THE DESIGN OF THE PRODON DATA JAVELIN

Providing performance feedback for indoor javelin throwing

TU Delft

MASTER THESIS
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0.1 PREFACE

Although I managed to write this thesis on my own, it would have been possible without the help of several people whom I would like to thank for their efforts.

Joost de jong, for the help with the electronics in this project. Without your expertise in Arduino and general technical knowledge, I would not have made it this far.

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My roommates, for cooking me dinner in the later parts of this project where I had not time to do it myself. you spared me a lot of pizza's

The rest of my friends, for a wonderful time in Delft.

Lastly, I would like to make a small remark. Although I took great care in making this master thesis, I suffer from dyslectic so that te might be some minor spellings issues in the report. My apologies in advance

0.2 SUMMARY

Introduction

Javelin throwing in the winter is not fun when the temperature approaches zero degrees. That is way javelin throwers move indoors for training. The problem with training indoors it that there is no room to throw a javelin 80 meters, so a different type of training is used. The javelin fitted with a rubber tip is thrown into a net. This way, the technique can still be practiced without the javelin's flight.

Unfortunately, the flight of the javelin can tell a lot about how well the javelin is thrown. Without that feedback, it is hard to know if an improvement in technique also results in a better throw. This project aims the fill that gap and provides performance feedback to the javelin thrower and the coach.

Javelin throwing context

First, the javelin throwing context is analyzed. The most critical parameters for measuring the performance of an athlete are the release velocity, release angle, and angle of attack. These parameters need to be measured with an accuracy of 0,25 m/s for the velocity and 1,5 degrees for both angles to give a realistic indication for the performance of the throw. The feel of the javelin is also crucial. It should hold the same as a standard javelin and should behave the same way when moving it around.

Sports data collection

The most used data collection now in day to day training is video recording, which can be played back in slow motion to dissect the technique of the athlete. As mentioned before, this does not tell everything about the performance of the throw. Several 3D tracking technologies are explored to find the best way the tracking the velocity and angles of the javelin. The best option seems to be a combined system of an inertial measurement unit inside the javelin with video tracking as an external reference system. The video can also be used to playback the recording of the throw. This way, the link between the technique and the performance of the throw becomes more apparent.

Development

For both the inertial measurement unit and the video tracking a proof of concept prototype is developed. The systems are combined to use the strengths of one system to fill in the weakness of the other. In this case, the video tracking can compensate for the drift of an inertial measurement unit, and the inertial measurement unit can reduce the noise in the video tracking data.

Product

A product name PRODON in build around the two tracking systems. It has active trackers front and back for the video tracking system to pick up. The inertial measurement unit is built into the back in a protective casing. The PRODON uses an app to communicate the collected performance data to the athlete and coaches. Combined with a video of throw, this can be a meaningful addition to indoor javelin training.

Evaluation

The accuracy of the prototype is tested in the situation where the javelin is thrown perpendicular to the camera. The velocity error calculated from this test is 0,02 m/s. The angle error tested came out to be 0,5 degree. Although these measurements fall below the set requirements, they are tested in a controlled 2D environment. Further testing in real conditions is needed to say for sure that this technology can provide accurate data.

0.3 TABLE OF CONTENTS

1

INTRODUCTION

In this chapter, the subject of the report will be introduced. This involves an introduction followed by the assignment, where the goal of this project is explained. Last, the approach of the project is covered.

Gerhard Stöck winner of the 1936 summer Olympics javelin throwing [REF-28]

1.1 INTRODUCTION

Javelin throwing is an Olympic sport, which dates back to the ancient Olympics games beginning in 708 BC. The aim of the sport is to throw a javelin as far as possible, a measurement of pure performance. The athlete can use a run-up of around 30 meters to generate a base velocity, after which the javelin is thrown. The throwing motion is like a whip. The arm remains almost straight throughout the motion, and the body tension creates the snap.

During summer, this athletics event is performed on the inside field of the track where there is 100 meters of grass for the javelin to land on. The distance a javelin travels together with the flight behavior provides valuable feedback for the athlete and coach. In winter, when training moves inside, this feedback is lost as there is no room for a full-size field, so a rubber pointed javelin is thrown into a net a few meters away, as can be seen in Figure 1

Currently, most coaches use video recordings to asses the technique of their athletes. Although useful to provide feedback for the technique, it says very little about the performance of a throw. A throw with the perfect technique with no power still does not give a good result.

This highlights the need for a device that can record the performance data of a javelin throw, providing the athlete and the coach with meaningful performance information.

Figure 1: Former Dutch national champion Jurriaan Wouters training indoors in Sweden

1.2 ASSIGNMENT

Problem definition

The main problem in indoor javelin training is the absences of performance feedback for the throw. The short distance between the release of the javelin and hitting the net does not provide enough time to judge the flight behavior or estimate a throwing distance as is used in outdoor training as performance feedback.

The angle of the javelin with the horizontal plane can be judged in a recorded video, but speed, trajectory and other parameters that might influence the javelin's performance are nearly impossible to judged it way.

It is possible to use video analysis systems to track the javelin during the short time between release and hitting the back of the net when training indoors. This is commonly used in movement science. However, these systems are expensive, take a long time to set-up, and are also time-consuming when it comes to data analysis. Hardly useful for day to day training where (nearly) direct feedback is required, and the budget is limited. Take the OptiTrack system[REF-57], for instance, their most affordable system used for movement science (8 flex 13 cameras) costs €11 065) going well above six digits for a more advanced system.

A product needs to be designed that captures the necessary performance feedback, processes this data and provides the athlete and coach with meaningful (near) instant feedback of the throw.

Goal

Design a product that can provide a javelin coach and its athletes with (near) instant feedback on the performance of a throw, when training indoors. The solution must be low-cost and provide meaningful information to users.

Vision

My vision for this project is to create a stand-alone product that can measure the performance of a javelin throw indoors while distracting from the regular training routine as little as possible.

1.3 APPROACH

The approach for this project is inspired by the double diamond model Figure 2. This model describes four-phase discover, define, develop, and deliver with a testing phase sometime added. In Figure 3 my version for the project is visualized. Each phase will be shortly explained.

2 Javelin throwing context

In this part first, the parties involved in javelin throwing are analyzed in the stakeholder analysis. Then the javelin throw and javelin flight are analyzed to gain better insight into how the force applied to the javelin is generated and how the javelin behaves after the release. The conclusion of the analysis results in a list of requirements that the design should meet.

3 Sports data collection

With the requirements for the sensor, technical analysis is done. The current data collection in javelin training is analyzed as well as data collection products in other sports. A few options for sensors are listed and are evaluated.

4 Development

The development of the product is done parallel in two directions with small agile development cycles. The electronics with all the components to make that work is developed. Simultaneously the javelin design is developed to create a product that feels like a standard javelin. In the design of the physical product, the electronics components are represented as a “black box” with specific dimensions. Both sides are checked with each other regularly to prevent developing two parts that do not fit together.

5 final design

Then the final design that can from the development phase is presented. The functionalities are explained as well as the added benefits of the product.

6 Evaluation

Last, the final prototype will be tested on how well it can perform in an indoor training session and evaluate if it fits the requirements and wishes set before. The findings are concluded, and there is a recommendation list for further development.

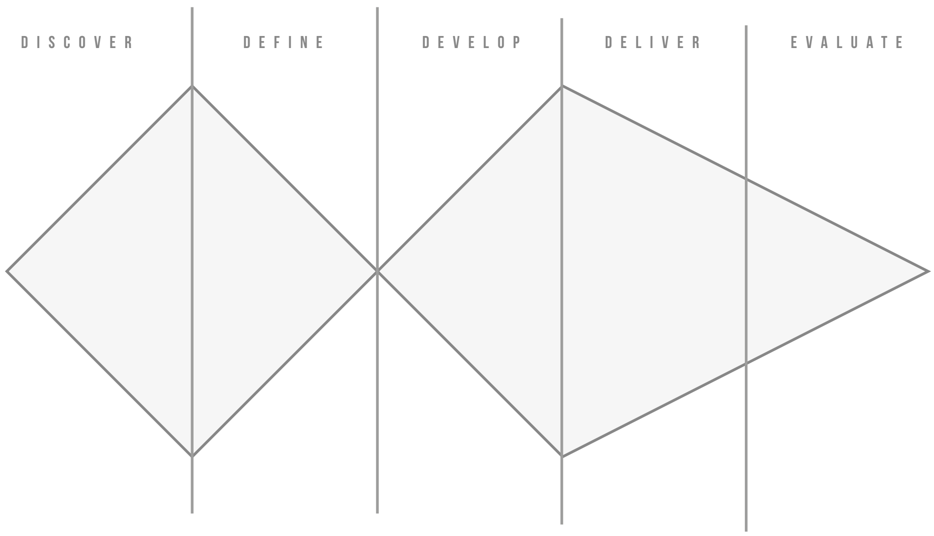


Figure 2: Double diamond model

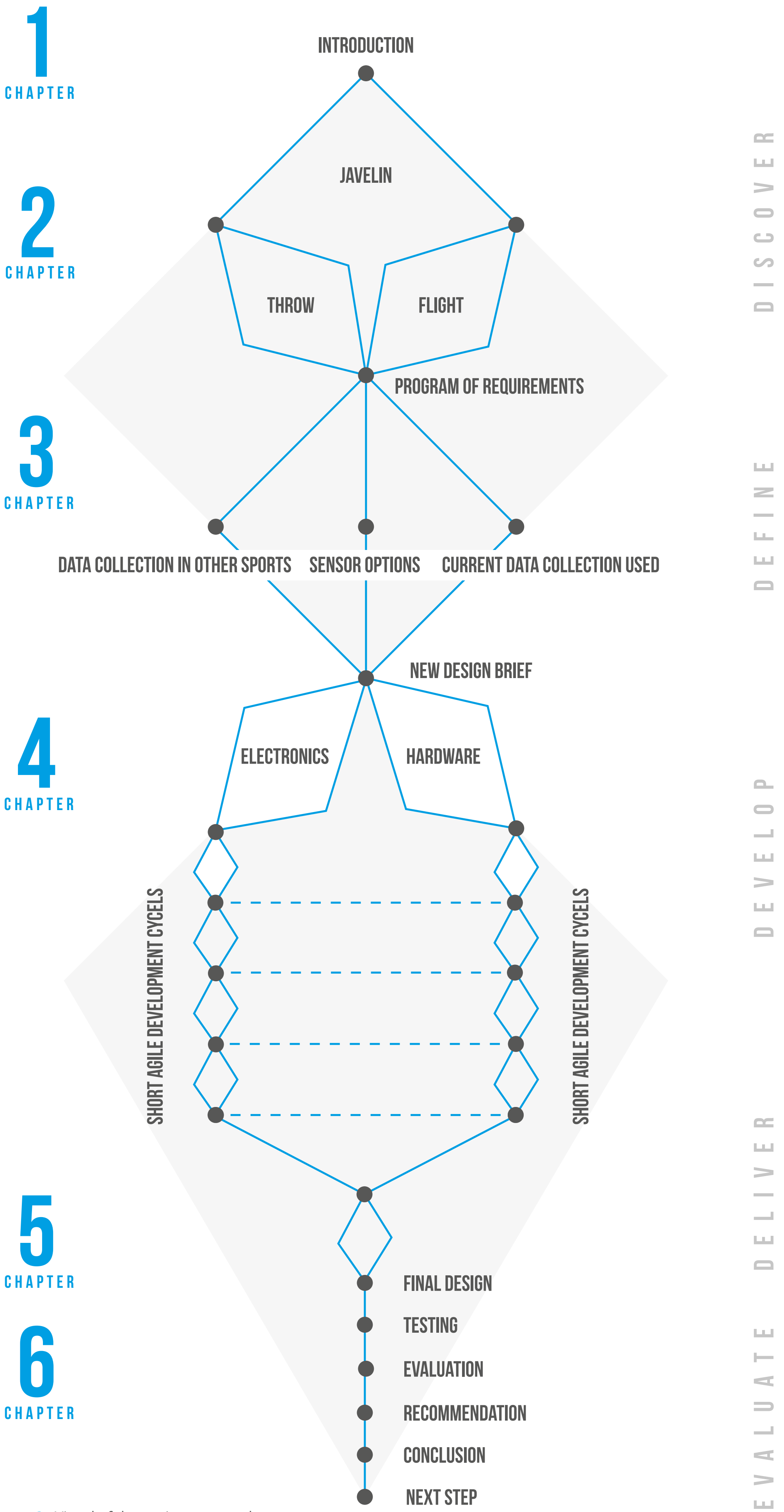


Figure 3: Visual of the project approach

2

JAVELIN THROWING CONTEXT

In this chapter, the analysis for the data javelin is explained. First, the whole javelin throwing context is mapped in several paragraphs. Then the technology options are explored. To conclude this chapter, a requirement and wishes list is made that the data javelin should meet.

Mildred “Babe” Didrikson at the 1932 Los Angeles Olympics[REF-8]

2.1 STAKEHOLDERS

A stakeholder analysis is done to get to know all the parties involved in the data javelin project. The stakeholders can be divided into two groups, the primary and secondary stakeholders. For each stakeholder, there is a short description of there needs.

The primary stakeholders are the most important and are those who are directly affected by the data javelin and have an influence on the design of the data javelin. Their input gives critical insights into the context and can be used to create a product that is designed for the user. The secondary stakeholders are also affected by the product, but can not directly influence the design of the product. They can, however, be indirectly responsible for some design criteria. In Figure 4, the stakeholders are visualized, which will be further explained on the next page.

For the needs of the primary stakeholders, an interview has been conducted with a javelin thrower. The interview can be found in Appendix A.1. More informal conversations with the coaches and athletes during training, together with training and competition observations, also gained useful insights into the needs of the users. The focus of the informal conversations is the same as described in the interview.

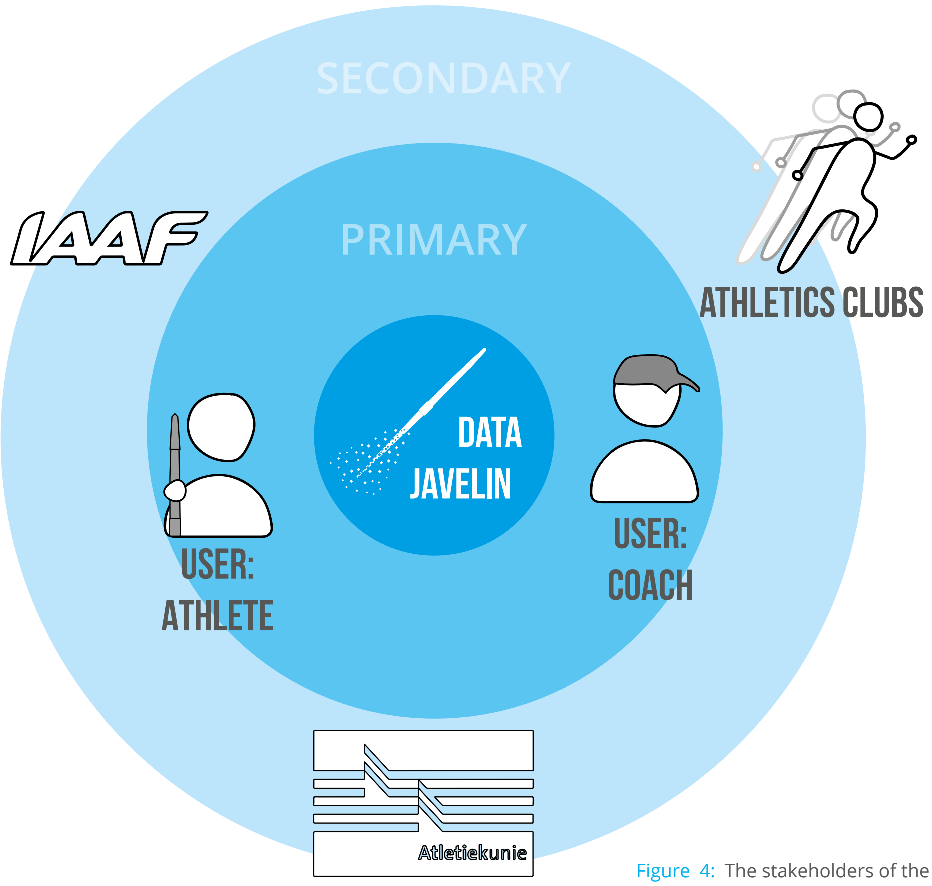


Figure 4: The stakeholders of the data javelin in an overview

Athletes

The first type of user is athletes. Their main goal is to improve their distance in the javelin throw. They rely on their coaches during training to provide feedback on their technique. Outdoors they can estimate the distance they throw, but indoors there is no way of telling if a throw was good or bad. Objective data about the throw can be precious as the feedback for an indoor throw.

