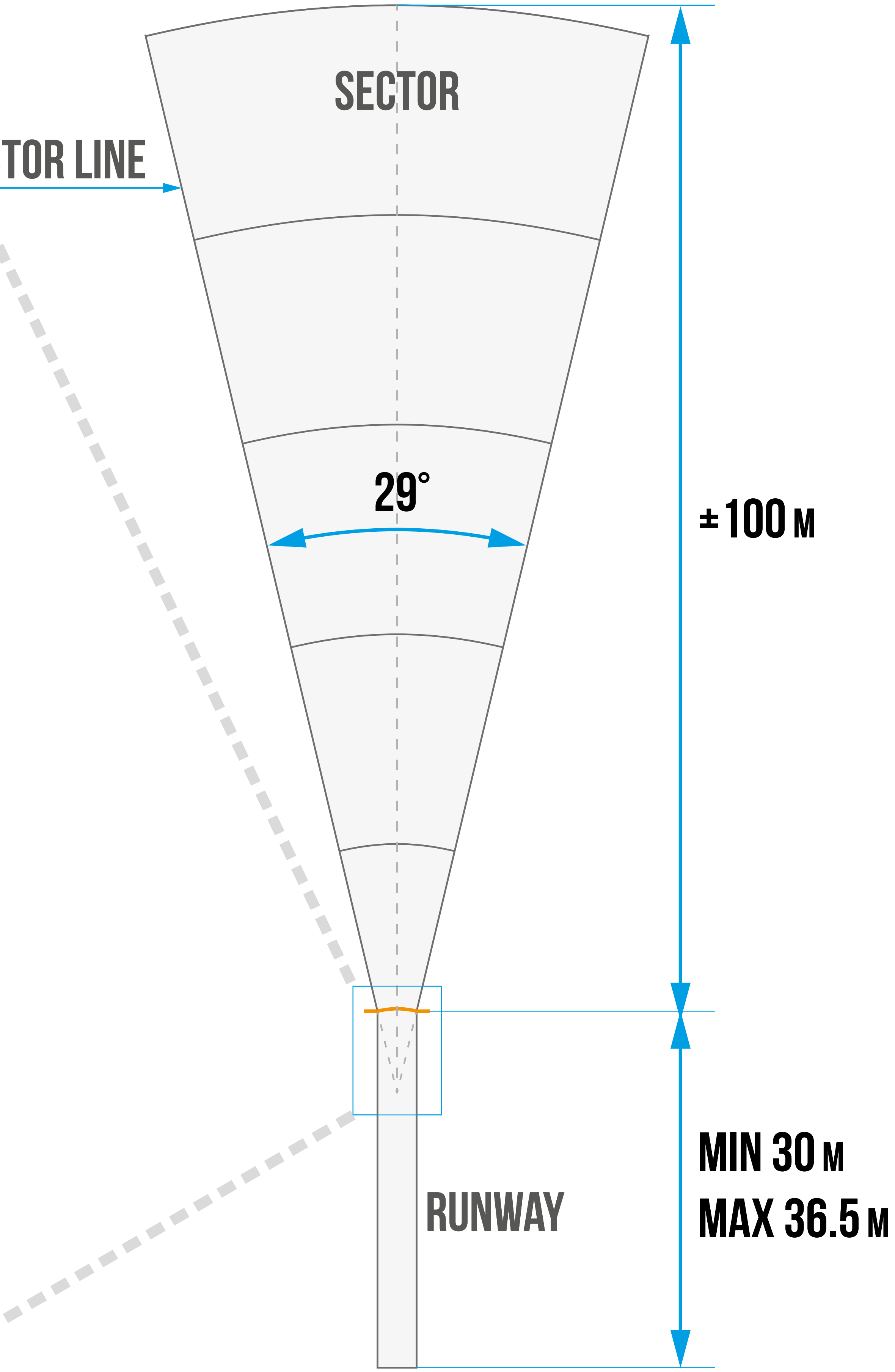



Figure 9: The measurements for the javelin approach and sector


SECTOR
TOR LINE
29°
±100 M
MIN 30 M
MAX 36.5 M
RUNWAY

# A.4 MOMENT OF INERTIA TEST

The moment of inertia of an object determines how easy it is to change the orientation of the object. It can be calculated for all three axes of an object (X, Y & Z). For a javelin, the moment of inertia about the pitch and yaw axes is the same since the javelin has the same shape no matter how you rotate it about its roll axes. The moment of inertia is calculated in [kg*m^2], where a higher value means more resistance against the rotation of the object.

In javelin throwing, the moment of inertia has two functions—the most important for the data javelin being control over the point of the javelin. To mimic the feel of a competition javelin, the moment of inertia should be similar. A much lower moment of inertia means the javelin is easier the change orientation resulting in a less stable point. A much higher moment of inertia, on the other hand, makes it harder to rotate the point requiring a lot of effort to do so.

A lower moment of inertia can have some advantages in winter training. The fact that the javelin can change direction quicker means that if the angle was not perfect when throwing the javelin will put less strain on the elbow and shoulders compared to a competition javelin.

The second result of the moment of inertia is visible during the flight. When the javelin is harder to turn, it will turn less in the same amount of time than a javelin, which is easier to turn. For the data javelin, this is not really interesting since the flight is only 5-10 meters long, and the initial condition is the most relevant to collect the feedback for the users.

## Measuring

The moment of inertia can be calculated for simple shapes such as a hollow tube, but for more complex shapes, like a javelin, it is easier to measure it through an experiment. A document by Michael Koken of the University of Akron named “The Experimental Determination of the Moment of Inertia of a Model Airplane” describes how this can be done. In short, a pendulum is created by suspending the javelin in the air by two roles on either end of the center of mass with a known length and distance apart. The javelin is then rotated around the axes shown in Figure 10. The time it takes to finish one oscillation is recorded and put in this formula:

$$I = \frac{m \cdot g \cdot D^2 \cdot T^2}{16\,\pi^2 \cdot h}$$

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Where I is the moment of inertia in [kg*m^2], m is the mass in [kg], g is the gravitational constant in [m/s^s], D is the distance between the ropes in [m], T is the time of one oscillation in [sec], and his the height of the roles in [m]. Recording the time is done by a stopwatch. To ensure the accuracy of time, 10 oscillations were recorded 10 times where the highest and lowers times were discarded. The mean value of the remaining 8 times was taken and divided by 8. Keeping in mind that the difference between the recorded times was within a half a second; otherwise, this would point to a mistimed so that well be done again.

# Results

| Test subject | Time | Mass moment of inertia |
|---|---|---|
| Javelin (2,60m) | 4,36 | 0,37 |
| 1,4m concept | 2,54 | 0,32 |
| 2m concept | 4,01 | 0,13 |

Table 3: Results of the moment of inertia test

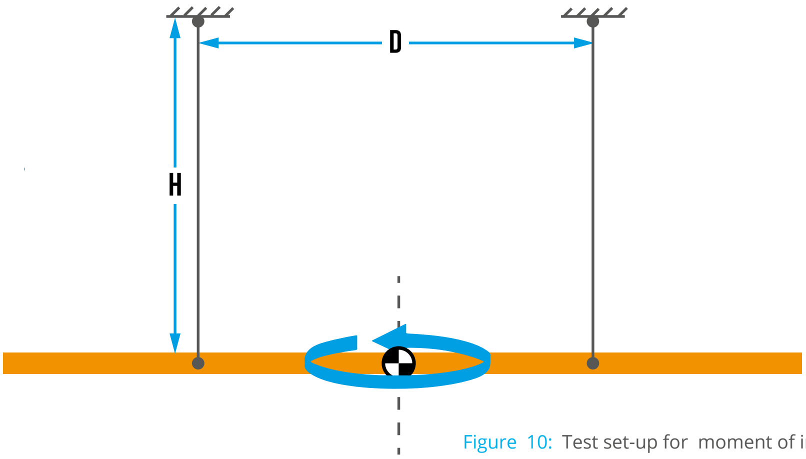



Figure 10: Test set-up for moment of inertia test



# PRODON Mock-up

The PRODON mock-up is also measured using this technique and compared to the measurements of a standard a javelin. The results can be found in Table 4. The mass moment of inertia of the PRODON is also calculated with the use of 3d modeling software (fusion360), which can be found in Figure 11. W Where Ixx and Iyy are the relevant numbers. The results seem to differ from each other. Although it can be seen that the numbers from the test are close to each other and the calculated value by the 3d modeling software is very close to the value of 0.42 [kg.m^2] found by Best et al. (1995). Testing the response of the prodon gives the same impression as the tested results do. The mass moment of inertia is slightly lower but close