Furthermore, the athletes want the same javelin-feel as they have when throwing outdoors. The use of the data javelin should not distract from the training. So it should be easy to use without long set-up times or lengthy data analysis.

Coaches

The second users are the coaches. They decide what and how the athlete's train. They have multiple athletes in their training group. The coaches give feedback to the athlete on their technique. This is usually done by eye, but sometimes slow-motion video feedback was also used. For the coaches, it is hard to see how well their athlete hit the javelin and what the release angle is. A list of throwing parameters will be very beneficial to the coaches' ability to provide feedback to the athletes.

Atletiek Unie

The Atletiekunie is the Dutch national track and field union. They want the Dutch athletes to compete on the highest level. To do this, they aim to support their athletes and improve their training. Data tracking has become increasingly more popular in sports and can make training more effective and efficient. The AtletiekUnie do not have enough funds to support all disciplines of athletics, so they choose to invest in their best disciplines. Javelin throwing is not one of them since no one representing the Netherlands attended the world championships.

IAAF

As the International Association of Athletics Federations, the IAAF has an interest in seeing their sport evolve. Improving indoor javelin training has the potential of lifting this sport to a higher level, which could get more attention to the sport.

Athletics clubs

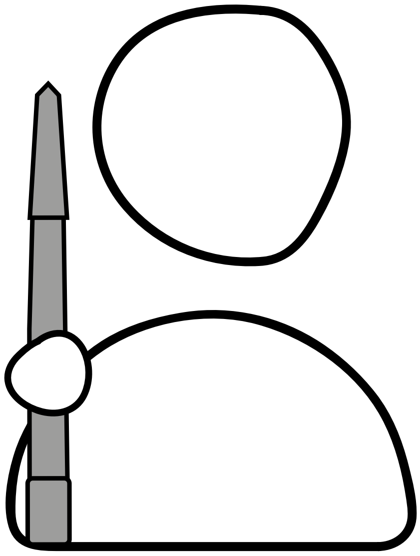
Similar to the AtletiekUnie and the IAAF, on a smaller scale, the athletics clubs want to support their athletes. They do this by providing training facilities and equipment. They spend around €1500.- on equipment per year and have many disciplines to support improved training equipment at a low cost would be ideal for them.

Takeaway

Athletes want to throw as far as possible and want the same trowing experience as outside. Coaches want to objective performance parameters. The AtletiekUnie, IAAF, and the athletics clubs all want to see the sport improve but have limited funds.

2.2 TARGET GROUP

The target group for the design consist of both the athlete that has to throw the javelin as the coach that gives feedback and can interpret the measured performance.



Age

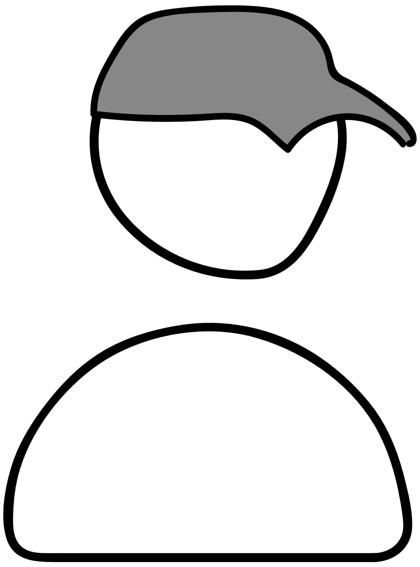
The age of the javelin thrower is between 18 and 50 years old. In athletics, javelin throwing starts at 12 years old. Before that time, they use ball throwing as a substitute. The first few years are only focused on getting to know the moment where the performance is less important. from 18 years; onwards, athletes use an 800g javelin. This is also the time where athletes get a feel for the technique, and performance becomes more important. .

Skill level

The design will be focused on intermediate to elite level Athletes. For beginners performing the technique right is the main focus. From intermediate athletes onwards, the performance of the throw becomes increasingly important.

Potential users

In the Netherlands, there are about 11.500 estimated potential javelin throwers, which is 0,005% of the total population. Of this potential half would classify as intermediate or above, which makes 0,0025%. If the same is true for the western world with a population of 893 million, the potential is 2,23 million. In reality, this number is much lower since multiple athletes use the same javelins, especially in training.



Location

The users of the product can mostly be found in the western world. In some areas, there is no need for indoor training since the winter temperature still allows for outdoor training. The most common javelin countries include Germany, Norway, Sweden, Finland, and some eastern European countries.

Budget

As described in the stakeholder analysis, the founding for training material mostly comes from the athletics clubs. In some cases, a javelin team might have a sponsorship deal. The average material investment of athletics clubs in the Netherlands is around €1500 annually.

Takeaway
The product will be designed for intermediate to elite level male throwers with an age of between 18 and 50 located in the northern part of the western world with a budget of around €1500 annually.

2.3 JAVELIN TRAINING JOURNEY

The intended use of the design is a training device. Mapping the training journey can yield useful insights on what is going wrong during training and how that can be improved. First, the situation for outdoor training is visualized. The same is then done for indoor training, after which the difference is explained.

Outdoor training journey

The journey of an outdoor javelin training session consists of three primary phases. It begins and ends with the storage of the javelin. Second, the javelins are transported from the storage to the approach. Each thrower uses 2 to 5 javelins, depending on how many javelins are available in total. During training, they throw a couple of javelins before collecting them, so more javelin per athlete mains less walking back and forward. Last, the training takes place. The full training journey is visualized in Figure 5.

When training outdoors, most javelin teams have a fixed track where they have their training sessions. At this location, there is a storage unit where the javelins can be stored. The distance of the storage unit to the approach is small, so the javelins are usually carried by hand or with a small cart.

A typical training consists of a warm-up with some stretching and coordination drills. After the warm-up, the javelin itself is involved. Each athlete throws in series of between 2-5 throws before they have to collect the javelins again. The throwing starts from a standing position and evolves to a more substantial approach step by step. At the beginning of the season, training has a specific technical focus. Later in the season, there is more focus on the full approach.

The performance of the throw is accessed by a combination of looking at the flight, distance approximation with reference object at a know distance from the line, and comparing the throw to the previous throws from the series.

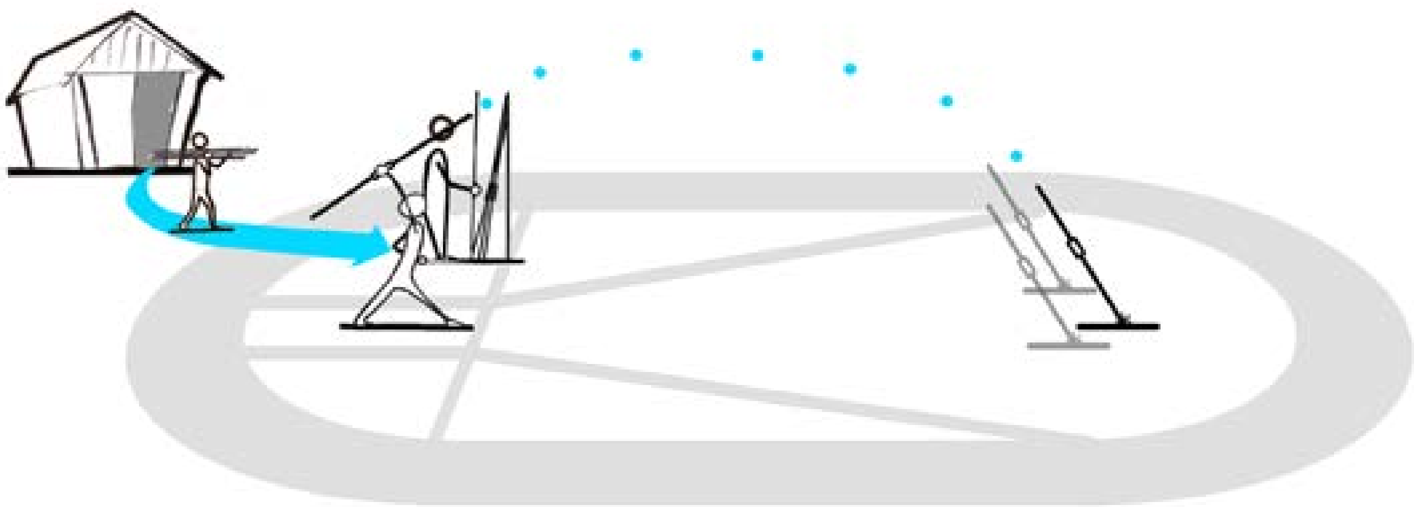


Figure 5: The journey for an outdoor javelin training

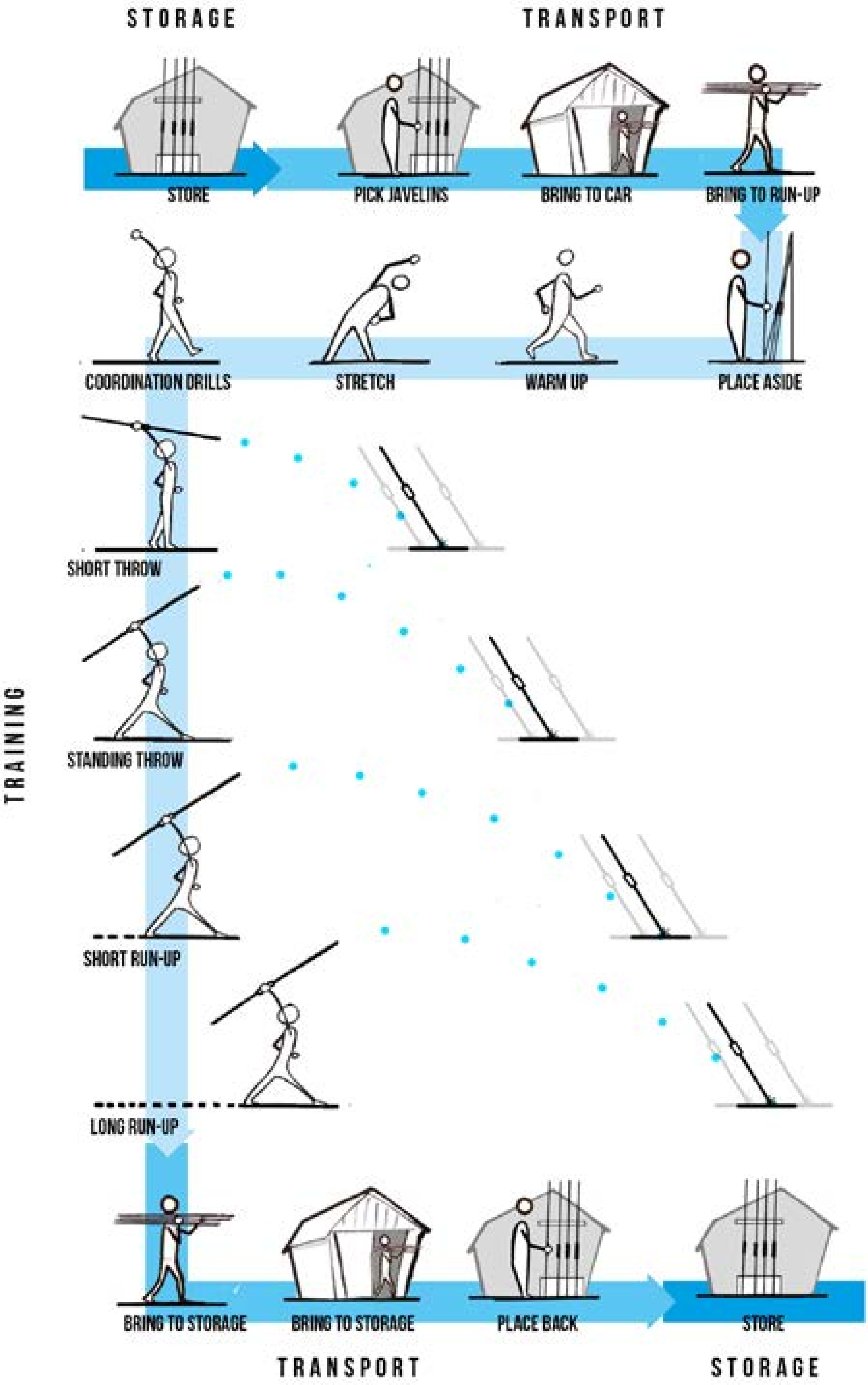


Figure 6: The journey for an outdoor javelin training

Indoor training journey

The journey of javelin training indoors also consists of the same primary phases and is illustrated in Figure 9. (storage, transport, and training) the difference being that the indoor training location is usually a gym or indoor athletics hall, which is rented by the javelin team. This means that they do not have a storage unit; therefore, they need to bring the training equipment with them each training. This also means that they are not allowed to attach something to the wall permanently. Damaging the training location is never a good idea, but especially when you do not own the place like is the case here.

Transporting a 2,6m tall javelin by car is hard to fit in a regular car without sticking it almost through the windshield. Mounting it on the roof is also an option but takes a lot more time and effort.

The biggest downside of training inside is that there is not enough space. You need a field of 100mx50m with a roof of 50m high to be able to throw a javelin like is done outside. Although these halls exist, they are far from common and are really expensive. The vast majority of javelin throws has to train on smaller indoor tracks or even in a sports hall. They throw a javelin with a rubber tip into a net. This way, they can practice the movement, but all of the ways to access the performance are lost.

Figure 8: Indoor training facility in Sweden

Takeaway

The length of the javelin makes it hard to transport it by car and maneuver it through hallways or door openings.

There is no storage at the indoor location, and it is not allowed to attach something to the walls.

When throwing a javelin into a net, there is very little feedback about the performance of the throw.

Figure 7: The journey for an outdoor javelin training

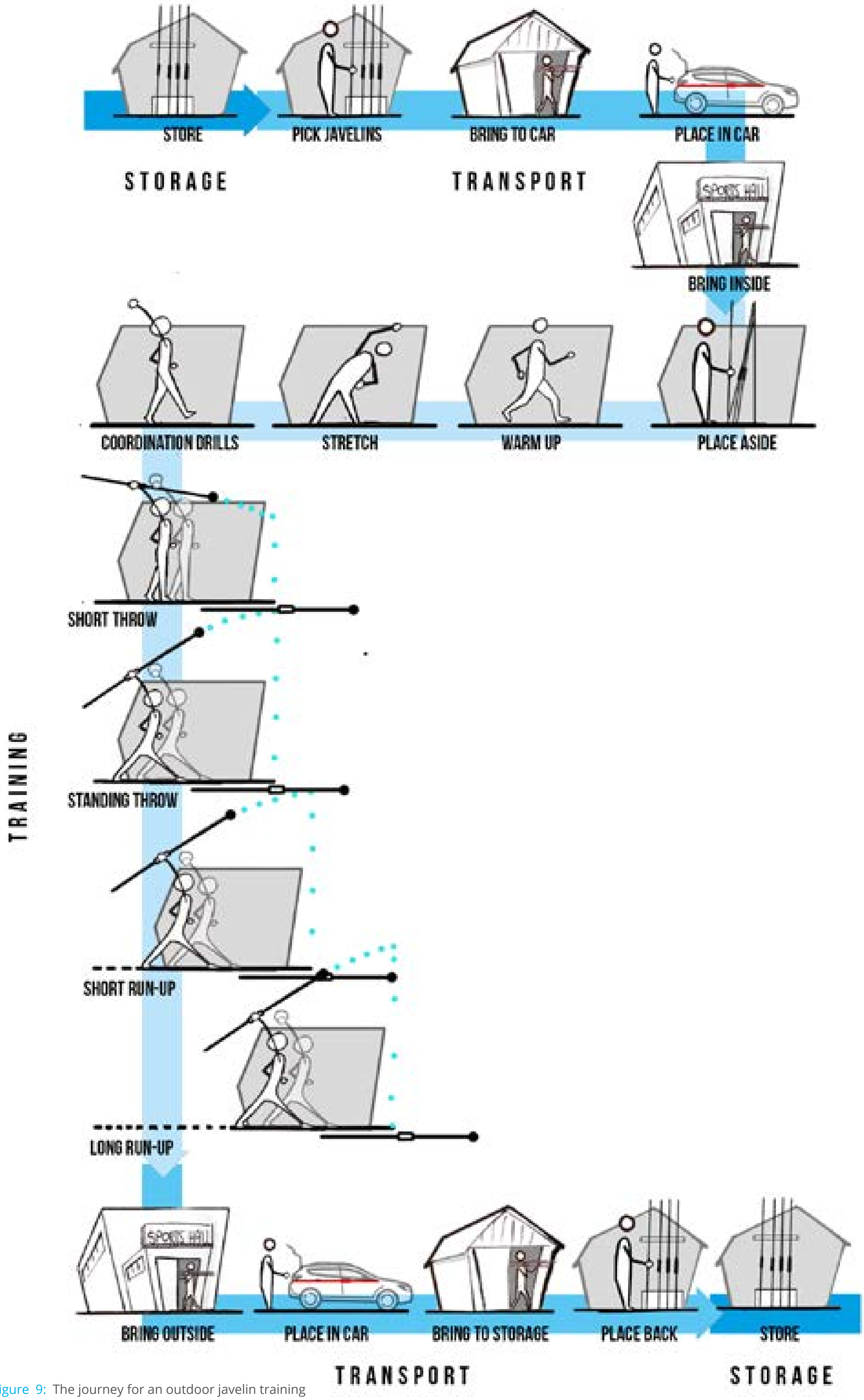


Figure 9: The journey for an outdoor javelin training

2.4 JAVELIN THROW

If we want to know how to measure the throwing performance of a javelin throw, it is key to understand how the javelin is thrown and how these forces are generated. First, the throwing technique is analyzed, which is divided into three phases. Then a speed and acceleration profile is formed to illustrate when the speed and acceleration of the release are generated.

Technique

The technique used to throw the javelin can be divided into three phases. These phases are:

- Run-up
- Transition
- Delivery

Figure 10 shows the full approach step by step. Each phase will be shortly explained in this chapter. A full explanation can be found in Appendix A.2.

Run-up

In the run-up, the base velocity of the approach is established. When doing a full javelin throw, the athlete starts off at the end of the approach. They smoothly accelerate in 10-12 steps. During this phase, the javelin is held close to the head, with the tip pointing to the throwing direction.

Transition

In the transition, the state of the athlete is transitioned from the run-up of the delivery. The purpose of the transition is to bring the body of the athlete into the right position for a powerful delivery. The transition consists of four to seven steps and can be divided into the following sub-phases:

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

During the transition, the speed should remain constant.

Delivery

During the delivery phase, the athlete throws the javelin, making use of its whole body, which creates an arc of tension from the hand to the foot. During the delivery, most of the final speed is generated.

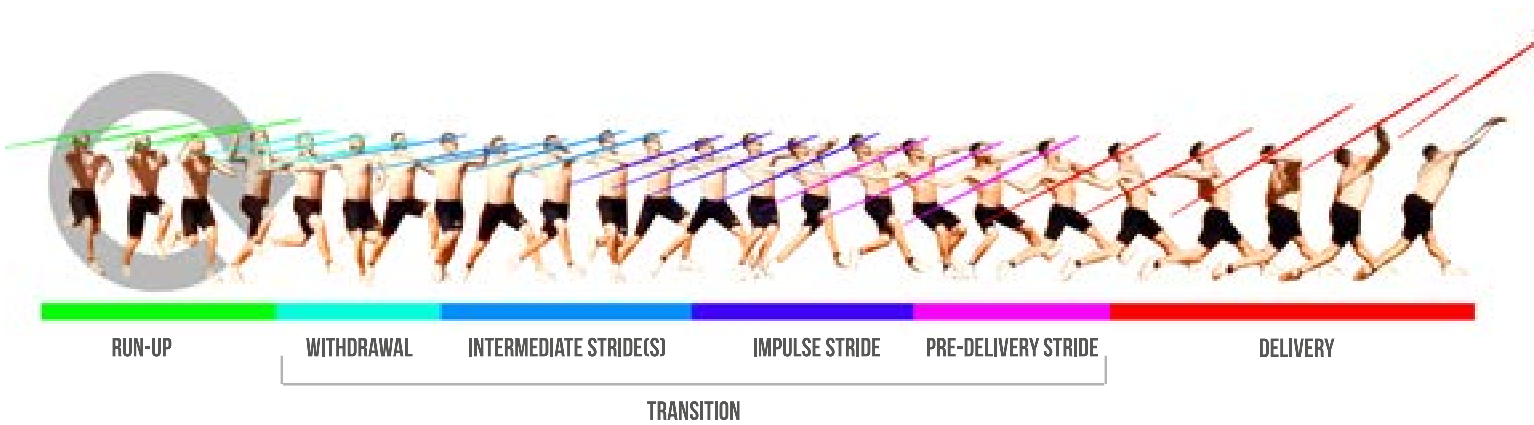


Figure 10: The full javelin throwing technique divided into phases. REF-64

Speed distribution

In the javelin throw, two main factors contribute to the total amount of applied force. First, there is the approach speed, which is mostly generated in the run-up. During this phase, the athlete accelerates fluently to a speed of 5.5m/s and 7.6m/s for elite throwers (Tidow, 1996) ideally, this speed is maintained during the later phases of the approach until the final delivery takes place.

The second part is the force generated during the delivery. According to Miller and Munro (1983), the final velocity for elite throwers of 28-30 m/s is reached within 0.15 s. The highest measured velocity of Tom Petranoff's world record at the time (99.72 m with an old rules javelin) is 32.3 m/s. (Gregor and Pink, 1985). This means that in the highest possible final delivery between 24.7-26.8 m/s of speed can be generated within 0.15 s. This results in an acceleration of 164.67-178,67 m/s^2 (or 16,7-18 g). A sensor needs to be able to record at least 18 g, to measure the performance of a throw. The sample rate is dictated by the acceleration time of 0,15s. A minimum of 10 samples is required for an accurate measurement; this results in a minimum sample rate of 0,015s or 67 Hz, while more samples will increase the accuracy of the measurements. An overview is made in Figure 11 , to illustrate what the speed and acceleration during a throw look like

After the release, no more force can be applied to the javelin, which marks the end of the influence of the athlete on the throw. The speed of the javelin will slowly go down until it hits the ground.

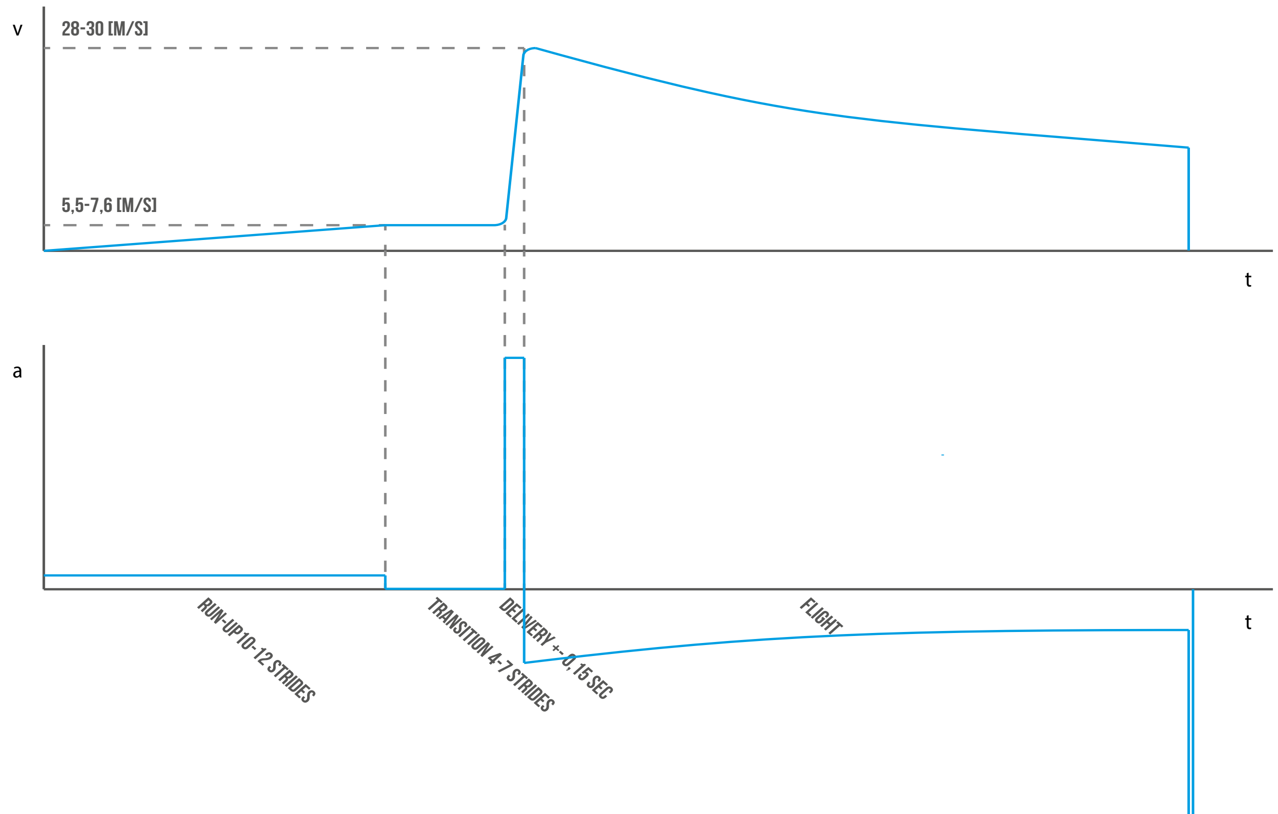
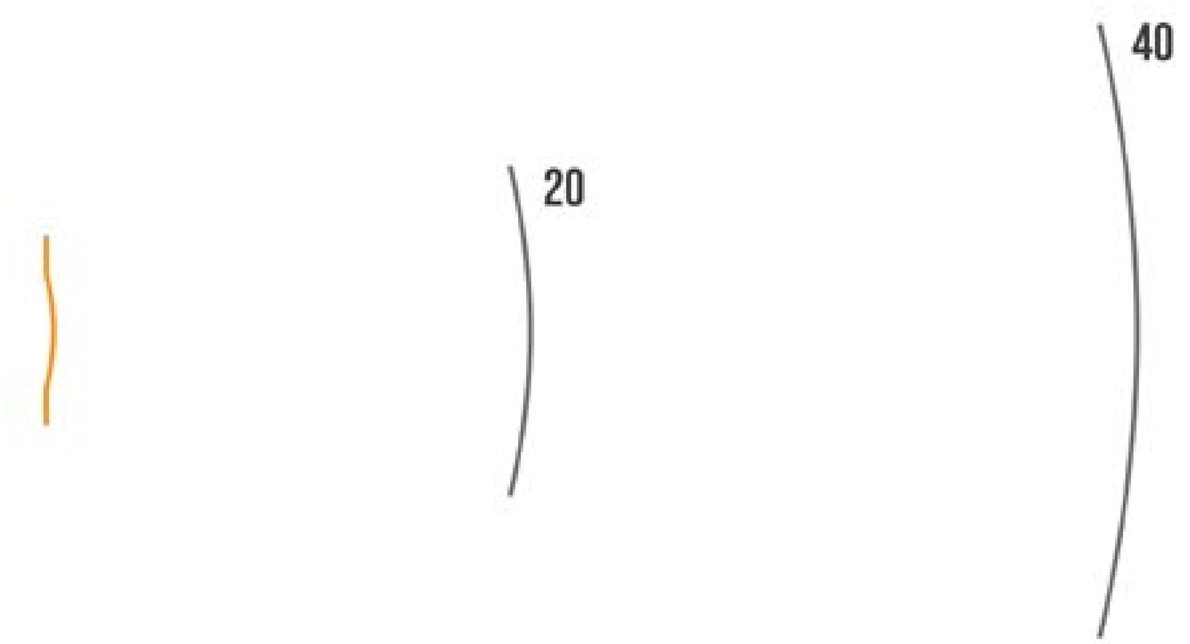


Figure 11: A simplified overview of the speed and acceleration during the approach and flight of the javelin

Throw performance

To get a feel for the throwing performance, the first and second place at the world championships javelin throwing for all the editions since 2001[REF-10] are plotted in Figure 12. The average distance between the first and second place, excluding the highest and lowest value is 1,25m. where all the distances lie between 84m and 95m

Takeaway
The speed of the javelin comes from the run-up and **delivery** — the latter contributing the most. A sensor to measure the performance must be able to measure at least a speed of 32,2 m/s with an acceleration of **18 g** and have a minimum sample rate of **67 Hz.**



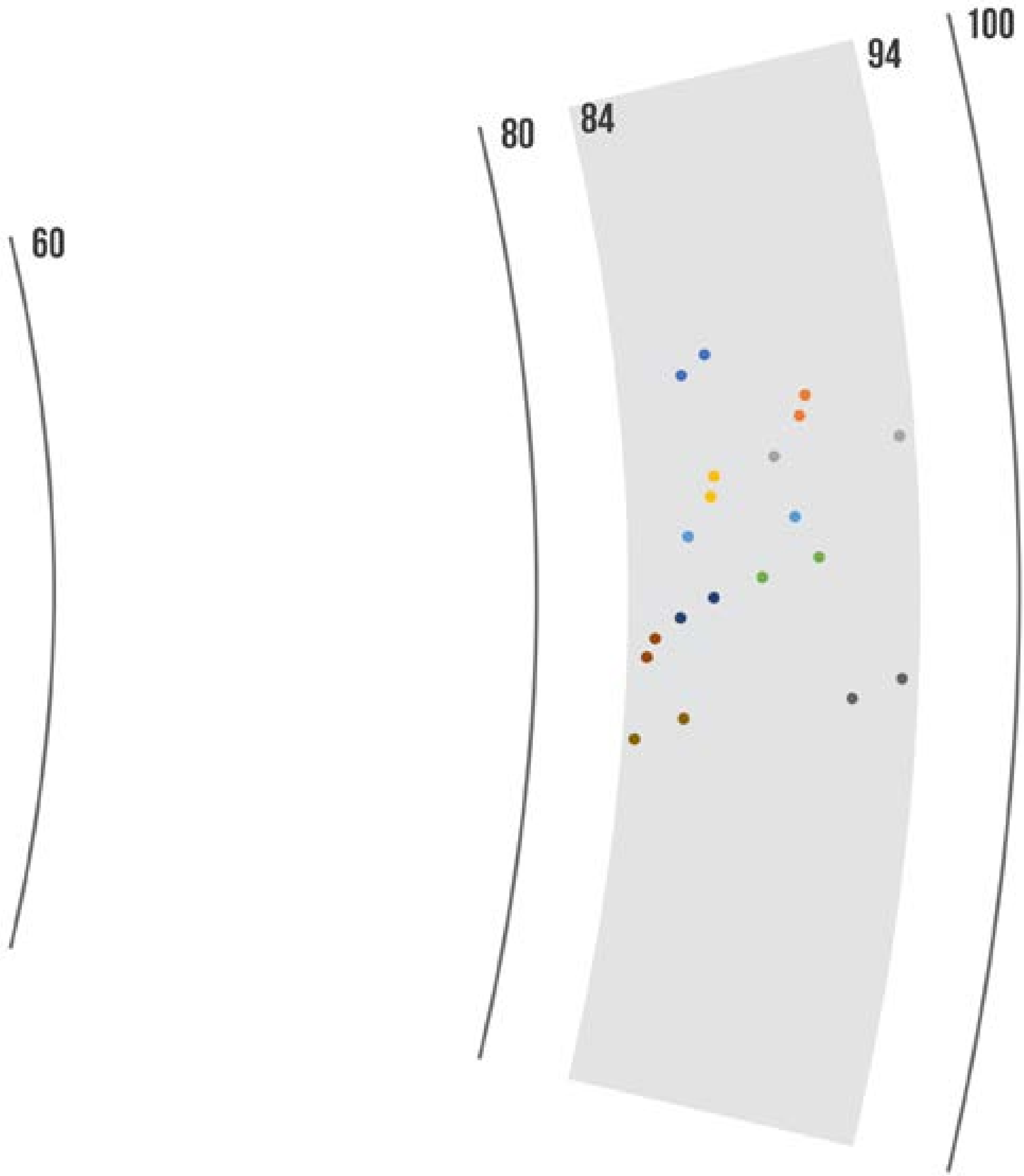


Figure 12: World championship distances for the first and second place each year since 2001. each color represents a different year.