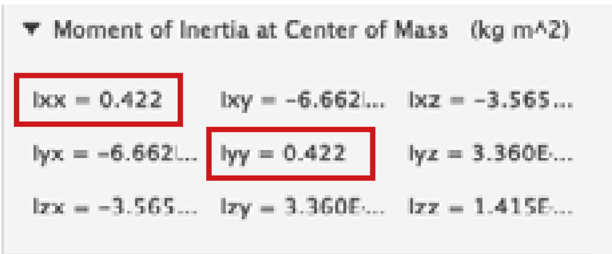



Figure 11: Fusion 360 mass moment of inertia calculations. Ixx and Iyy are the relevant numbers.

| Test subject | Time | D | h | m | Mass moment of inertia |
|---|---|---|---|---|---|
| javelin (2,60m) | 4.13 | 0.44 | 0.48 | 805g | 0,34 |
| PRODON (mock-up) | 3.87 | 0.44 | 0.48 | 861g | 0,32 |

Table 4: Results of the moment of inertia test

# A.5 PARAMETERS

## External parameters

- Gravity
- Wind speed & direction
- Air density

### Gravity

Depending on where you are in the world the gravity can change. The standard gravity defined by the International Bureau of Weights and measures is g = 9.80665 m/s2, which means an object falling under standard gravity in a vacuum would accelerate with 9.80665 m/s2 towards the earth. (https://en.wikipedia.org/wiki/Gravity/ 15 sept). The value of g can vary with latitude from about 9.78 m/s2 at the Equator to about 9.83 m/s2 at the poles.

### Wind speed & direction

The air is responsible for the lift and drag forces on the javelin. The relative air velocity and direction determine the size of these two forces. If there is no wind, the relative air velocity factor is the opposite of the direction of the javelin. When the wind is introduced, the wind speed factor is added to the relative wind velocity. In a headwind, an athlete wants to reduce the frontal area of the javelin so it will be thrown under a smaller angle. With a tailwind, the opposite is true. Even side wind can change the aerodynamic behavior of the javelin with a curtain spinning direction found by Best et al. (1995). This influence is insignificant and hard to model so that it will be left out.

### Air density

The density of the air determines how easy it is to pass through the air. Lower densities make it easier than higher densities. The density of the air decreases at higher altitudes. The density also changes with atmospheric pressure, temperature, and humidity. In science, the international standard atmosphere is set at 1.225 kg/m$^3$, so this will be the standard air density used in the model, but can be changed for any reasonable value.

## Javelin parameters

- Mass
- Mass distribution
- Mass moment of inertia
- Shape
- Stiffness

### Mass

The mass of a javelin for male throwers must be at least 800 grams. The athlete tries to stay as close as possible to the limit to achieve the highest acceleration of the javelin. The formula for force is F=m*a, where F is the force, m is the mass, and a is the acceleration. This means that with the same force, the acceleration is higher if the mass is lower. To optimize the acceleration, a javelin should be as close to 800 gr as possible without going below this limit.

### Mass distribution

The center of mass of the javelin is located 10mm from the tip side of the grip cord. The distribution of the weight is mostly in the front due to the tapered tail and weight in the tip.

### Mass moment of inertia

The moment of inertia is dependent on the mass distribution of the javelin. More mass in the tip and tail of the javelin will make the javelin more resistant against pitch rotation. Since the new rules javelin was introduced in 1984 (bron 16 sep) the center of mass was moved 4 cm forward, the surface area in front of the center of mass was reduced while the surface area behind the center of mass was increased making the javelin behave more like an arrow pointing in the direction of the wind. The flight path of a javelin can be found in Figure 12. This made the flight of the javelin more stable while reducing the possibility of giving the javelin lift.

### Shape

The shape of a javelin is narrowed down significantly by the rules and regulations found in Appendix A.3. But there is still some small variation in shape between manufacturers. The material also affects the shape. An aluminum javelin is thicker than a steel javelin due to its specific weight. The shape of a javelin determines the aerodynamics. More surface area in front of the center of mass results in more lift

### Stiffness

A more stable flight is considered to be beneficial for the final distance. The stiffness of a javelin is responsible for the stability during flight. The downside of stiffness is that these javelins are less forgiving for technical errors and can injure the athlete easier. Elite-level athletes make use of the stiffer javelins. A higher distance rating usually goes side by side with a higher stiffness rating, but are not directly linked.

## Throwing parameters

The parameters that are influenced by the athlete are the throwing parameters. They are the most relevant for the data javelin for measuring the performance of the athlete and include:

- Release speed
- Release height
- Release angle
- Angle of attack
- Angular momentum

### Release velocity

The release velocity Is the velocity the javelin has at the moment it is released. Before this moment, the velocity of the javelin is increasing due to the approach and the throw. After the release, the athlete can no longer influence the velocity. In elite throwing competitions, the release velocity is usually between the 28-30 m/s.

### Release height

The release height is determined by the reaching height of the athlete minus the height lost by spreading the legs apart in the release.Best et al (1995) found that the release height is around 2m

### Release angle

The release angle is the angle between the ground and the direction the center of mass of the javelin is traveling in after the release. Common release angles lie between 25 and 45 degrees.

### Angle of attack

The angle between the release angle and the angle the javelin makes with the ground is called the angle of attack. Without wind when the angle of attack is 0, the javelin has the smallest frontal area, . An angle of attack bigger or smaller then 0 will result in a bigger frontal area resulting in more drag.

### Angular momentum

The angular momentum refers to the rate of turn of the javelin and is expressed in rad/sec.

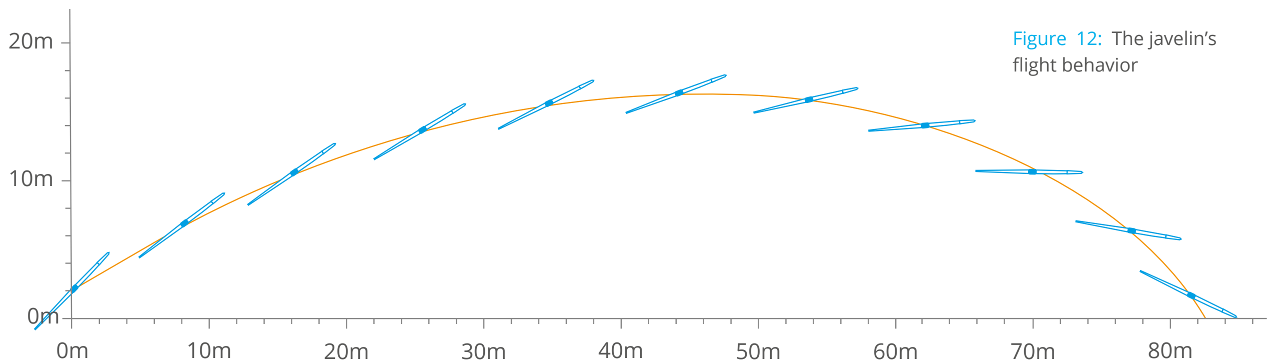



Figure 12: The javelin's flight behavior

# A.6 MATHEMATICAL MODEL

A mathematical model is created to create a better understanding of how the flight of the javelin works. It can also provide an estimate for the throwing distance if a throw indoors would have been done outdoors.

The model is created iterative, starting with a basic projectile flight in a vacuum, adding complexities along the way.

There are some effects that are to hard to implement and have a small influence on the final distance. Spin, in combination with side wind from the right direction, can cause a slight increase in lift. On the other can vibrations in the javelin reduce the lift and increase drag. These two effects will be excluded.

The model is going the stay in a 2D plane since making a 3D model proves to be challenging for the authors of same of the aerodynamic paper in the literature studies.