2.5 JAVELIN CHARACTERISTICS

In this paragraph, the minimum requirements for a design will be explained. First, the requirements for a competition javelin will be summarized. After which the javelin feel will be explained, ending up with minimum physical requirements for a design.

Competition javelin requirements

There are many requirements a javelin has to comply with to be used in a competition. A summary of these requirements can be found in Table 1 and Figure 13. The full rules and regulations can be found in Appendix A.3.

For a training device, the primary purpose is that it should prepare the athlete as well as possible for competition. There are no rules or regulations on what can be used as a training tool. The shape or size does not matter as long as it is safe to use. Since the aim of the design to simulate a javelin throw indoors as well as possible, the rules that apply to a competition javelin serve as a guideline.

	Weight	min. 800 g
L0	Total length	2600 - 2700 mm
L1	Distance tip to Cm	900 - 1060 mm
L2	Distance back-end to Cm	1540 - 1800 mm
L3	Length of metal tip	250 - 330 mm
L4	Length of corded grip	150 - 160 mm
D0	Diameter thickest point of shaft	25 - 30 mm
L5	Distance beginning grip to cm	10-12 mm
D2	Corded grip	Do +8mm

Table 1: Summary of the competition javelin requirements

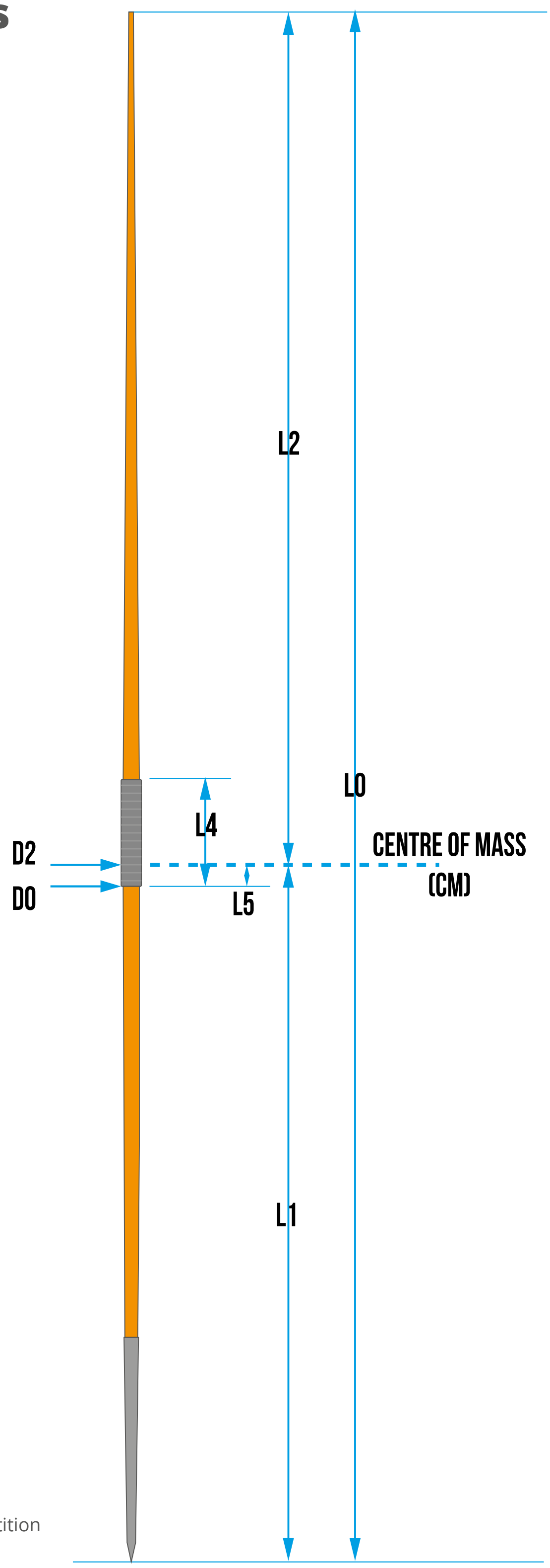


Figure 13: Summary of the competition javelin requirements

Javelin feel

The purpose of the design is to mimic an outdoor throw indoors and give additional feedback that is lost when throwing into a net. While doing this, the design should feel like a competition javelin.

There are two factors that determine the feel of a javelin. First, there is the interaction with the athlete during the approach. Here the most crucial aspect is the grip cord. It should feel the same and have the same dimension as the grip cord on a competition javelin. Another import factor during the later parts of the approach is the point of the javelin next to the head. It serves as a reference for the athlete to know where the javelin is pointed to. If the athlete does not see the point, it is hard to judge the direction it is pointed to with an arm extended out backward.

Second, there is the way the javelin behaves when moving it. The weight should be the same. The javelin's center of gravity must be located in the right position to the handle. The weight distribution, which makes the javelin rotate about its center of gravity easier or harder, also contributes to the behavior of the javelin. Since the javelin is quite long and has a more substantial tip, the mass moment of inertia about the center of gravity is relatively high. This makes the tip of the javelin stable, so the athlete has more control of where the tip is pointed to. According to Best et al. (1995), the mass moment of inertia of a javelin is around 0,42 [kg m^2]. I tested the moment of inertia with a test that is described in appendix A.5. Where the moment of inertia was measured at 0,37 [kg m^2]. The same test can later be used to test different concepts of the design

Last, the stiffness of the javelin also determines the behavior of the javelin. A stiffer javelin means it can flight more stable but also impacts the joints in the arm of the athlete. A less stiff javelin does the opposite. Since the flight stability is less of a factor indoors the stiffness should not be to high to make the impact on the joints less.

Takeaway
The feel of the javelin is determined by the interaction with the hand on the corded grip, a sight reference and the measurements shown in Figure 14

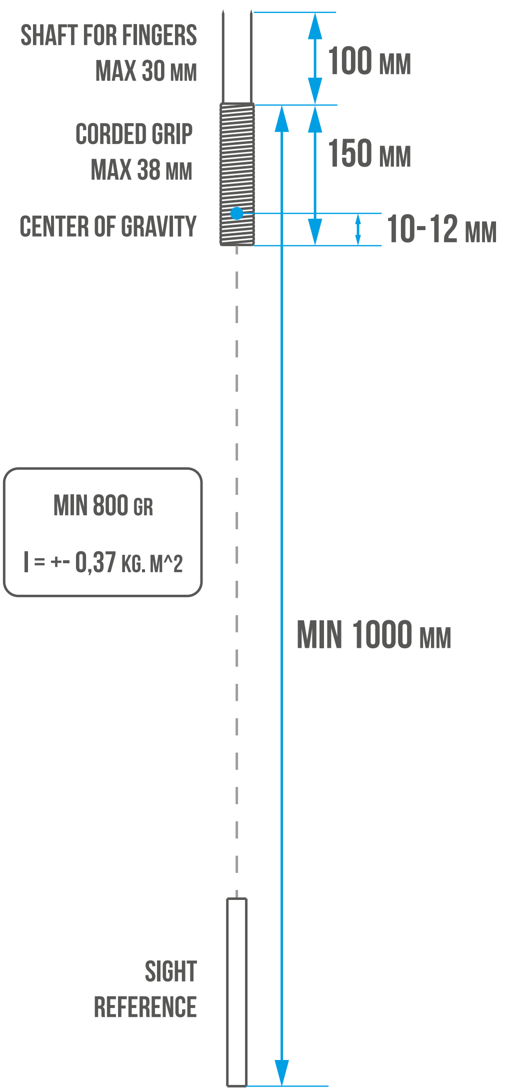


Figure 14: Minimum requirements for data javelin

2.6 JAVELIN FLIGHT

Getting to know how the flight distance of javelin can be calculated will reveal the most important factors to optimize this distance, which is the eventual goal of javelin training. In this paragraph, a 2D mathematical model is formed that describes the flight of a javelin. The most influential parameters will become visible from a sensibility analysis.

Moment of release

The moment of release is essential for the design. Before this point in time, the athlete can manipulate the throwing parameters. After the moment of release, the initial conditions are established, and the javelin is only subject to the external parameters.

Parameters

When calculating the distance, a javelin can travel during a throw. A set of initial values is needed, which are called the initial conditions. They are the values that determine the outcome of the calculation. The initial conditions are:

- Release speed
- Release height
- Release angle
- Release angle of attack
- Angular momentum
- Spin
- Gravity
- Wind speed & direction
- Air density
- Javelin mass
- Javelin characteristics
- Vibrations

The initial conditions can be divided into three groups. External parameters, javelin parameters, and performance parameters. A full description of each parameter can be found in A.5

External parameters

The external parameters are the conditions the Athlete and coach have no control over. They include gravity, wind speed, wind direction, and air density. The external parameters stay the same over the full duration of the javelin flight. The external parameters depend on the location on earth and the weather. The distance a javelin would travel can be calculated for a wide variety of locations and weather types. The external parameters are responsible for the gravitational, lift, and drag forces. An overview of the external parameters is shown in Figure 15

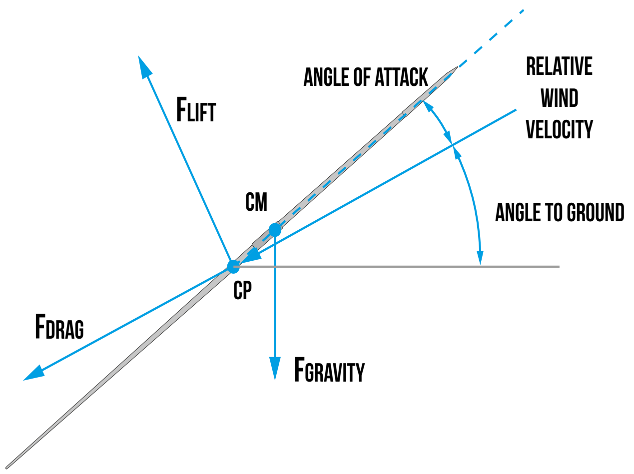


Figure 15: An overview of the external parameters

Javelin parameters

The javelin parameters are dependent on the type of javelin the athlete uses. Although limited to the rules described in A.3 Rules & regulations, these parameters can slightly vary for different types of javelins. The javelin parameters include mass, mass distribution, shape, the moment of inertia, and stiffness.

Performance parameters

The Performance parameters are the most interesting for the design. These parameters can be directly influenced by the athlete and say something about the quality of the throw. They include release speed, release height, release angle, angle of attack, and angular momentum at release. An overview of the performance parameters is shown in Figure 16

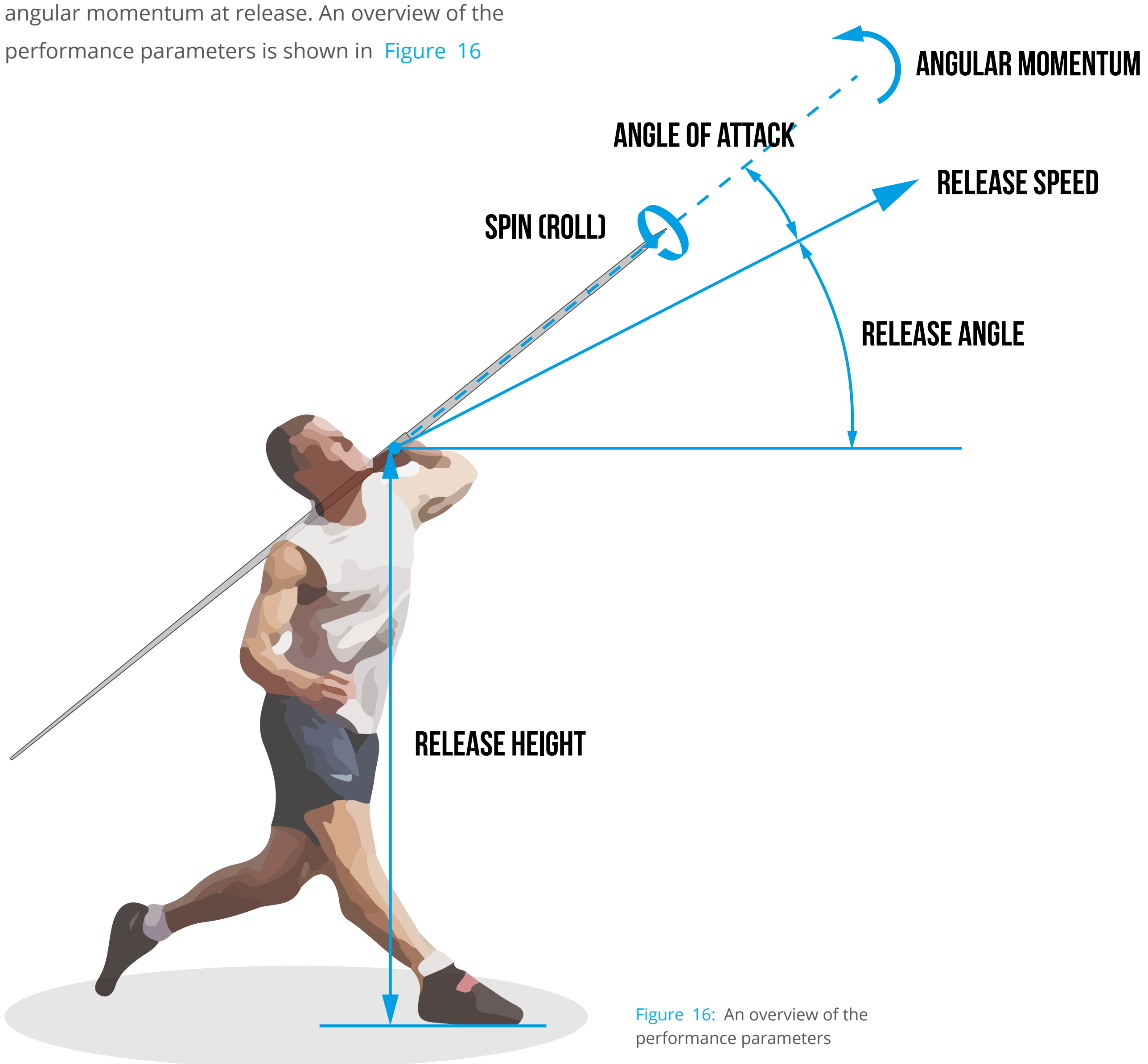


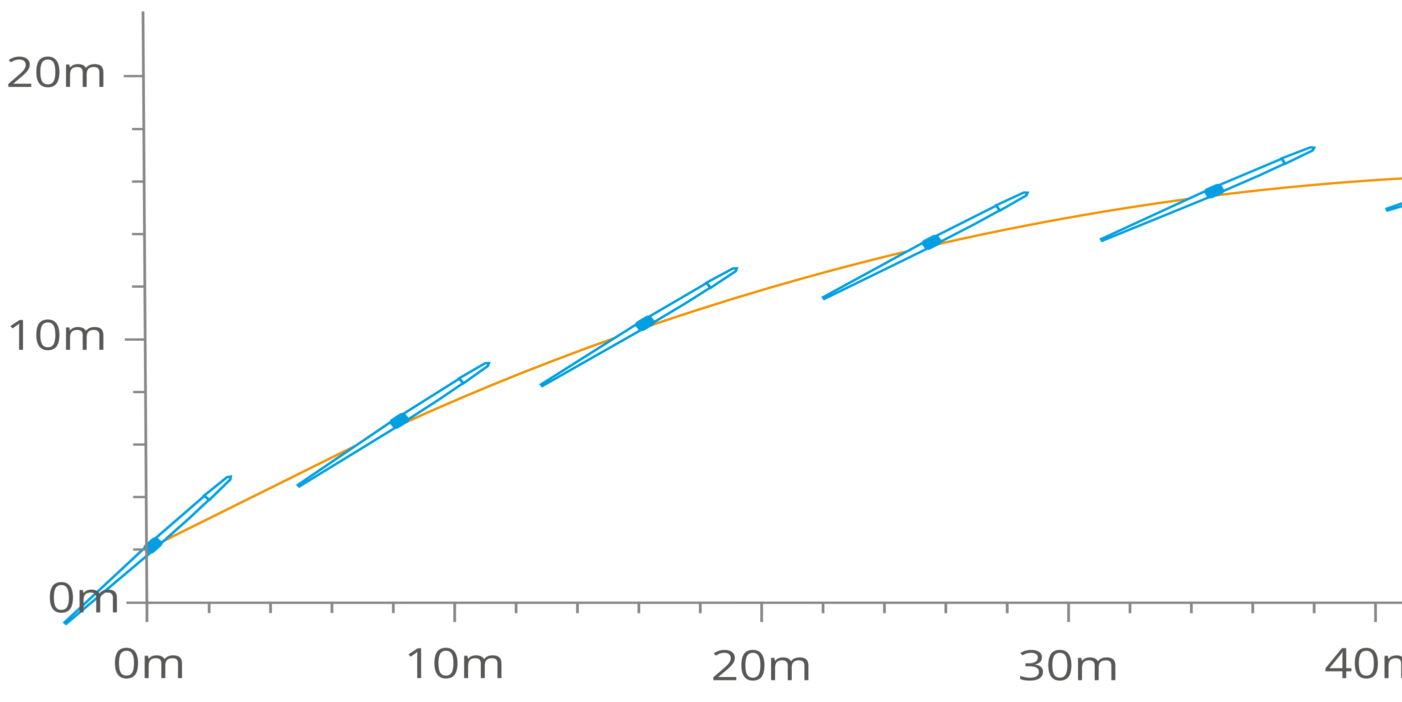
Figure 16: An overview of the performance parameters

Mathematical model

With the list of parameters, a mathematical model is made which can simulate a javelin throw outdoors from the initial conditions. The model starts basic and is made more complicated along the way. An explanation of the model can be found in Appendix A.6, as well as the validation of the model. Figure 18 shows how a javelin behaves during a typical flight; this figure is based on a figure from XXX . To find what the most critical parameters in the mathematical model are, a sensitivity analysis is done, where the effect of each parameter on the final distance is calculated by going through the range of one parameter at the time. The release velocity, release angle, angle of attack, and wind conditions are proven to be the most influential on the simulated distance, which also corresponds with the literature. The sensitivity analysis can be found in Appendix A.7., and the results can be found in Figure 17.

Now that we know that the release velocity, release angle, and angle of attack are the essential parameters to measure, the mathematical model can also be used to determine the accuracy of the sensors need to have. The average distance between the first and second place is found in paragraph 2.4 of 1,25m is used for this purpose. Changing the release velocity 0,25m/s will result in a distance change of 1,25m. For both angles, the requirement is set at 1,5 degree

Takeaway
The most critical performance parameters for the throwing distance of a javelin are release velocity, release angle, and angle of attack. To measure these parameters, the moment of release should be known. The sensor should be able to measure velocity with the accuracy of 0,25m/s and the angles with 1,5 degrees.



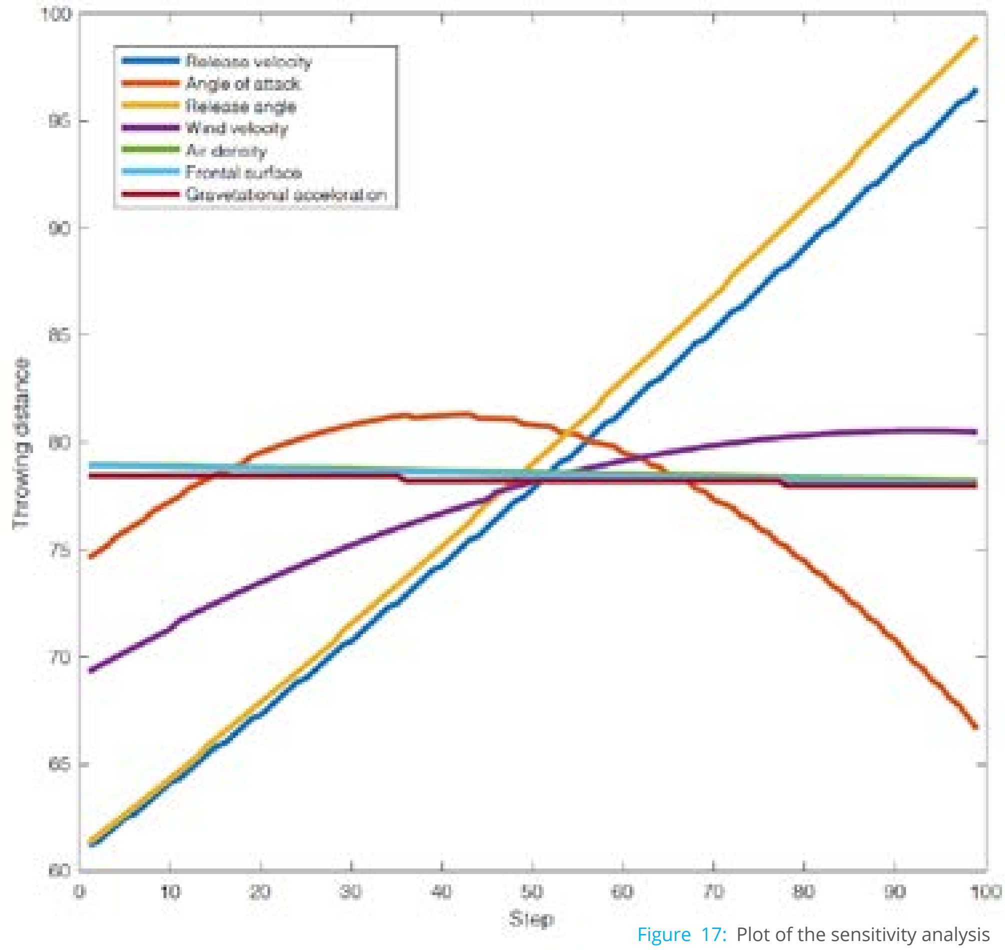


Figure 17: Plot of the sensitivity analysis

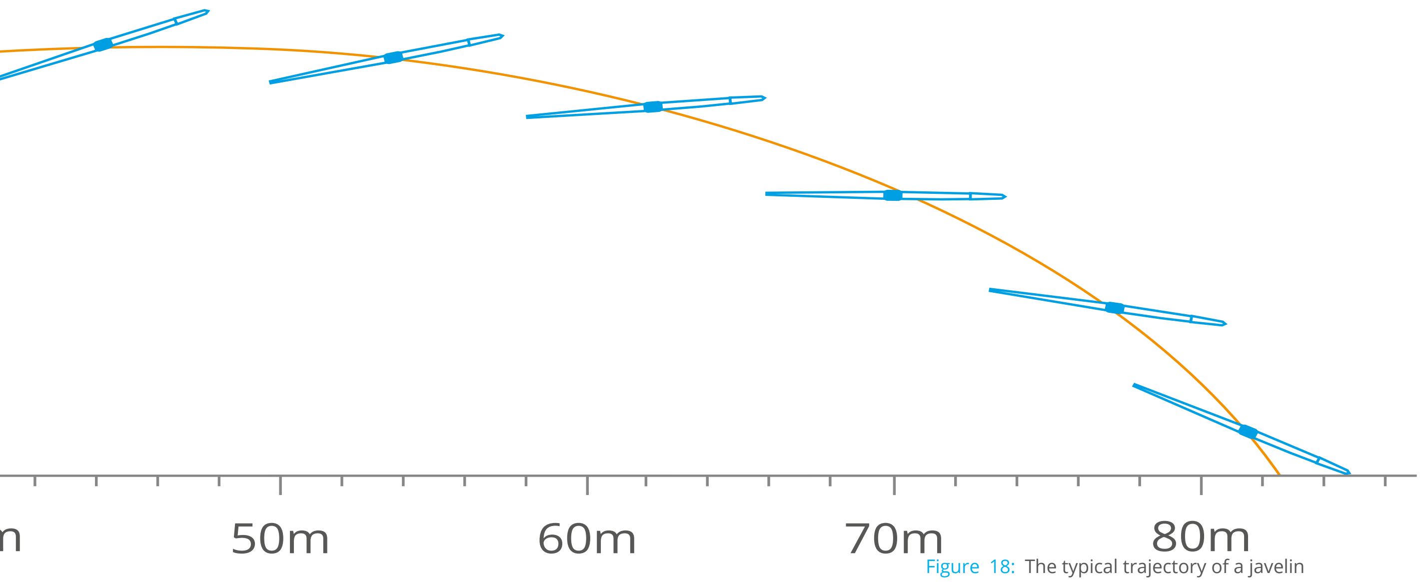


Figure 18: The typical trajectory of a javelin

2.7 TAKE-AWAY SUMMARY

The take-aways from each paragraph are summarized here. These take-aways will form the basis for the requirements and wishes in the next paragraph.

2.1 Stakeholders
Athletes want to throw as far as possible and want the same trowing experience as outside. Coaches want to objective performance parameters. The AtletiekUnie, IAAF, and the athletics clubs all want to see the sport improve but have limited funds.

2.2 Target group
The product will be designed for intermediate to elite level male throwers with an age of between 18 and 50 located in the northern part of the western world with a budget of around €1500 annually.

2.3 Javelin training journey
The length of the javelin makes it hard to transport it by car and maneuver it through hallways or door openings.

There is no storage at the indoor location, and it is not allowed to attach something to the walls.

When throwing a javelin into a net, there is very little feedback about the performance of the throw.

2.4 Javelin throw
The speed of the javelin comes from the run-up and **delivery** — the latter contributing the most. A sensor to measure the performance must be able to measure at least a speed of 32,2 m/s with an acceleration of **18 g** and have a minimum sample rate of **67 Hz.**

2.5 Javelin characteristics
The feel of the javelin is determined by the interaction with the hand on the corded grip, a sight reference and the measurements shown in Figure 19

2.6 Javelin flight
The most critical performance parameters for the throwing distance of a javelin are release velocity, release angle, and angle of attack. To measure these parameters, the moment of release should be known. The sensor should be able to measure velocity with the accuracy of 0,25m/s and the angles with 1,5 degrees.

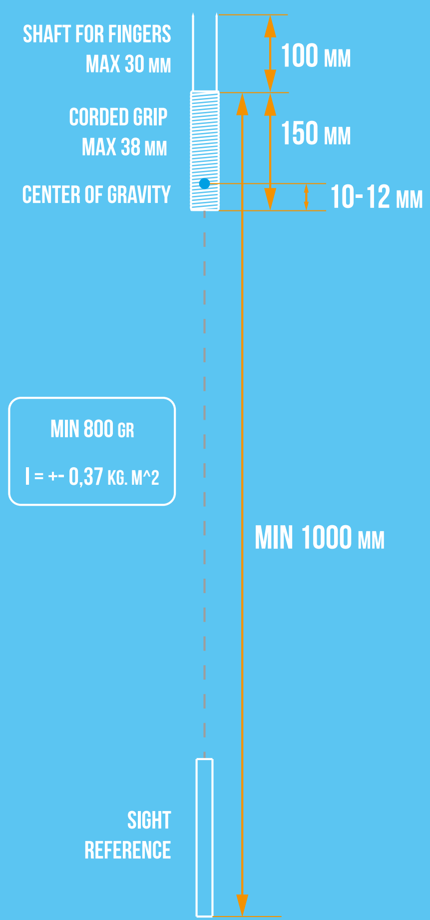


Figure 19: Minimum size requirements for data javelin

2.8 REQUIREMENTS AND WISHES

A list of requirements and wishes is put together for the information found in the second chapter that the design should meet. The requirements are split into electronics and hardware requirements. These are the requirements the design has to meet to work correctly. The wishes are a good addition to the design but are not vital.

Requirements

Electronics requirements

ER-1 To value the performance of an athlete, a sensor must be able to record the following data:

- **Release speed**
- **Release angle**
- **Angle of attack**

ER-2 A sensor must be able to measure the release velocity with an accuracy of **0,25 m/s**

ER-3 A sensor must be able to measure the angle of attack and the release angle wit an accuracy of **1,5 degrees.**

ER-4 The sensor must be able to withstand accelerations of at least **18g** en declarations of **30g**

ER-5 A sensor should have a minimum sample rate of **67 Hz.**

ER-6 A sensor should work in an **indoor** environment such as a sports hall or indoor athletics track.

ER-7 The product should work for at least **2 hours** (max length of a training session)

ER-8 The product can provide feedback within **30s** after each throw.

ER-9 The sensor should be able to determine the moment of release.

Hardware requirements

HR-1 The javelin should **feel the same** as a standard javelin when holding it. Specifically, the grip cord dimensions and material should be the same.

HR-2 The center of gravity in relation to the grip should remain the same. at **10-12 mm** from the beginning of the handle

HR-3 There should be some kind of **visual reference** for the athlete to know where the javelin is pointed to of at least 1000 mm from the end of the grip, so the P90 male can see the tip when the javelin is expended backward during the throw (Dined)

HR-4 The weight of the product should be between **800gr** and **850gr**

HR-5 The design should not be plastically deformed when hitting the net with **33 m/s**

HR-6 The mass moment of inertia of the design should be within 10% of the mass moment of inertia of a standard javelin. which is between 0.378 and 0,462 kg.m^2

HR-7 The design should not cost more then **€1500** (average annual material investment)

Wishes

W-1 The Battery life is preferably more than 10 hours (a week of training)

W-2 The device can calculate final distance

W-3 The wind is added to the final distance calculation so the athlete can train for different wind conditions

W-4 Fit in a small car without needing to enter the front seat area. For a VW up this would mean a max length of approximately 1600mm

W-5 It would be nice if the weight of the javelin can be changed to accommodate different age groups or female athletes with the same javelin. I can also be useful for training with less stress on the joints with a low weight javelin or strength training with a heavier javelin

W-6 The product will work for left and right-handed athletes without any changes.

3

SPORTS DATA COLLECTION

This chapter is going to take a closer look at how the speed and angles of the javelin can be measured. First, the current data collection for javelin throwing will be listed and explained why they are not sufficient enough. Then products in other sports that fulfill the same function are listed. Finally, the technology options for the data javelin are summarized. REF-54

Finish javelin thrower Tapio Rautavaara in 1949

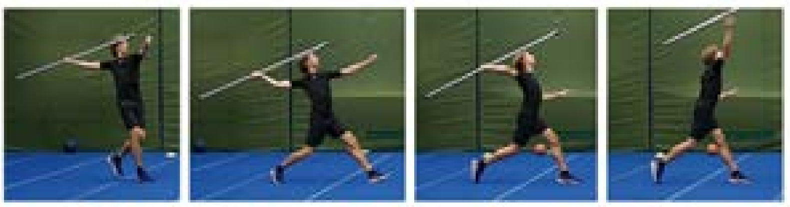
3.1 CURRENT DATA COLLECTION

Currently, there are two types of data collection in javelin throwing. First, there is data that is collected during day-to-day training, which mostly consists of video recordings. Second, there is the flightScope athletics, a relatively new product for day-to-day training that can measure some release parameters. Last, there is the sports research where researchers try to understand what is happening during the throw with specialty equipment for motion tracking.