## Process

When I was making the mathematical model, I started off with a ballistic trajectory in a perfect vacuum, which means that the object has an initial speed and direction, but no active proposition during the flight, and there are no aerodynamic forces. Because of its shape and relatively low weight, aerodynamics play an essential role in the javelin flight.

## Static vales

During the flight, specific values will stay the same for the duration of the flight. These values are static values and are shown in Table 5.

| Parameter | Symbol | Value |
|---|---|---|
| Average gravity | $g$ | 9,81 m/s$^2$ |
| Air density | $\rho$ | 1225 kg/m$^3$ |
| Mass | $m$ | 800 gr |
| Drag coefficient | $Cd$ | 0.5 |
| Cross-sectional area | $A$ | 0.001 m$^2$ |

Table 5: Static values for mathematical model

## Initial conditions

A set of average initial conditions is made based on data found in the literature. These values, shown in Table 6 will be used to check if the mathematical model gives a sensible answer.

| Parameter | Symbol | Value |
|---|---|---|
| Release velocity | $v$ | 28.5m/s |
| Release Angle | $\theta$ | 35° |
| Angle of attack | $\alpha$ | 0° |
| Release height | $y$ | 2.1m |
| Wind speed | $v_{wind}$ | 0m/s |

Table 6: Initial conditions for mathematical model

# Javelin flight in vacuum

The first step in the mathematical model is to look at a javelin in a vacuum. The javelin will start off with the initial conditions, as mentioned above. It is easier to look at the displacement in x and y separately. After the release at t = 0, the only force working on the javelin is the gravity. The horizontal displacement is not affected by gravity, so the vx will remain constant, resulting in the following equation for the x displacement.

$$x = v_0 \cdot cos(\theta_0) \cdot t$$

Wherein x is the displacement in the x-direction, v0 is the initial velocity, θ0 is the initial release angle, and t is the time.

The vertical component of the displacement is similar to that of the horizontal only with the second integral of the gravitational acceleration added, resulting in the following formula.

$$y = y_0 + v_0 \cdot sin(\theta_0) \cdot t - {}^1\!/_2 \cdot g \cdot t^2$$

Wherein y is the displacement in the y-direction, y0 is the release height, v0 is the initial velocity, θ0 is the initial release angle, t is the time, and g is the gravitational acceleration.

I am combining the two results in a parabola of the trajectory of an object in a vacuum. The shape and size of the object do not matter. With the absence of air, there is no mass or area value in the equation.

The final mark of a javelin in a vacuum under the standard initial conditions is 80.69m The trajectory is visualized in Figure 13

APPENDCES

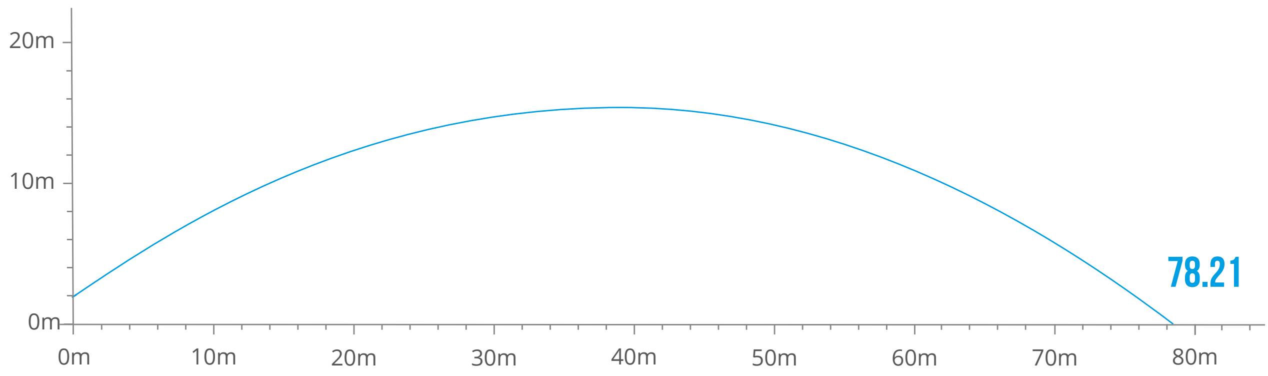



Figure 13: Javelin trajectory in vacuum

# Javelin flight with aerodynamics

The Aerodynamic forces need to be added to make the mathematical model more realistic. These forces are the drag and lift forces. The location where the aerodynamic forces act is called the center of pressure. In the new rules javelin (Apollo Olympic javelin), this point is located about 25.5cm back from the center of mass, according to Best and Barlett(1987).

## Aerodynamic drag force

The drag force that acts on the javelin point in the same direction as the relative wind. It is also exponentially dependent on the speed, making it the most crucial factor in calculating the drag. The drag force can be calculated with the following formula.

$$F_{drag} = {}^{1}\!/_{2} \cdot \rho \cdot v^2 \cdot C_D \cdot A$$

Wherein Fdrag is the drag force, rho is the air density, v is velocity, Cd is the coefficient of drag, and A is the projected frontal area.

During a throw, the frontal area A can change when the angle of attack gets closer to 90°.

## Aerodynamic Lift force

The Lift forces are perpendicular to the relative wind direction. The formula of the lift looks a lot like that of the drag. The only difference being the drag coefficient is replaced with the coefficient of lift. This makes the following formula.

$$F_{drag} = {}^{1}\!/_{2} \cdot \rho \cdot v^2 \cdot C_L \cdot A$$

Wherein Flift is the lift force, rho is the air density, v is velocity, Cl is the coefficient of lift, and A is the projected frontal area.

Since these formulas are nearly the same, these forces change hand-in-hand.

## Next step

The next step would be the incorporate an angle of attack dependent frontal area, lift and drag coefficient, to make the model even more realistic. A beginning was made for the frontal area by measuring the frontal area under 10-degree increments of the angle of attack form 0 to 90 and curve-fitting the results the make a polynomial function that can calculate each angle in-between. As shown in Figure 15, but the lift and drag curves with a different angle of attack proved to be difficult and are left out due to time constraints.

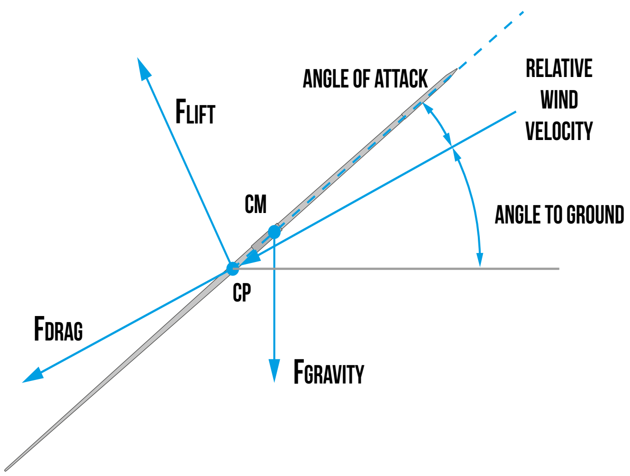



Figure 14: An overview of the external parameters

| Degree | Area |
|---|---|
| 0 | 1017.876mm² |
| 5 | 5165.353mm² |
| 10 | 9960.725mm² |
| 15 | 1.47E+04mm² |
| 20 | 1.94E+04mm² |
| 30 | 2.83E+04mm² |
| 40 | 3.63E+04mm² |
| 50 | 4.32E+04mm² |
| 60 | 4.88E+04mm² |
| 70 | 5.29E+04mm² |
| 80 | 5.54E+04mm² |
| 90 | 5.63E+04mm² |

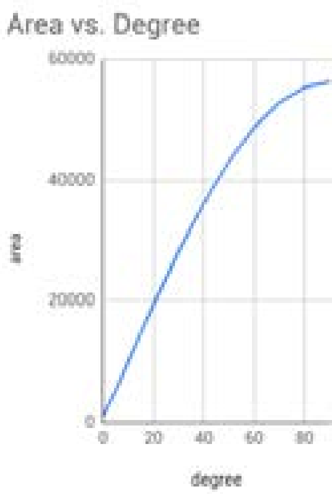



Figure 15: Frontal area vs angle of attack

# Model validation

To validate the mathematical model, a set of release conditions is used by Best et al. (1993) and Berlett and Morriss (1991). The release height, wind velocity, air density, and gravitation acceleration are not specified in this set of release conditions, so for those values, the standard initial conditions are used. Within the time frame, this was the best set of conditions available to validate the model. Recording them myself would be a lot of effort for a small gain. However, what becomes clear in Figure 16 is that the recorded distance and the simulated distance are very close.