Video playback

According to the javelin coaches, I talked to the most used data collection in training is video recording. They use the video primarily to playback the throws of their athletes and focus on the technique. The coach looks for the key positions explained in paragraph 2.4. and illustrated in Figure 20. The movements between the key positions are also analyzed. Some coaches make use of an additional application on a smartphone or tablet that allows them to draw lines over a video. This is illustrated in Figure 21. The angle of the javelin with the ground can be calculated between the two lines. It only gives the angle of the javelin with the ground and not the release angle and angle of attack required to access the performance of the athlete. Furthermore, the angle between the two lines is only a 2D view of a 3D situation and is drawn by hand, which makes it not very accurate. Thus video playback is most useful to access the technique of the athlete afterwards.

Figure 20: Key positions of the javelin throw



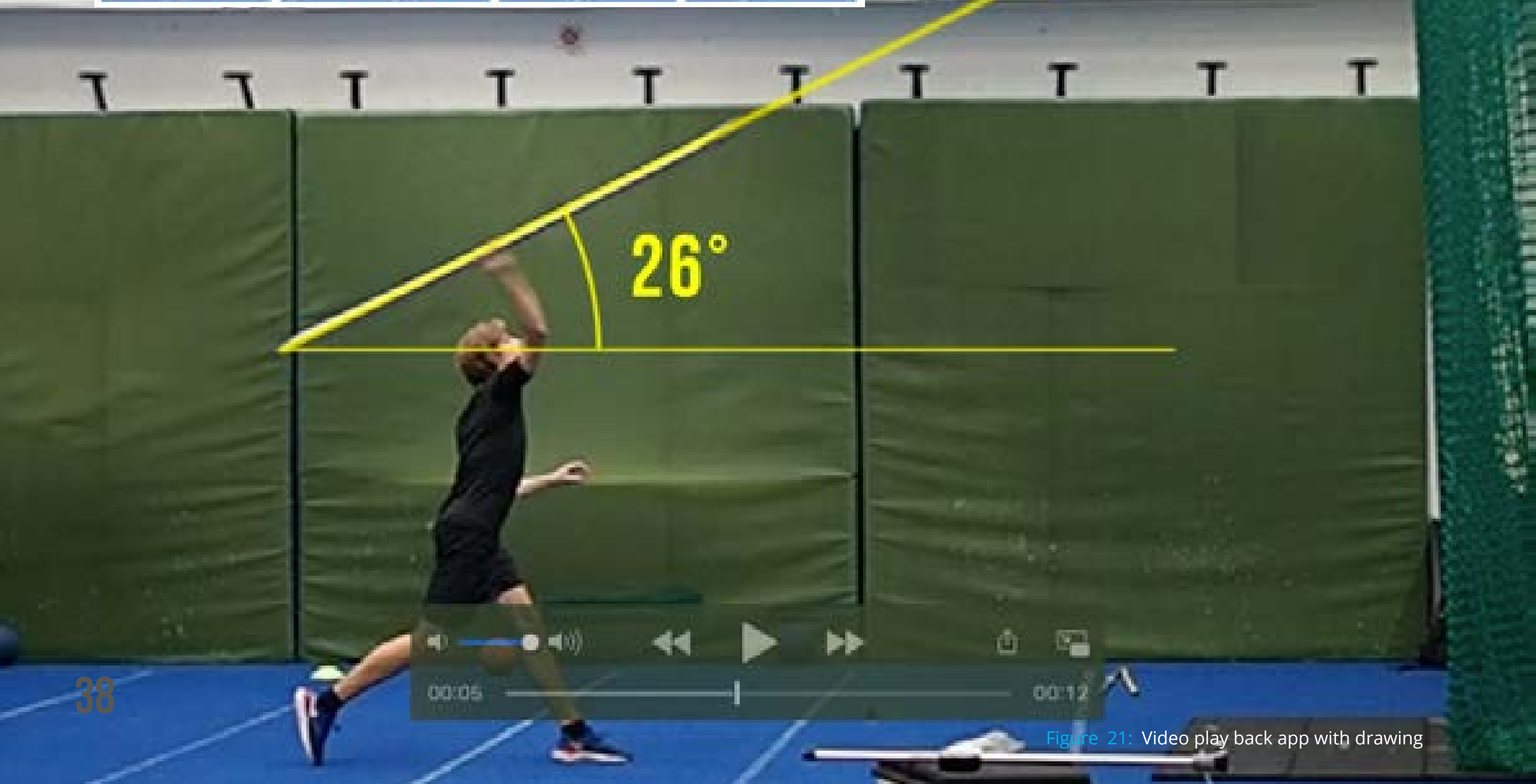


Figure 21: Video play back app with drawing

FlightScope Athletics

The FlightScope Athletics (Figure 22) is a device that can measure release speed, release angle, and release direction of a javelin. It uses a Doppler radar in combination with video software for flight analysis. The Doppler radar can measure the speed of an object at a distance by measuring the reflected microwave signal from the object and analyzing how the signal changed. Tracking a ball which has the same shape no matter what way it is rotated can be done quite well with a Doppler radar—tracking an object that changes shape when rotating like a javelin and vibrates after release is more difficult. That is why the FlightScope Athletics can only give the release speed, release angle, and release direction, where the list of measurements for the other throwing disciplines with the same product is more extensive. It also includes a final distance prediction. The biggest downside of the FlightScope Athletics is the price at €13 386. It is too expensive for most athletics clubs that only have a training material budget of around €1500 a year.

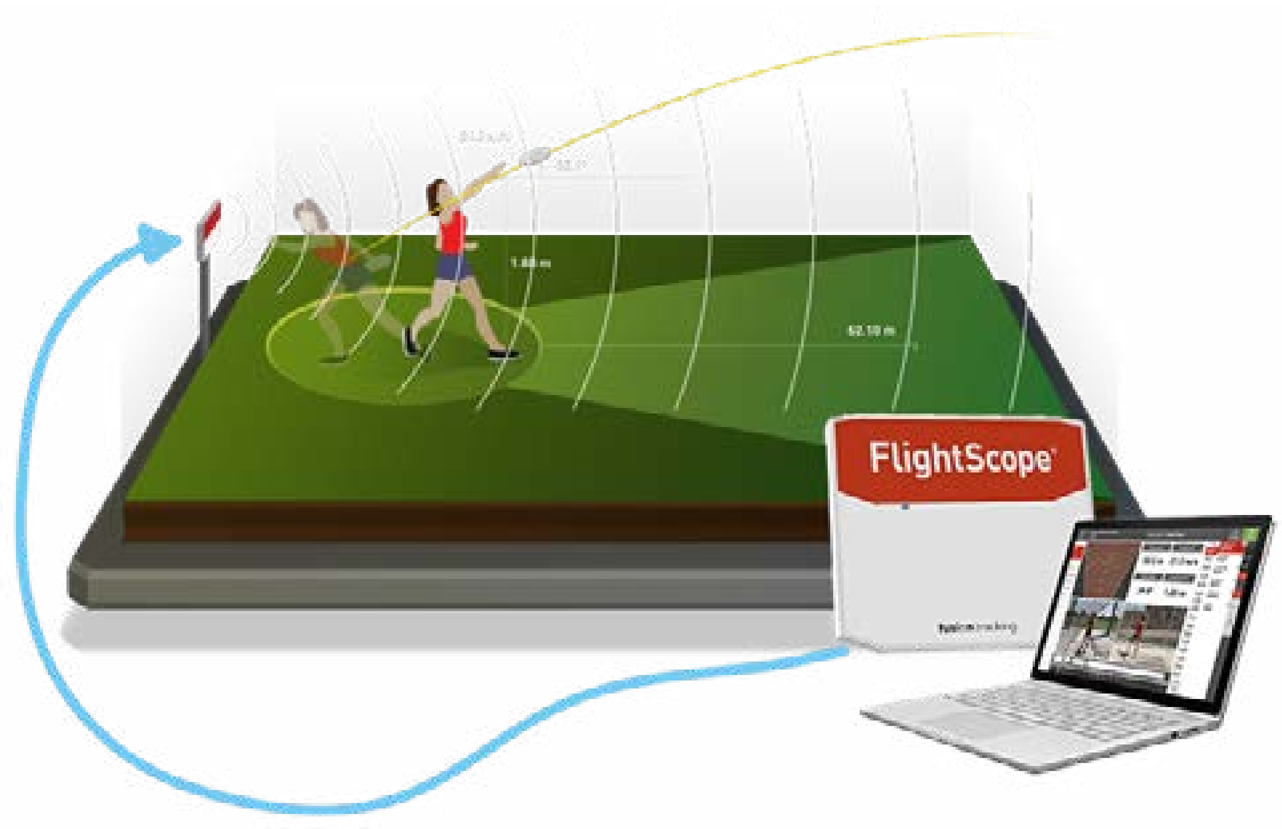
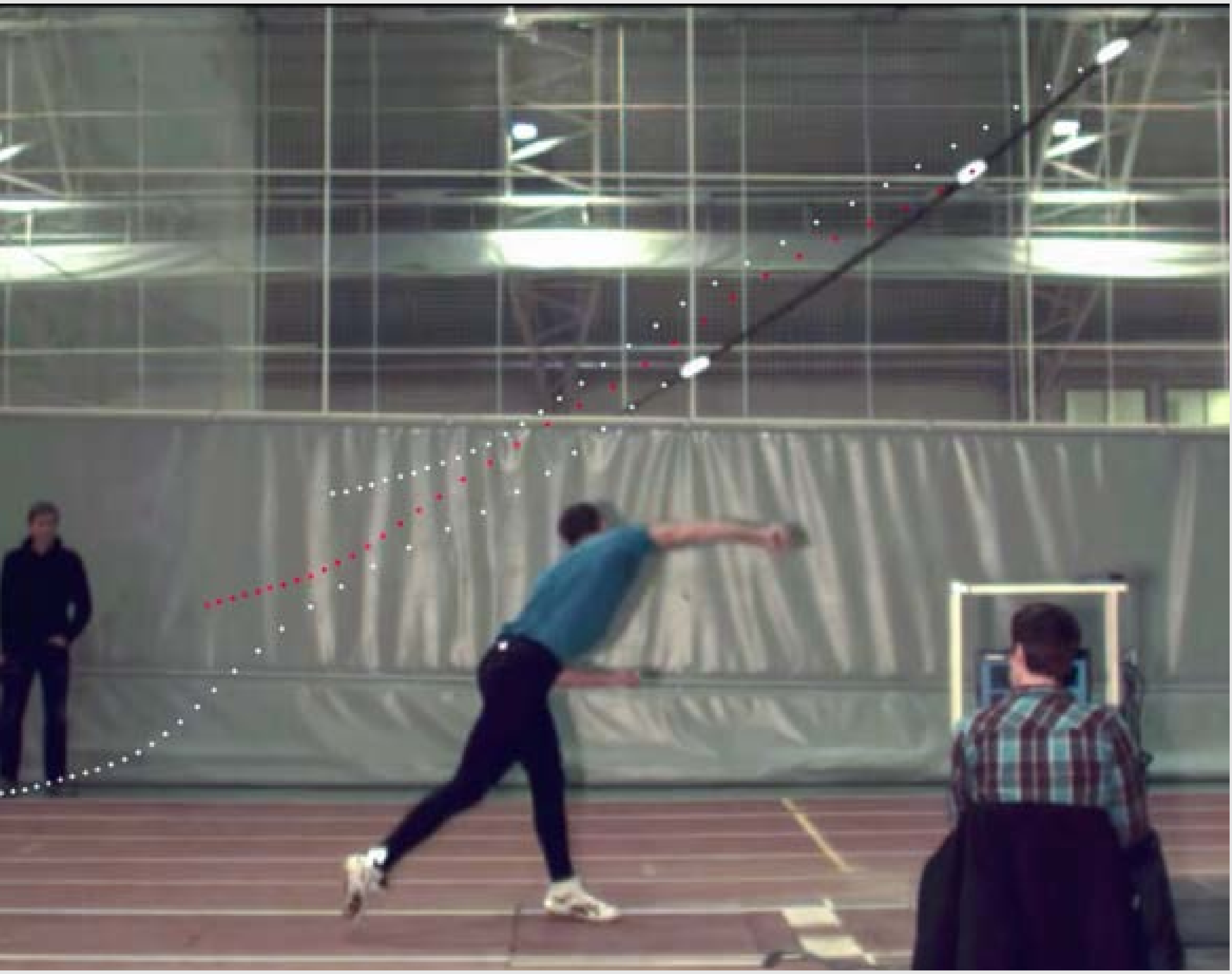


Figure 22: The FlightScope Athletics REF-26

Video motion capture

Motion capture is used in the movie industry as well as in sport science. High-speed cameras are used to capture the position of a body part or an object multiple times a second. Trackers are used for recognizing the position. These trackers can be LED lights or reflectors. Depending on the set-up, the position of the tracker needs to be mapped manually or is done by the software. A motion tracking set-up consists of between 2 and 48 cameras and requires a lot of set-up and processing. This makes video motion capture expensive and time-consuming. A two-camera set-up at OptiTrack will cost around €2000 and takes a while to set up with camera installation and calibration. The long set-up time makes it not suitable for a changing location where the set-up most be done each time. These cameras can reach an accuracy of 0.5 Mm in 3D space.



Takeaway

Currently, video playback is the most common analysis in javelin training. The other options available are expensive and time consuming to set-up. There is a need for a cheaper and easier alternative.

Figure 23: Video motion capture images of Tero Pitkämäki, an elite javelin thrower from Finland. Both side (left on page 40) and rear view (right on page 41)[REF-15]

3.2 DATA COLLECTION IN OTHER SPORTS

Data collection gained a lot in popularity over the years in other sports. In this paragraph, some examples of products that provide data collection in other sports will be explained. These products can give useful input that can be used in the design.

Flightscope Mevo

Just like the FlightScope Athletics, the FlightScope Mevo uses Doppler radar to track a golf ball. In the lower end, Mevo, video flight analytics, is left out to keep the cost low. With a price of around €500, this product is much more affordable than the FlightScope Athletics. FlightScope provides the possibility to connect an external camera to the Mevo so the golf player can see the swing in combination with the measured parameters. The Mevo is also very portable due to its small form factor, which can fit inside a pocket.

Figure 24: The Flightscope mevo and the app during a golf game[REF-26]

Adidas micoach smart ball

The Micoach smart ball is a football that provides the user with speed, rotation, and trajectory measurements. They do this with an IMU that is suspended in the middle of the ball (Figure 25), which is connected to a smartphone via Bluetooth. A video of the kick can also be saved together with the measurement data, just like the FlightScope Mevo.

This can also be a beneficial feature in the design of the data javelin to combine the video playback the coaches already use with the measurement that the product can provide.

Takeaway
In other sports, there are lower cost trackers that can track all types of balls. Most of them allow for video to be added to the recording.

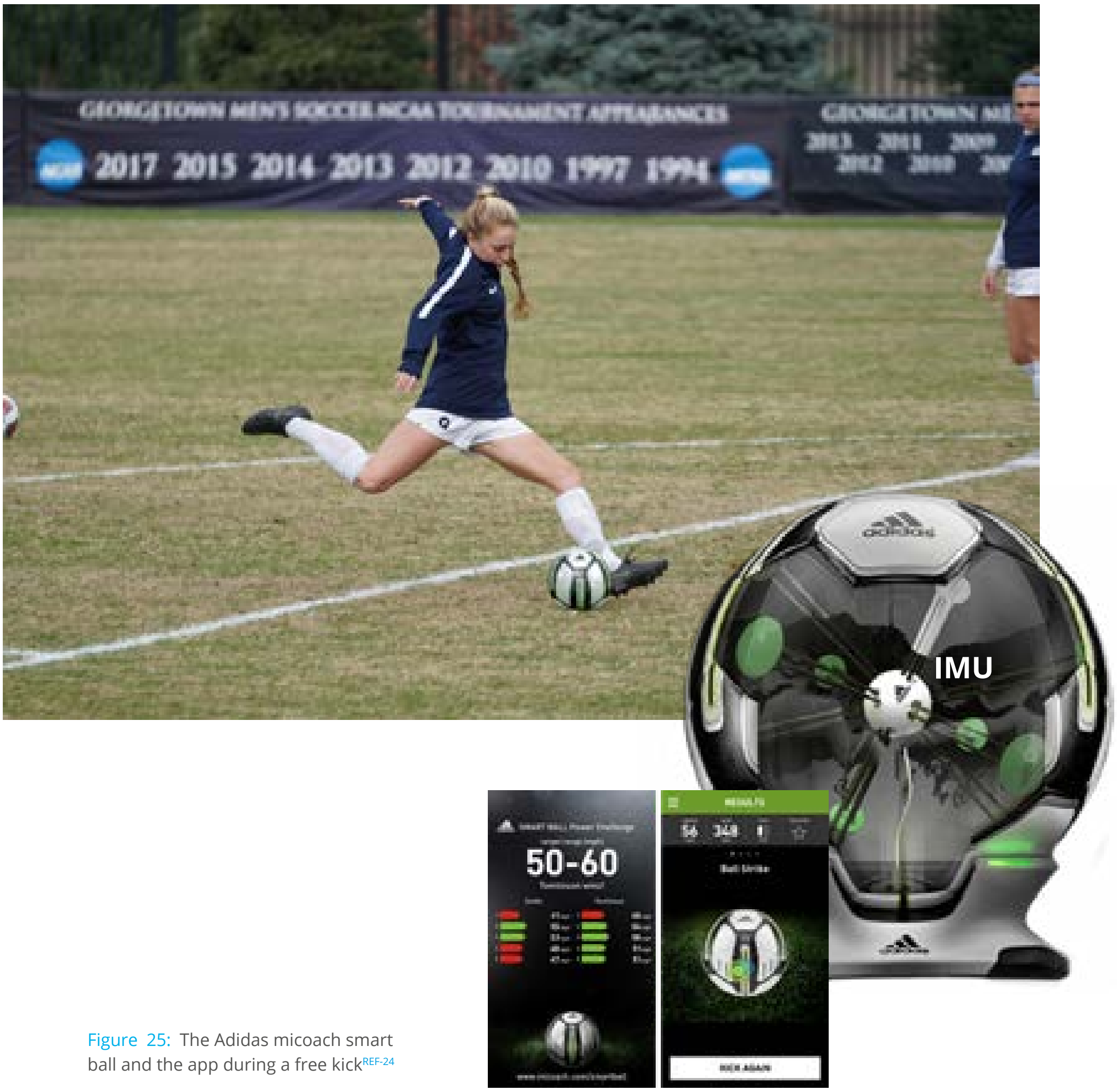


Figure 25: The Adidas micoach smart ball and the app during a free kick[REF-24]

3.3 3D MOTION TRACKING TECHNOLOGIES

In paragraph 2.6 , the release velocity, release angle, and angle of attack are named as the most important parameters to measure the performance of the athlete. In order to measure these parameters, the design should be tracked in 3D space. This paragraph lists the options for 3D object tracking technologies. Some technologies are found in the previous paragraphs, and some technologies are added after a technologies search online.

Doppler radar

Doppler radar is the technology used in flightScope products. According to their information, it is challenging to track a javelin due to its shape and the vibrations after release. The flightScope products are also 10 times the average annual material budget of an athletics club. A more affordable FlightScope Mevo kind of javelin tracker would have even more difficulties tracking a javelin.

Inertial measurement unit

Inertial measurement units measure the acceleration and ration in 3 directions. They can prove only relative changes, so they need a known position and orientation to work from.
They can reach very high refresh rates.

Ultra wide band positioning

Ultra wide band positioning is used a lot in warehouses. Here the refresh rate and accuracy demands are lower than for sport science measuring. Brendan found this technology not suited for his data discus. Since the speed of a javelin is slightly higher, it is most likely also not suited for the

Laser tracking

Laser tracking like Brendan Spiekerman uses in his Pithon data discus. Can reach and refresh rate of 120Hz and have an accuracy of 2mm, which is within the requirements. However, the system works best when mounted to a wall, which is not possible in rented training locations, and it also requires 5 sensors to be visible at every moment, which is very challenging while meeting the hardware requirements.

Video tracking

Video tracking set-up used in sport science is very accurate but comes with a high price and high set-up time. A lower end option with a stereo camera, for instance, would reduce both the price and set-up time but will lose on accuracy.

Sensor fusion

Sensor fusion refers to the use of multiple sensor inputs to produce a more accurate result; then, one of the sensors would do on its own. Sensor fusion is used a lot in VR gaming, for instance. Here an IMU is combined with a real-world reference system like the laser positioning or camera tracking to provide an accurate real-time 3D position of a controller or headset.

It seems that none of the technologies on its own can reach the sensor requirements. Fusing two sensors, as is done in VR headsets, seems to be the best option. For the outside reference system, camera tracking can give an added benefit of recording video of the throw that is measured. Since video playback is already used a lot by javelin coaches, it can have an added benefit in providing the coach and athlete with feedback. Combining the video playback with IMU data can reduce the noise of the camera system. This combination is already used by PlayStation VR, which can be a good inspiration.

Doppler radar (flightScope)

- \+ Low set-up time
- \+ Can use normal javelin
- \- Hard to track a javelin.
- \- Expensive
- \- Requires advance signal analysis

Laser tracking

- \+ Accurate to 2,4mm
- \+ Reliable data
- \- Requires at least 5 sensors to be visible at all times.
- \-

Inertial Measurement Unit (MiCoach Smart Ball)

- \+ Could make stand alone device
- \+ Small and light
- \- Drifts over time
- \- Needs to start from stand still to know the speed

(Stereo camera) Video tracking

- \+ Low set-up time compared to full sports science set-up
- \+ Minimal modification to javelin
- \- Noisy signal

Ultra wide band positioning

- \+ Only a small beacon needed to track
- \- Does not meet refresh rate requirements
- \- 10 cm accuracy is to low.

Takeaway

None of the technologies can reach the sensor requirements on its own. Due to the added benefit of video playback video tracking combined with and IMU seems to be the best option.

3.4 DESIGN BRIEF

After the information gathered in the javelin throwing context and the sports data collection chapters, the context for the project has become a lot clearer. With this new information, the initial assignment is revisited, and combined with the new information; a design brief is formed.

Goal

The initial goal of the project was to give the athlete and coach feedback of the performance of the throw. The most contributing factors for the performance are found the be release velocity, release angle, and angle of attack in paragraph 2.6 . So this goal can be narrowed down to Design a product that can provide a javelin coach and its athletes with release velocity, release angle, and angle of attack measurements when training indoors. The solution must be low-cost and provide meaningful information to users.

Target group

The target group, as mentioned in paragraph 2.2 , are intermediate to elite level male throws and their coaches.

Scope

The product will only be designed for indoor javelin throwing. The indoor training location where the design is going to be used should already allow indoor javelins to be thrown in either a net or a piece of fabric. The product will only be designed for adult male throwers to make the design process more manageable. Different weight variants can be designed later.

Time frame

At the end of the 100 days of this graduation product, there should be some kind of solution to lack of feedback javelin throwing indoors.

Johannes Vetter -
Men’s Javelin Throw
diamond league -
Paris 2017

4

DEVELOPMENT

During the concept phase, the development of the data javelin is split into two directions. First, there is the electronics development. Here the system that allows the javelin to be tracked in 3D space is developed. In the analysis phase, the choice is made for an IMU with an external reference system, which needs to be developed further. These systems are developed separately and are later combined; Second, there is the physical product that needs to take shape. The shape is partly influenced by the requirements set in the previous chapter, but it is also influenced by the sensor that needs to fit in the product and the interaction with the system.

Glenn Morris-USA during the 1936 Olympics in Berlin[REF-53]

4.1 INERTIAL MEASUREMENT SYSTEM

The eventual goal of the development of the inertial measurement system is to provide a wireless system that can read acceleration and orientation values. This is done iteratively. This development is explained in this paragraph, and the release speed angles are calculated with this method.

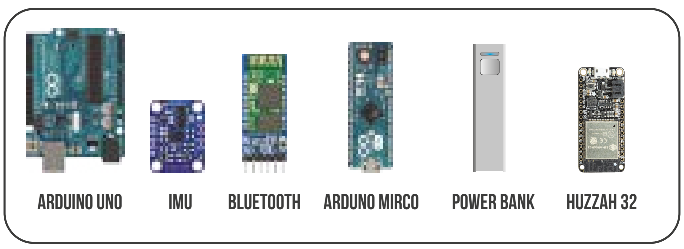
To make an inertial measurement unit (IMU) system. You need a microprocessor, an IMU (inertial measurement unit), and a power source. Making this system wireless and suited for the design of a data javelin requires an external power source and components that can fit inside a 30 mm tube.

The best way for me to develop an IMU system is by using an Arduino. The microprocessors are easy to program. There is a lot of information about them and are ideal for connecting and testing different sensors.

Before starting this project, I had no experience working with IMU's, so I had to start for the beginning. Figure 26 shows the configuration of the step in the process. Each step is now shortly explained.

The first step is to select an IMU to learn how they are used. After some searching online and talking to people that used IMU's before I settled on the BNO055 IMU from Adafruit, this chip is easy to use for beginners due to its internal sensor fusion providing more reliable data without complicated algorithms. This IMU has a refresh rate if 100 Hz, which enough to record a javelin throw (ER-5). Online instructions helped me a lot in getting to know the BNO055 IMU. The most important finding so far is that the IMU needs to be calibrated to give accurate readings. The calibration is done by holding it up with each axis as shown in figure XXX

The second step is a small one. In this step, a much smaller Arduino is used that is able to fit inside a 30 mm tube. Connection the BNO055 to a new Arduino means that some of the drives do not work correctly, but after fixing that, the smaller Arduino is able to receive data for the IMU again.



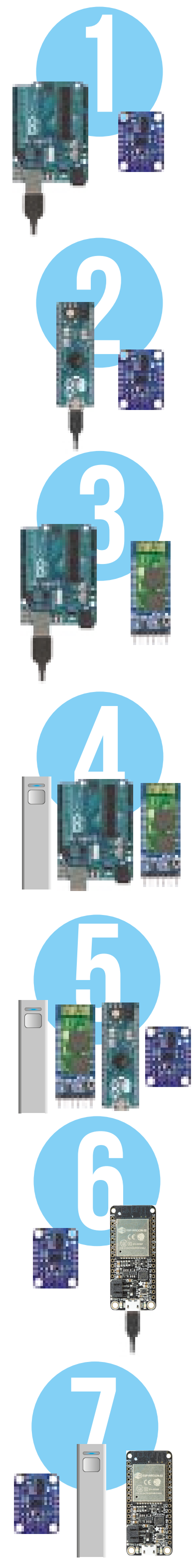


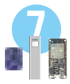
Figure 26: IMU system development step by step

The third step is taken towards making the system wireless. Achieving wireless communication is done by connecting an HC-06 Bluetooth chip to an Arduino UNO and using it to send a simple message from the Arduino to my computer over Bluetooth.

Making the system even more wireless is done by using a power bank to provide an external power source. The Arduino is now able to send information to the computer without being connected by a wire.

Step five is the first time the whole system comes together. When adding the IMU to the wireless Bluetooth set-up, the Arduino can send the information gathered by the IMU over Bluetooth to the computer instead of just a simple message.

Reducing the number of parts in the system will make the final prototype easier to integrate into the rest of the javelin. Therefore the electronics expert (Wolf) suggested using the HUZZAH32, which is an Arduino like product with an integrated Bluetooth and WI-FI chip. Using this chip allows getting rid of the separate HC-06 Bluetooth chip, making for a more integrated system. The HAZZAH32 is first tested with a wired connection without the use of Bluetooth and later with the Bluetooth while still relying on the power from the wire.



The last step in making a testable prototype is connecting the battery. Previously this is done by plugging in a micro USB cable in the micro USB port, but this connection proved to be not stable enough. Instead, the power bank is stripped of its casing with also gets rid of some unnecessary weight and wiring a male connector to the pins where the USB port was. The female connector is wired to the HAZZAH32 to make the connection complete.

Some findings while working with and learn about an IMU.

- There is some noise in the signal even when it is entirely still, which needs to be filtered to have more accurate readings.
- It is better to use quaternion coordinates, which is a different kind of coordinate system with 4 values instead of the traditional XYZ axis, for the rotations of the IMU. Quaternions will eliminate some problems with sensor reading of the angle. However, the concept of the quaternions is challenging to understand and goes beyond the scope of this project due to limited time.
- The drift that is mentioned of an IMU is hard to see without knowing the state is should be in, so it is better to test that when combining the IMU with the visual tracking later.

Figure 27: Arduino, IMU and battery inside a case 3d printed housing

Getting release speed, release angle, and angle of attack reading from the accelerometer and the gyroscope request the sensor readings to be recorded.

In this prototype, this is done by a program called CoolTerm, which is a terminal that can read the data sent by the Arduino just like the serial monitor but is also able to record the data to a text file that can be uploaded to Matlab to perform the calculations.

The acceleration is multiplied with the duration of the reading (1/67s) to get the speed reading and added to the current speed. This results in the plot shown in Figure 28.

The moment of release is the point where the speed increase becomes steady after the throwing impulse. This is because the prototype is thrown downwards. If thrown upwards, the velocity would slowly decrease after the moment of release. The speed at the moment of release of this throw is 5,99m/s, according to the imu data.

The moment of the release, the angle of the prototype with the horizontal plan is -25,7 degrees according to the gyroscope.

The release angle of the prototype can be calculated by calculating the direction of the velocity vector. However, this value is not very accurate, so it is better to rely on visual tracking for the release angle.

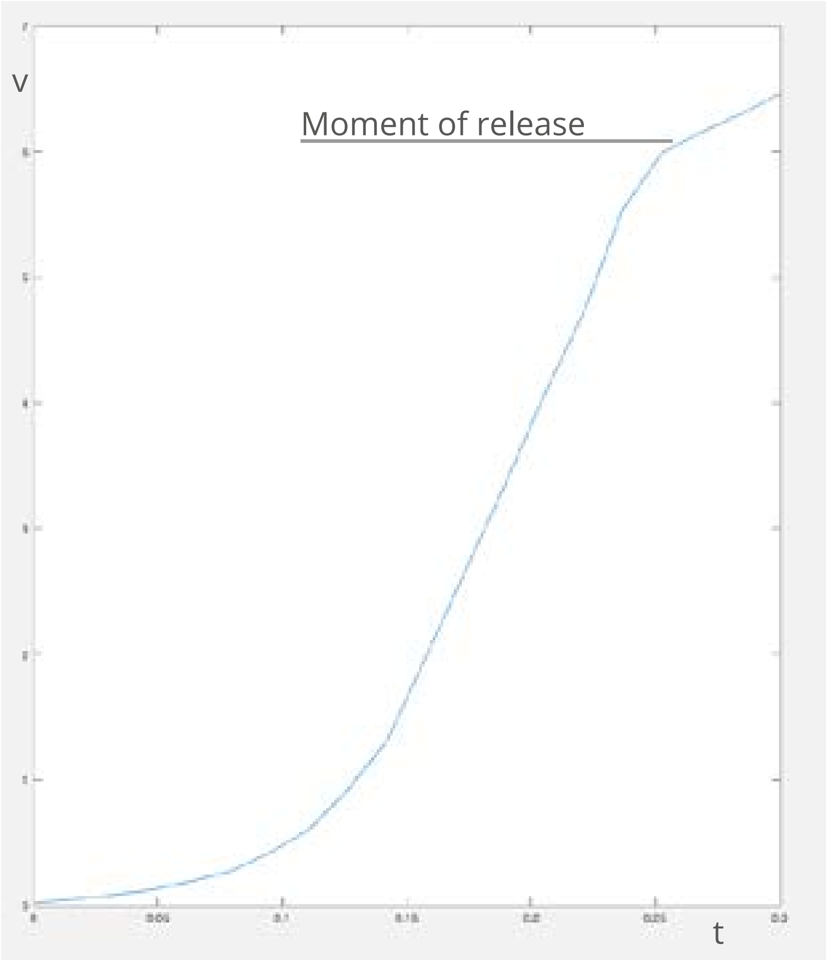


Figure 28: Velocity vs time of the IMU readings

4.2 VISUAL TRACKING SYSTEM

In this paragraph, the development of the visual tracking system is explained. Then the release velocity, release angle, and angle of attack are calculated with this method.