| Throw/(D= distance/m) | $V^{R}(0)$ $(m \cdot s^{-1})$ | $\gamma(0)$ (degrees) | $\alpha^{E}(0)$ (degrees) | $\beta^{R}(0)$ (degrees) | Range (sim) R/m | d(0) (m) | Sim. dist. (m) Ds= R−d(0) | Difference D−Ds |
|---|---|---|---|---|---|---|---|---|
| M1,1 (87.42) | 30.3 | 33.6 | −2.7 | −8.5 | 89.44 | 2.33 | 87.11 | 0.31 |
| M1,2 (83.22) | 29.2 | 32.2 | −7.9 | −5.5 | 82.70 | 1.95 | 80.75 | 2.47 |
| M1,3 (81.62) | 29.2 | 32.0 | −5.4 | −6.0 | 85.28 | 2.33 | 82.95 | −1.33 |

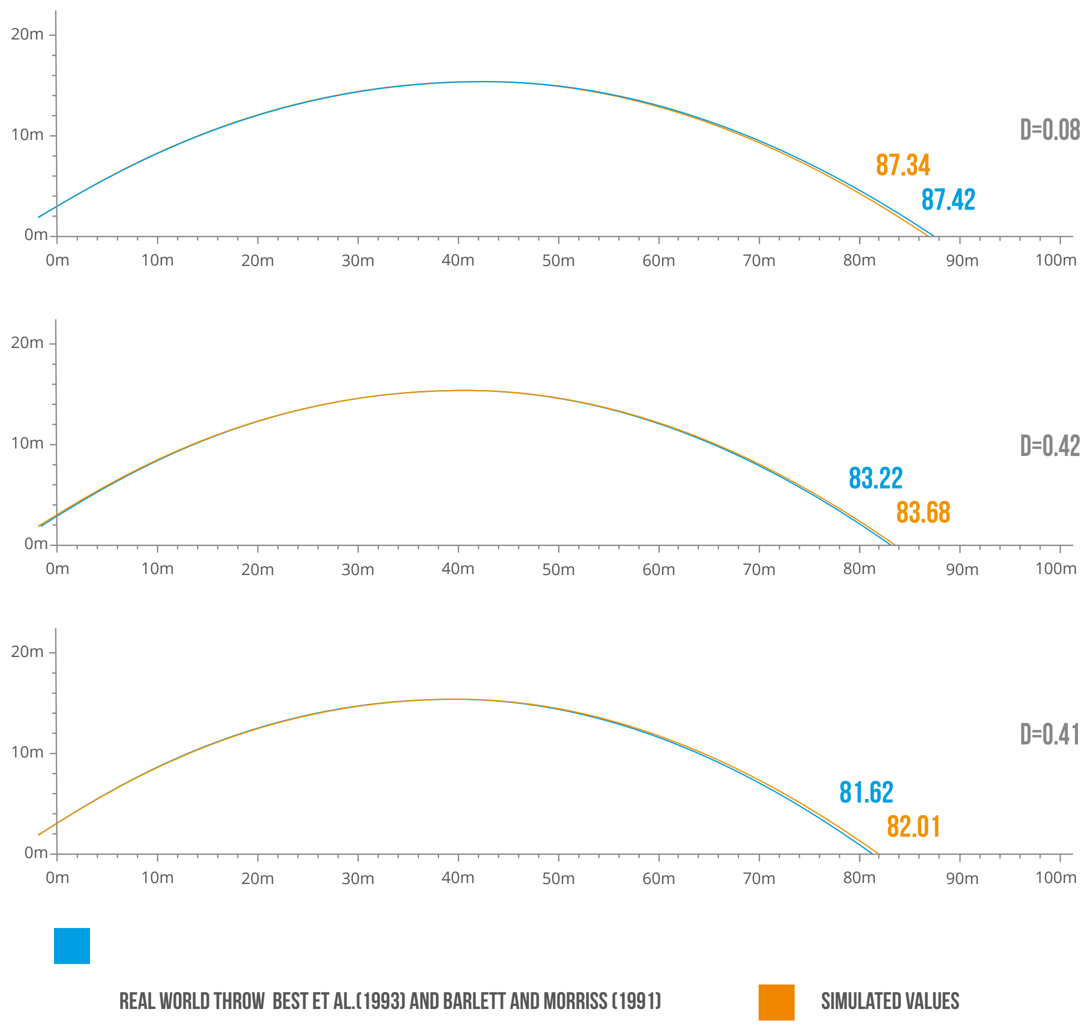



Figure 16: Model simulation versus real world distance

APPENDICES

# A.7 SENSITIVITY ANALYSIS

A sensitivity analysis is done to find out what effect each parameter has on the final throwing distance.

## Method

The mathematical model explained in Appendix A.6. is adjusted to facilitate the sensitivity analysis. For each parameter, the range is divined with the minimum and maximum values for that parameter. For the release angle and the angle of attack, an educated guess is used since no specific data could be found for those values. Table 7 shows the ranges of each parameter. One parameter is the time each parameter will go through its range in 100 steps while keeping the rest at its standard value. This will go on until all the parameters are done.

## Results

The results of the sensitivity analysis can be found in Figure 17. Here you can see that there are four parameters that change a lot throughout their range. These parameters are release velocity, angle of attack, release angle, and wind speed. The rest stays close to the standard distance of around 78m. There is no changing frontal surface area and lift and drag coefficient implemented in the mathematical model, so the behavior of a javelin thrown at a high angle of attack is not representative of real-world behavior. Therefore, the angle of attack will be excluded from the results. The paper found in the literature studies has not mentioned the angle of attack as one of the main contributors for the final distance with complies with the exclusion of this parameter.

## Conclusion

The release angle and release velocity are performance parameters that have much effect on the final throwing distance. The wind speed is not changeable by the athlete but can influence the throwing distance a lot. Training for different wind conditions can be beneficial for the athletes' ability to adjust to the circumstances. Erik also mentioned this during his interview in Appendix A.1

| Parameter | Range |
|---|---|
| $g$ | 9,76 - 9,83 |
| $\theta$ | 20 - 50 |
| $\alpha$ | -20 - 20 |
| $v_0$ | 25 - 32 |
| $\rho$ | 1.225 - 0.821 |
| $v_{wind}$ | -33.3 - 33.3 |
| $A$ | 0.001 - 0.0007 |

Table 7: Range for each parameter

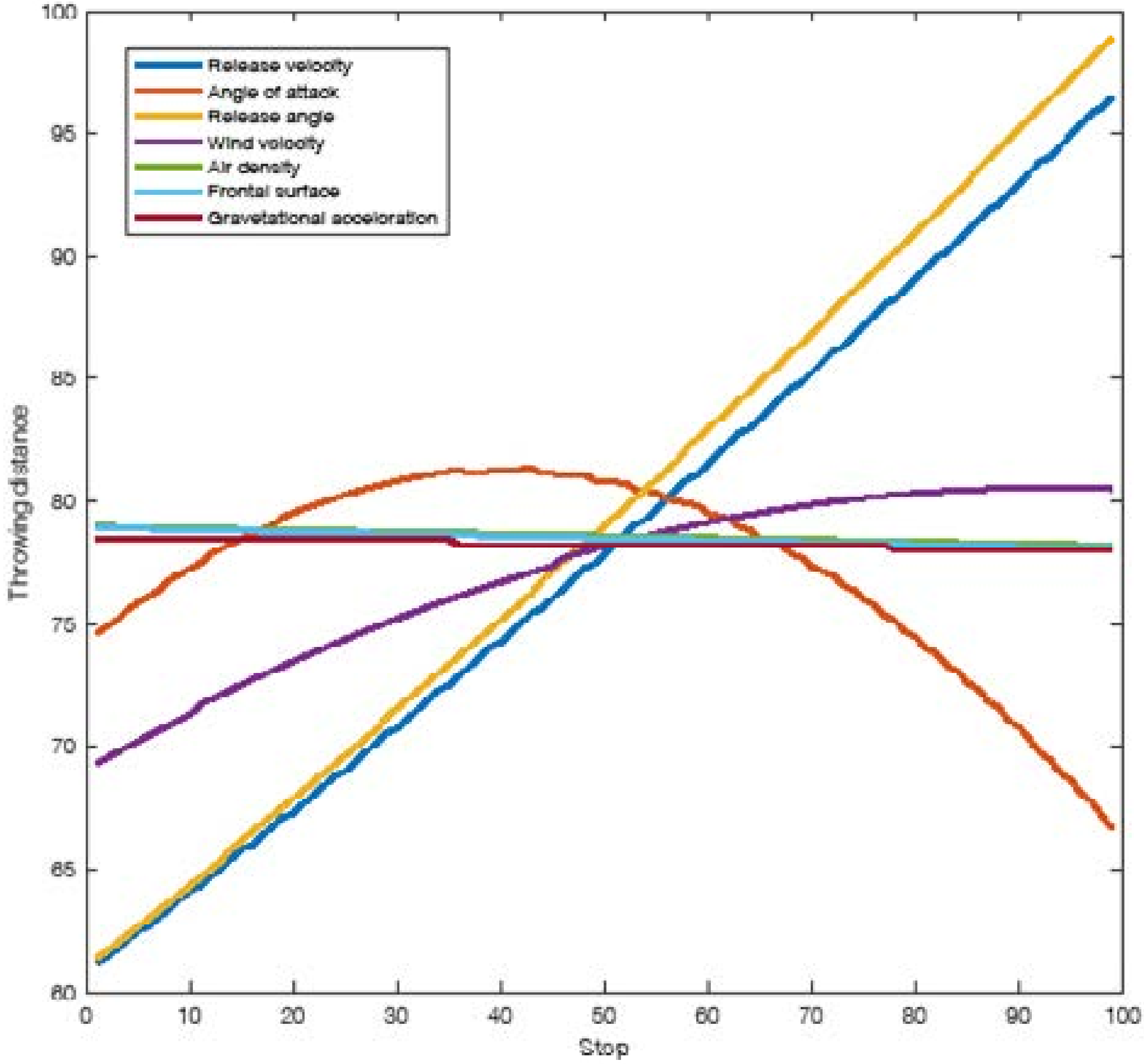



Figure 17: Plot of the range of each parameter

# A.8 TECHNOLOGIES

***Lighthouse***

The lighthouse technology is used by HTC in its Vive virtual reality headset. They make use of IMU sensors to measure the orientation of the headset. To correct for the drift, IMU's can have the lighthouse technology uses two base stations that sweep an infrared laser plane first over the x-axis on one station and then over the y-axis of the same station. The second base station then performs the same operation. Photo-diodes on the device can detect at what time the light hits the senor. Knowing the angle of the infrared plane at that time, the system can calculate a line going out into space when the x and y values are known. The second station will create another line which will intersect the first line. If the distance between the stations is known, this will create a point in space where the Photo-diode is located. It is also possible to use one base station if the location of the sensors relative to each other is known. This system requires a line-of-sight to operate at least 5 sensors to get an accurate measurement.

Although the static accuracy of this system is very accurate with a standard deviation lower than 0,5 mm (htc vive paper), the dynamic accuracy is unstable with an accuracy of 1 mm to 43 mm and even 802 mm in the worst case.

The lighthouse technology has a range of 5 meters and usually requires the base stations to be mounted to a wall, to reduce jitter caused by the motors.




Figure 63: Showing the HTC Vive VR headset with the lighthouse tracking technology

## HTC Vive

### *Inside-out tracking*

Another system htc uses to correct for the drift in its virtual reality headsets is inside-out tracking. In the HTC Vive Cosmos, they use 6 cameras to get a frame of reference from the outside world. This means that there is no additional base station needed creating a stand-alone device. The vibration and roll rotation rate of a javelin will make outside-in tracking difficult.




Figure 64: The HTC Vive Cosmos VR headset with inside-out tracking

## Inertial Measurement Unit

Inertial measurement units, or as they will be referred to from now IMUs, can commonly be found in your smartphone. They are a self-contained system that measures linear and angular motion (https://www.xsens.com/tags/imu/ 24 Juli). They do this using three-dimensional accelerometers (measures acceleration) and gyroscopes (measures angular velocity). A three-dimensional magnetometer (measures direction, strength, or relative change of a magnetic field (https://en.wikipedia.org/wiki/Magnetometer 24 Juli) can also be added to calibrate the IMU relative to the earth's magnetic field.

The disadvantage of an IMU is that the system is continually integrating the acceleration for time to calculate velocity and position. This means that a small measuring error will accumulate over time, leading to a difference in where the sensor thinks it is and where it is, called drift. The same is true for the gyroscope, with the orientation of the senor. The magnetometer can be used to reference the sensor to the gravitational forces of the earth. Another sensor can also be added to adjust for the drift.

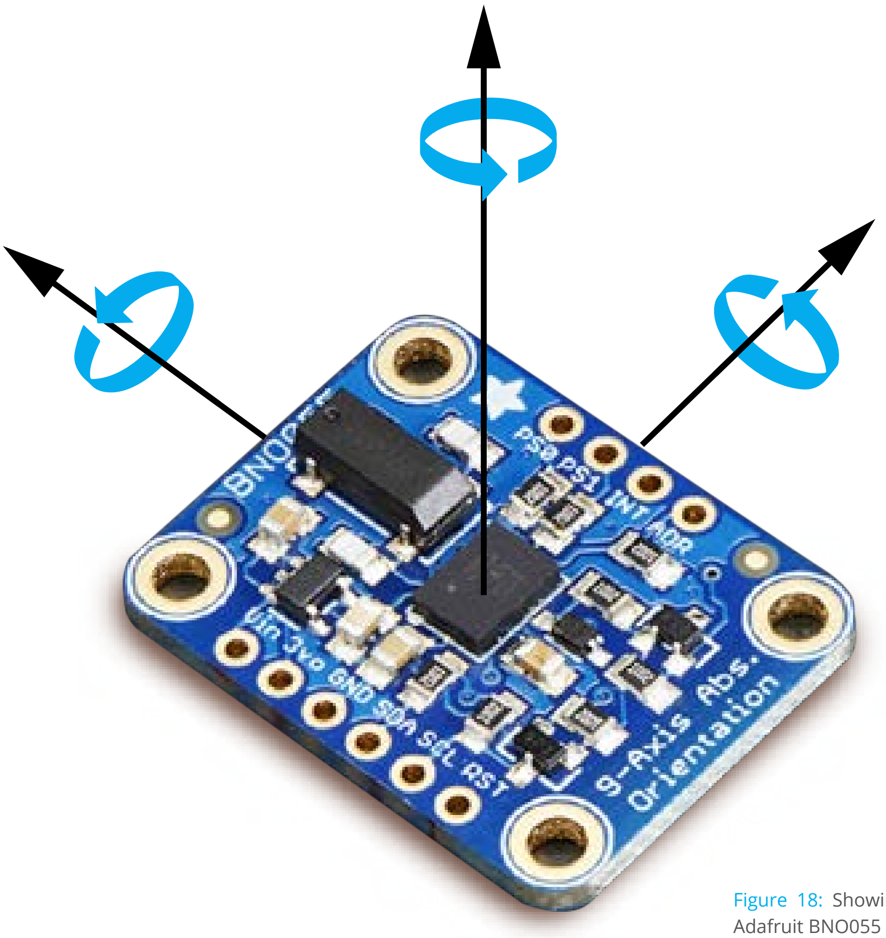



Figure 18: Showing the Adafruit BNO055 IMU[REF-43]

## Ultra wide-band positioning

Ultra-wide-band or UWB, as it will be referred to from now, is a wireless technology that can track position through triangulation and can reach an accuracy of 10 cm. This technology is used in factories or warehouses to track the position of people or products. It uses anchors with a known location that sends out radio energy at specific time intervals (pulses). These pulses can be received by tags that only operate when a pulse is sent, making the energy consumption of the tag low. The tag bounces back the signal to the anchors which can calculate the distance between the anchor and the tag. If this is done at least three times, the position can be calculated, as shown in Figure 19.

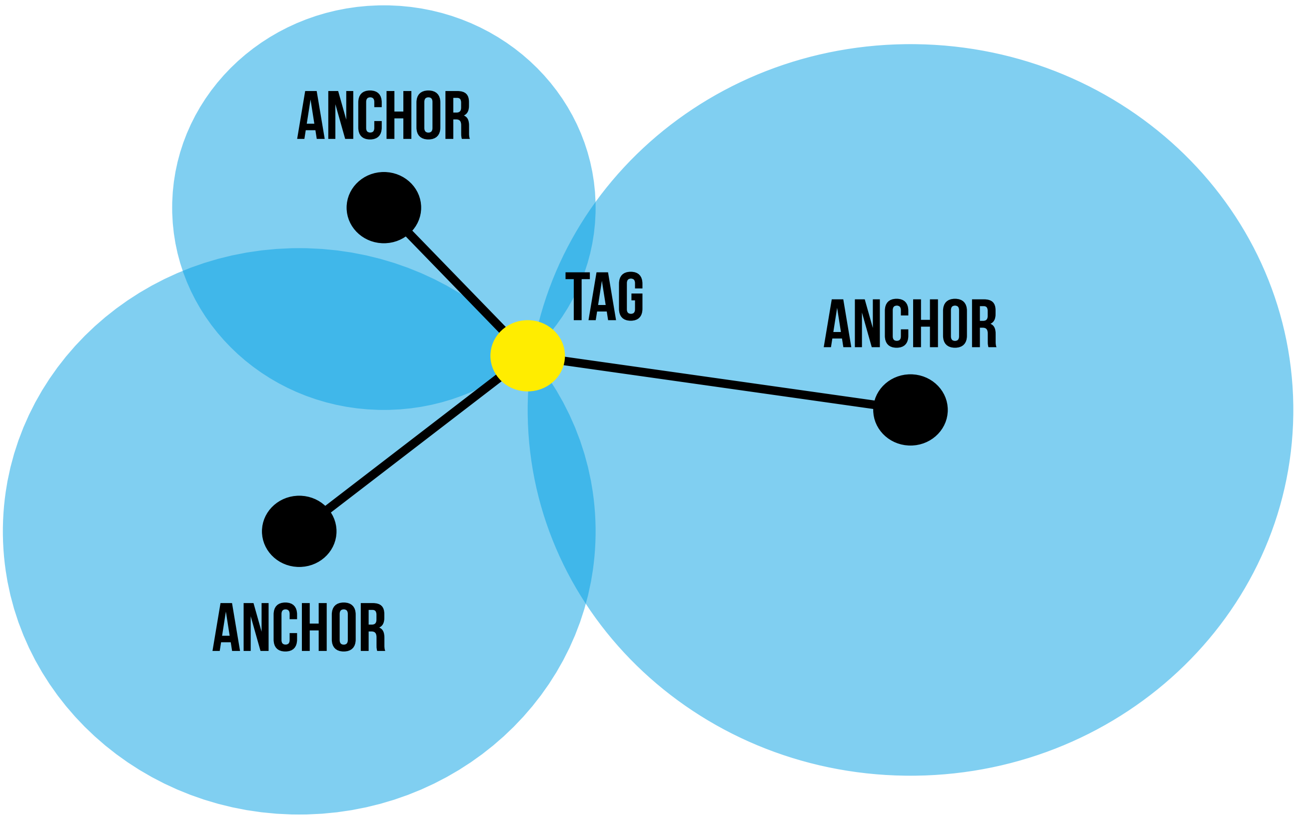



Figure 19: Showing the position of a tag can be found by thee anchors

# A.9 CAMERA CALIBRATION

Camera calibration is done by holding a checkerboard pattern of known size at different orientations in front of the camera. A program can calculate the lens distortion and provide a flat image when the distortion is compensated.

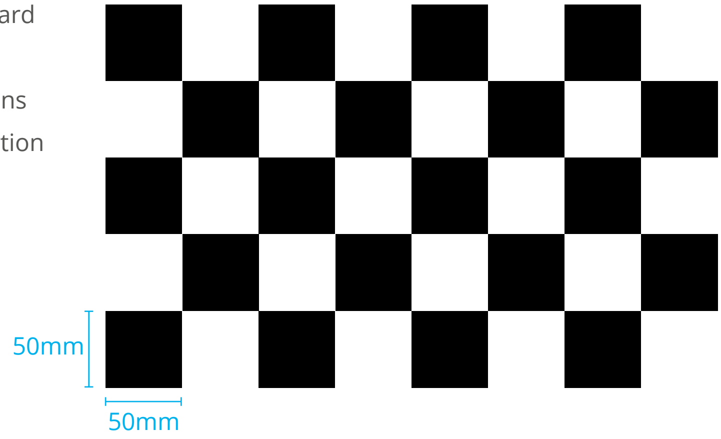



Figure 20: checkerboard pattern used for camera calibration


Figure 21: Types of lens distortion. No distortion is the result of the calibration[REF-19]

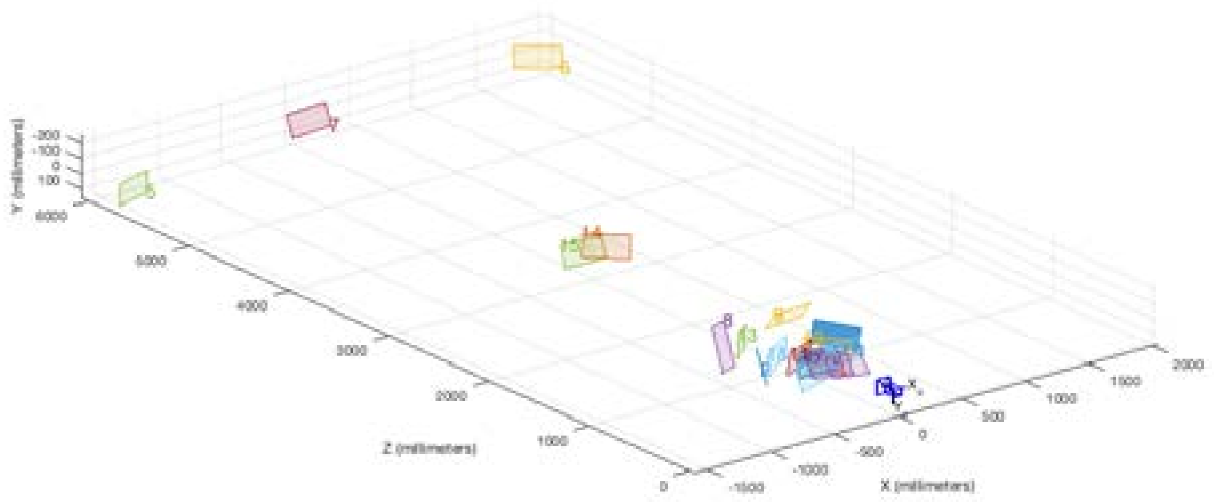



Figure 22: The location and orientation of the calibration boards in space.

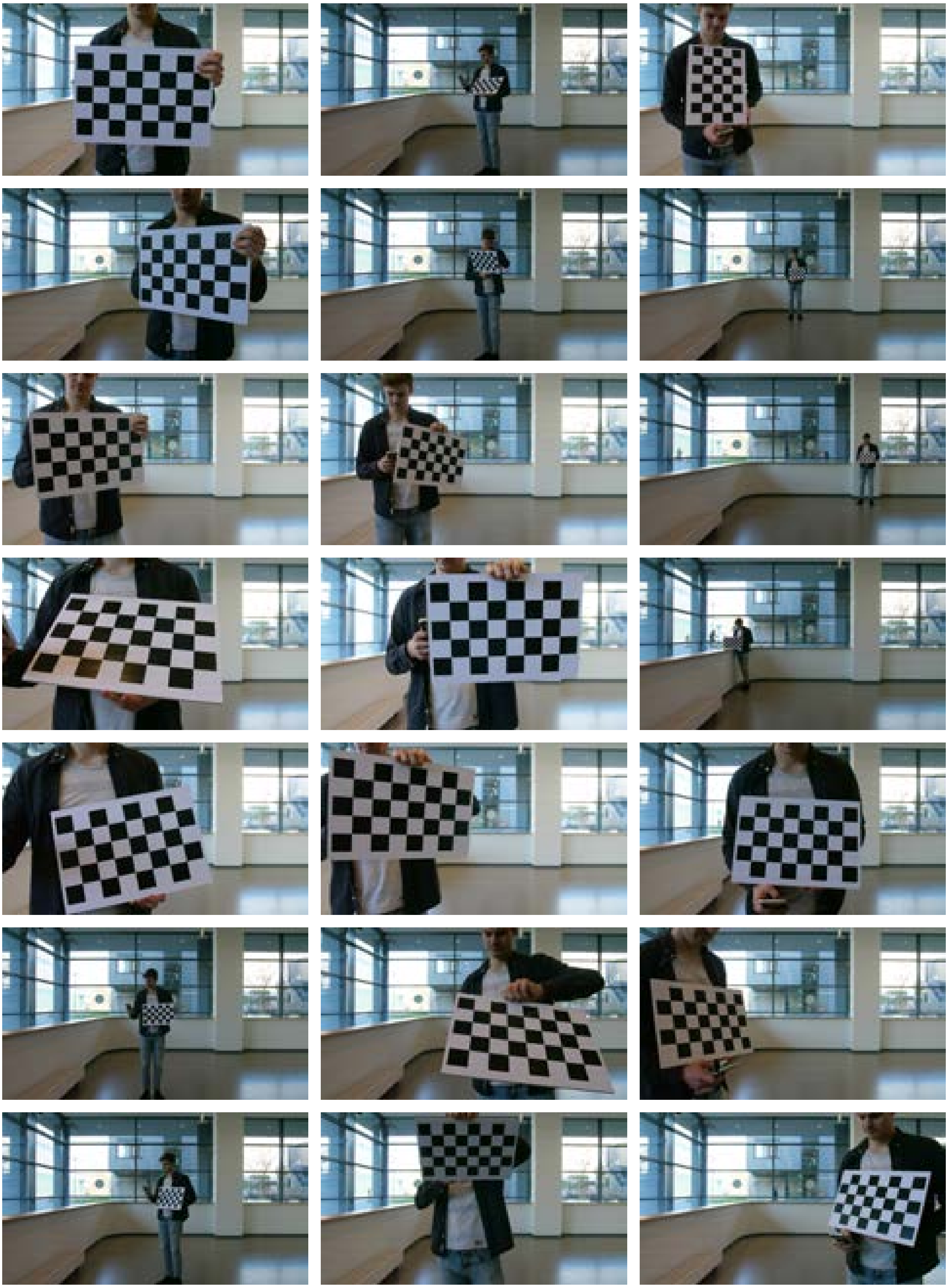
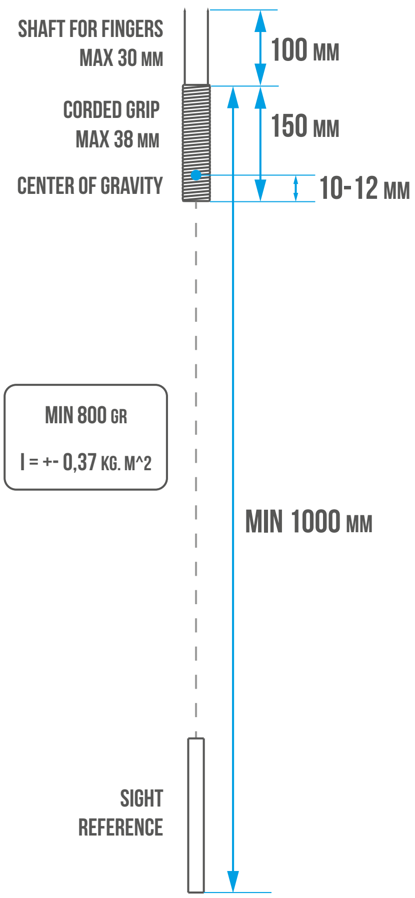


Figure 23: The checkerboard calibration photos

# A.10 SHAFT DEVELOPMENT

The shaft of the javelin determines the overall shape.  shows the minimum requirements for the shaft set in paragraph 2.5. The shaft also needs to house the electronics components. Easy installation and accessibility of the electronic components will make the product cheaper to produce. Paragraph 2.3 showed that the length of 2.60 could cause some problems during transport since an indoor javelin is being transported more often than an outdoor javelin. This will influence the overall experience of the product. What is also important for the shaft is that the mass distribution is correct to allow the design to feel like a standard javelin. I also stated that I aim to change the javelin training as little as possible.

A long installation time will distract the athlete from training, so it needs to be as low as possible. The javelin training I came up with a few options for the shaft design, which fit most of these criteria. The aerodynamics of the javelin play a minor role since the release parameters are the most important, and the aerodynamics have influence after the release. The shaft options make use of an aluminum tube. This material is chosen because of its strength to weight ration, impact resistance, and price. Table 8 shows an overview of how the options score on the criteria. A modified javelin is also included, which is used a lot during indoor training.



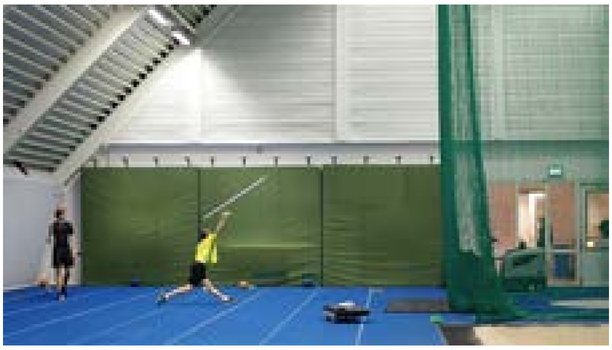



Figure 24: Testing the 1.40m prototype in training

Figure 25: Testing the 2m prototpye in training

| | MODIFIED JAVELIN | 2M CONCEPT | 1.4M CONCEPT | TWO PART CONCEPT |
|---|---|---|---|---|
| MASS DISTRIBUTION | - | + | - | + + |
| TRANSPORT | - | + | + | + |
| INSTALATION TIME | + | + + | + + | - |
| TOTAL | - | + + + + | + + | + + |

Table 8: Scoring shaft concepts on criteria

APPENDCES

| Installation time: | Mass moment of inertia: | Transport: |
|---|---|---|
| ++ No installation time | ++ Same as competition javelin. | ++ Can fit in trunk |
| + short action (1-3 seconds) | + Almost the same | + Fit in trunk plus back seat |
| - Multiple actions (4-10 seconds) | - Too low | - Gets into the front seat area |
| -- More then a minute. | -- Too high | -- Does not fit in car |

Figure 26: 2m concept (right) and 1.4m concept (left) in car

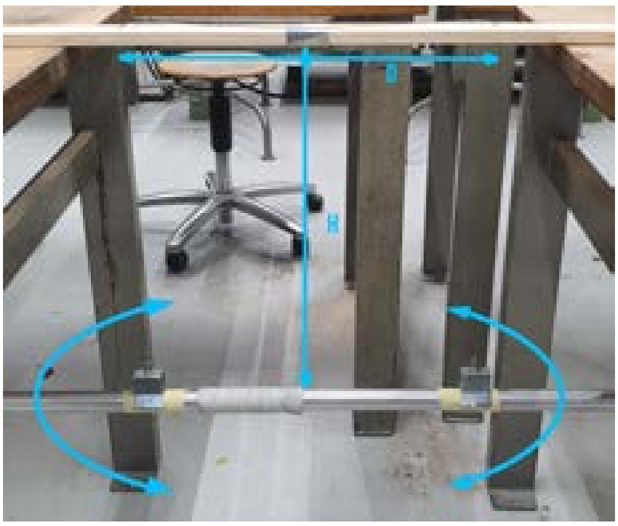


Figure 27: Moment of inertia test see Appendix A.4

# A.11 CHARGER IDEATION

During this project, I also thought about how the product could be charged. I decide on a wireless charging system that would make the charging interaction easy. Figure 28 is a page of ideation sketches for the charger. Due to time constraints, I was not able to develop the charger further, but most of the ideation sketches can be implemented in the current design without having to change much.

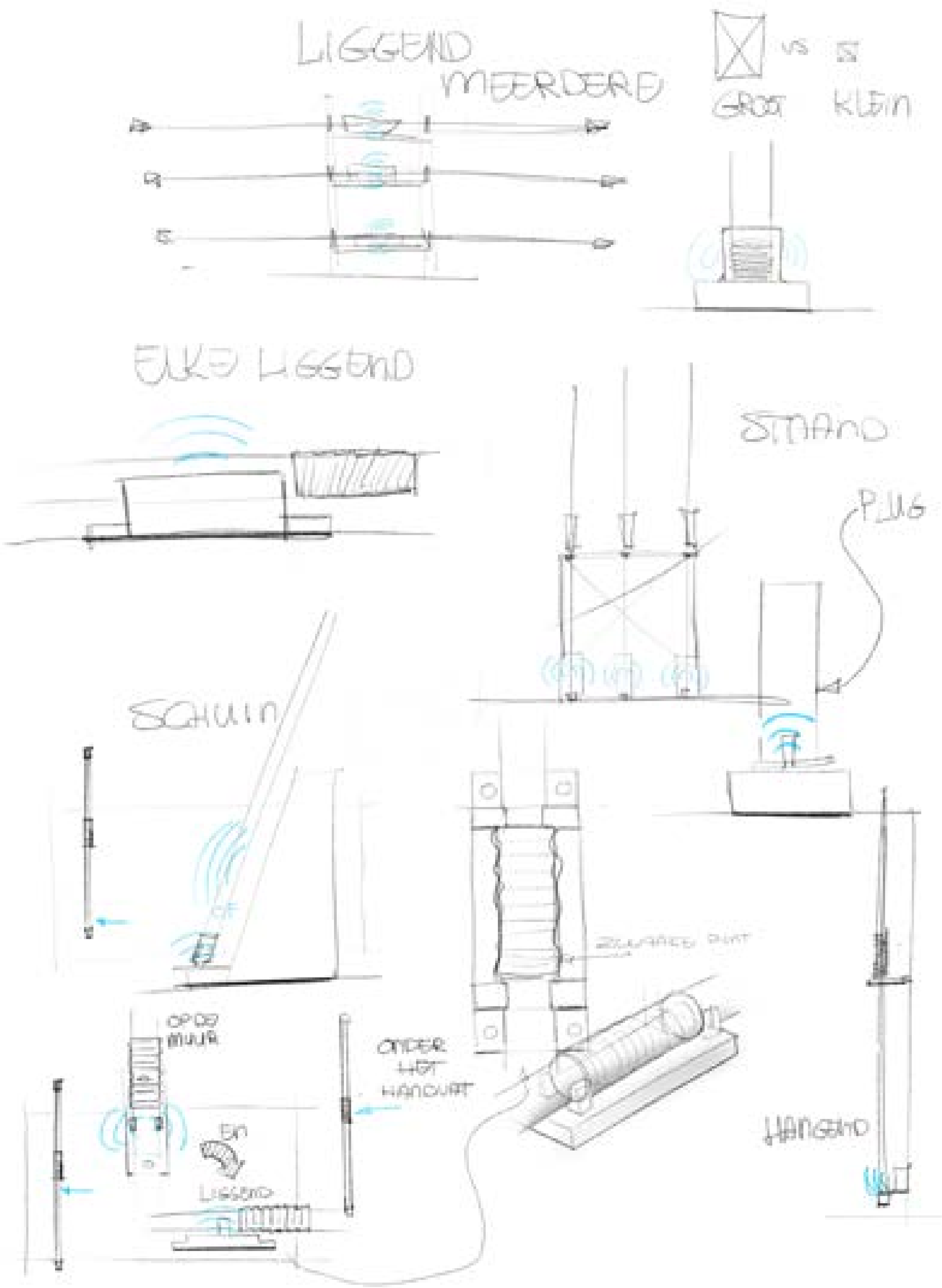



Figure 28: Ideation sketches for a wireless charger

# A.12 MARKET SIZE THE NETHERLANDS

According to a document from the Dutch track and field association around 140.000 of the people in The Netherlands are a member of a track and field club. Most of these people are only doing recreational long-distance running. 23.000 People, older than 12, participate in one of the disciplines of track and field. In their junior years (17.000 people), children commonly practice a wide variety of disciplines making the number of people that practice javelin throwing a lot higher than the number of disciplines there are in track and field.

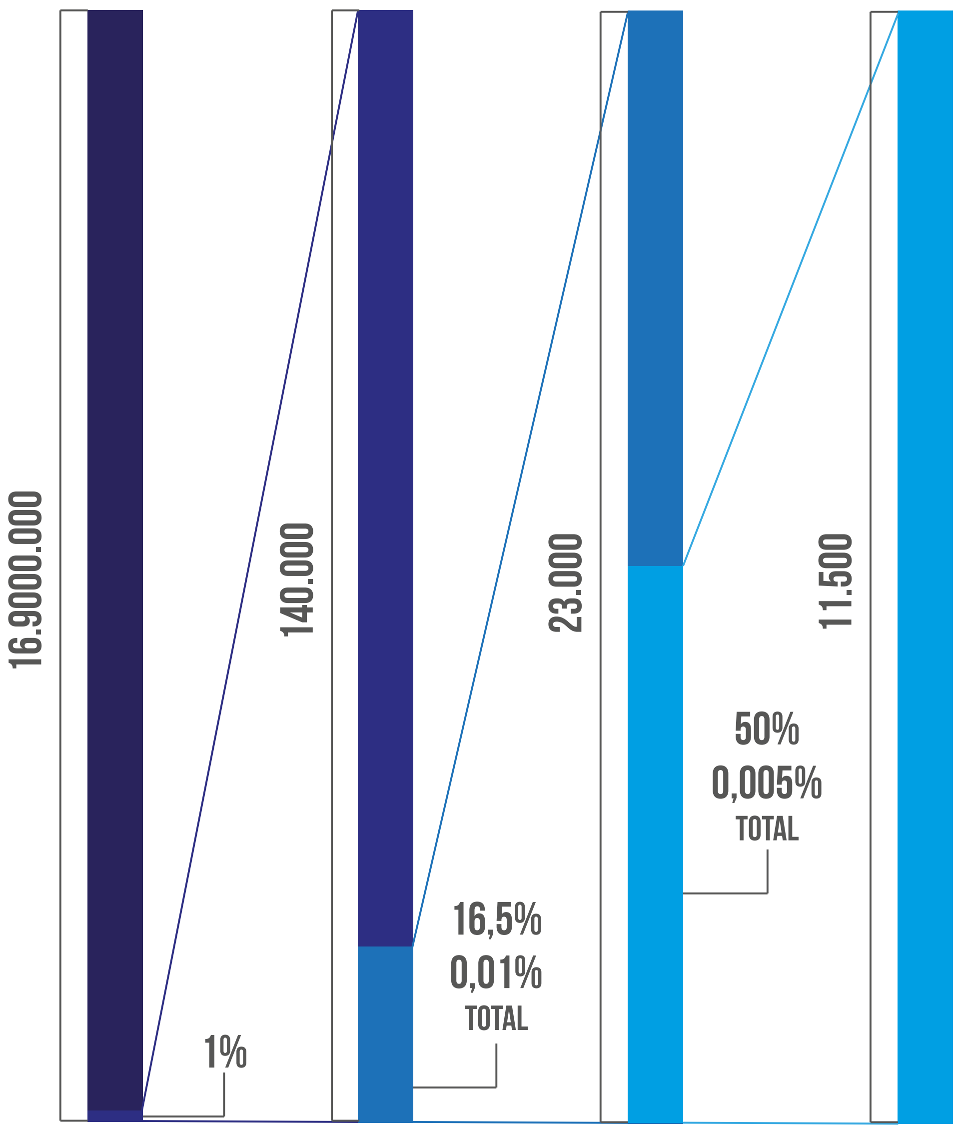



Figure 29: Showing the potential market size calculation of 11.500 people