Many visual tracking programs can track an object in a video. For this project, I chose to build a Matlab script, which provides more freedom in the tracking possibilities and can make calculations within the same application.

The basic principle of the script is that it divides each frame of a video to loose images. For each image, the script can see the hue, saturation, and lightness values of each pixel. Together these values describe the color of the pixel. Threshold values can be set for each of the values, to select only a specified color. If a cluster of pixels falls within the threshold values for both hue, saturation, and lightness, the script will recognize this area. If the area is above a specified size, the script will record the location of the center point of the area.

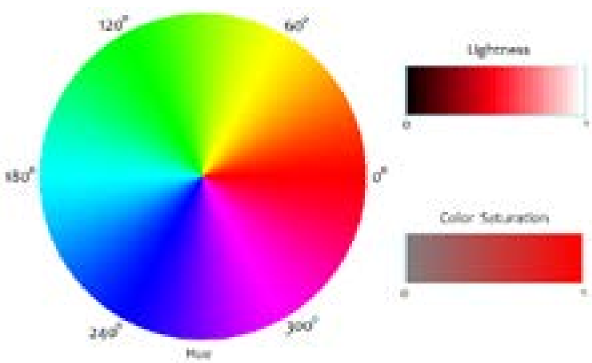


Figure 29: Hue, saturation and lightness color values

My Matlab code started with the code provide by Matlab user image analyst, which can track the green cap of a pen. First, I made a video of a small tube with two pieces of red tap against a clean background to test the script. Figure 30 and Figure 31 are the results of the first tracking test.

The camera needs to be calibrated to use a video for video tracking. The calibration achieves a truly flat image. More details on video calibration can be found in Appendix A.9

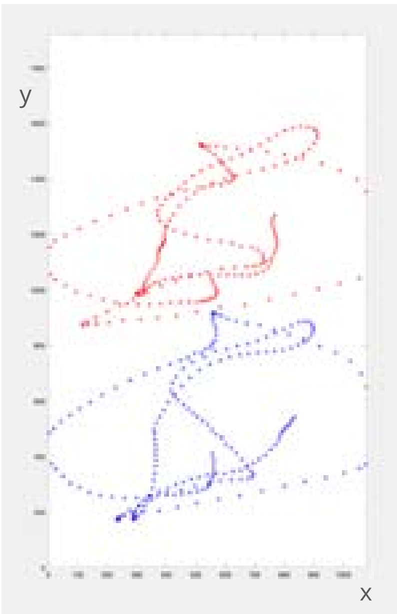


Figure 30: Plot of the locations of the red markers. red is the top marker and blue the bottom marker

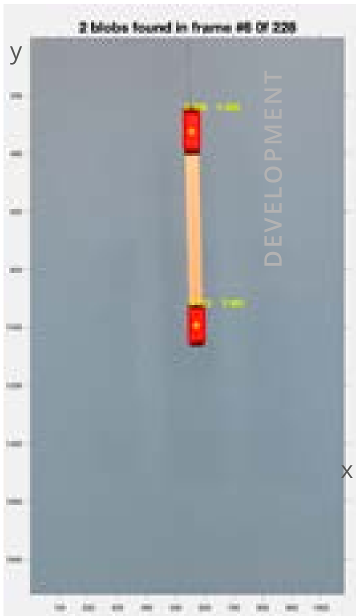


Figure 31: Frame from first tracking video

Next, the same thing is done for another video where the tracked object is thrown. In this video, another problem accord. Since the threshold values for the orange markers are close to the color of my face in this light. The script had difficulties tracking only the markers. This shows the problem with using colored markers. They only work when there is nothing of the same color within the same frame. In the case of the data javelin with red markers, the athletes can not wear any red clothing or have anything else red laying around.

The solution to this problem is well known within the video tracking industry. Using reflective markers or active markers that emit light on their own) can be used to create a color value in the frame that is not found normally. For the data javelin, the best option would be to use active markers since there is already a power source inside of it. Adding reflective markers would mean that additional lights need to be added to give the reflectors something to reflect, adding unnecessary steps to the set-up process of the system.

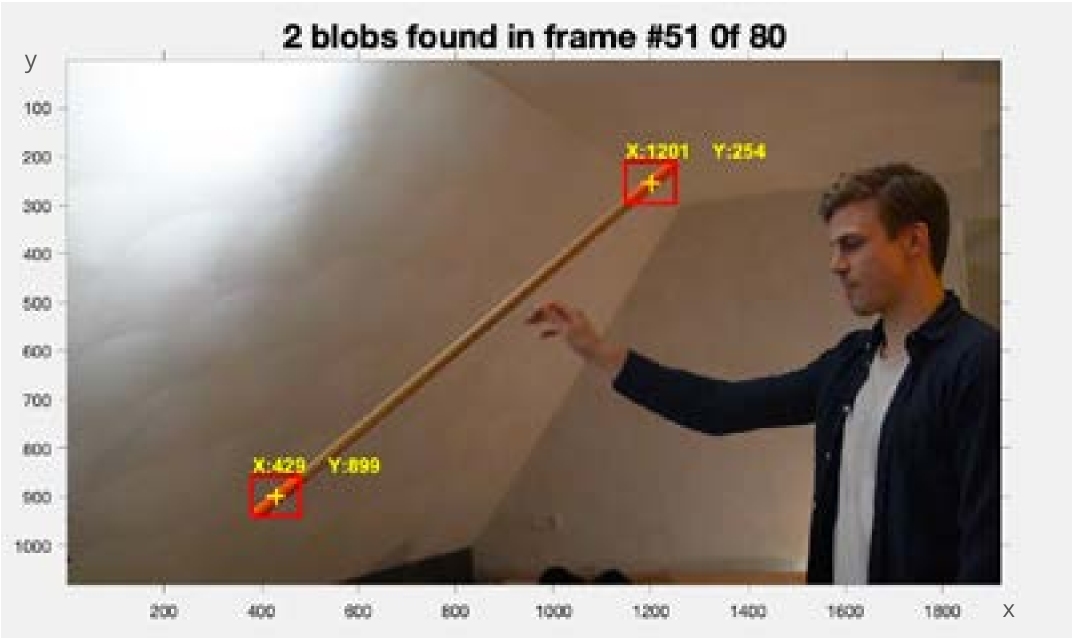


Figure 32: Frame from the second tracking video of a stick with two markers.

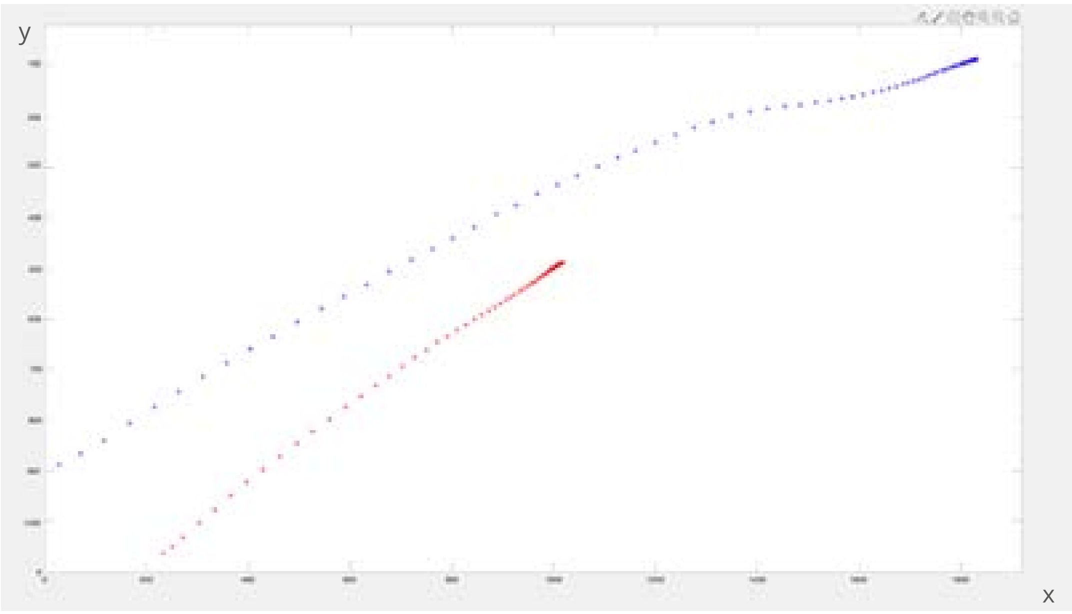


Figure 33: Plot of the locations of the orange markers s. red is the front marker and blue the back marker

A new prototype is made to test out the use of active markers (Figure 3). Figure 4 shows a frame from the video that is used to track the active markers. Since the markers emit their own light, they are easy to recognize in the frame by the script.

Speed calculation

With the positions of both markers recorded. The release speed, release angle, and angle of attack need to be calculated. The first step is to find the location of the center of mass. The center of mass sits in between the two markers since the prototype from Figure 34 is equally distributed. This gives the following result shown in Figure 36 where the green dots are the location of the center of mass. The release speed mentioned in the requirement refers to the speed of the center of mass during the release.

The moment of release is also necessary for finding the release angles and release speed. In a standard throw, this would be the highest speed recorded since the javelin in throw upwards and is not accelerated by the athlete anymore, but since this throw is downwards, the prototype is still accelerated by the gravitational acceleration. In this test, the moment of release is the point were the speed shifts a rapid increase to a slow increase as shown in Figure 37.

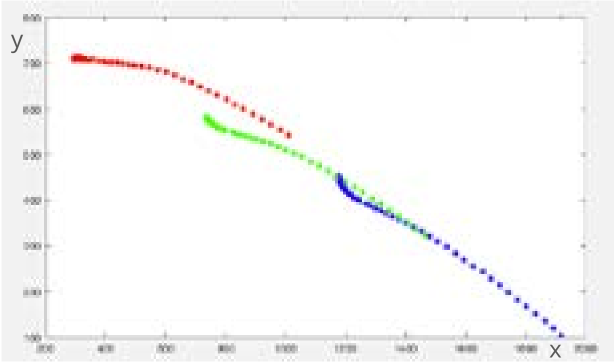


Figure 36: A plot of the marker location of the video shown in Figure 35. red is the back marker, blue is the from marker and green the location of the center of mass.

To calculate the release speed, two values are needed. First, we need to know the frame rate of the video. In this case, it was 180 frames per second (FPS). So each frame is 1/180 seconds long. Second, the size of one pixel needs to be calculated. This can be done by measuring the distance between the two markers in reality and measuring the pixel distance in the frame. Dividing one by the other gives the real-life size of one pixel in the frame (pixel scale).

Figure 34: Prototype with active markers

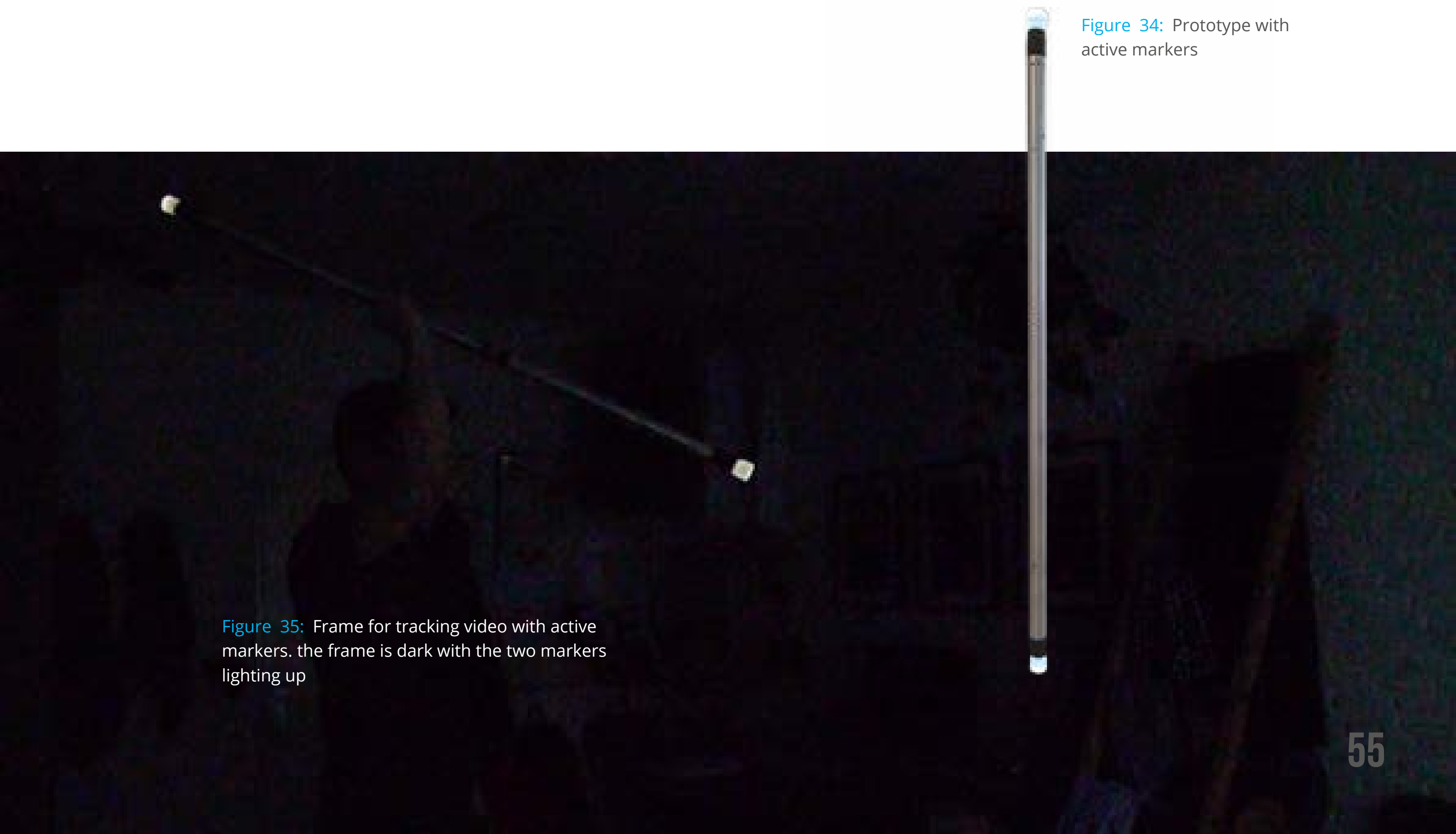


Figure 35: Frame for tracking video with active markers. the frame is dark with the two markers lighting up

The release speed can now be calculated by taking the pixel distance the center of mass moved from the current frame to the previous frame and multiplying that by the pixel scale. Doing that gives to following speed plot found in Figure 6. The speed at the moment of release is 6,32m/s according to the video tracking data.

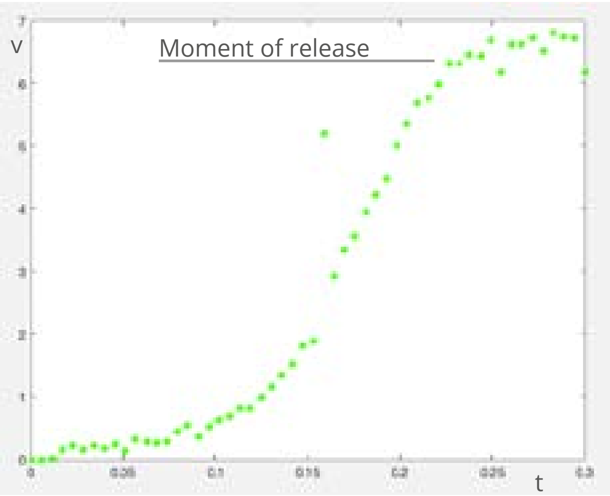


Figure 37: Velocity vs time plot of the center of mass

The speed data is a bit noisy and has a weird data point around 0,15s, but it gives an idea of how the speed of the prototype evolves. To achieve better data, the output needs to be filtered. Due to time constraints and the difficulty of proper data filtering, the method used is curve fitting with is part of the toolbox of Matlab. A polynomial is used to fit the curve from Figure 37 the best. the result is found in Figure 38.

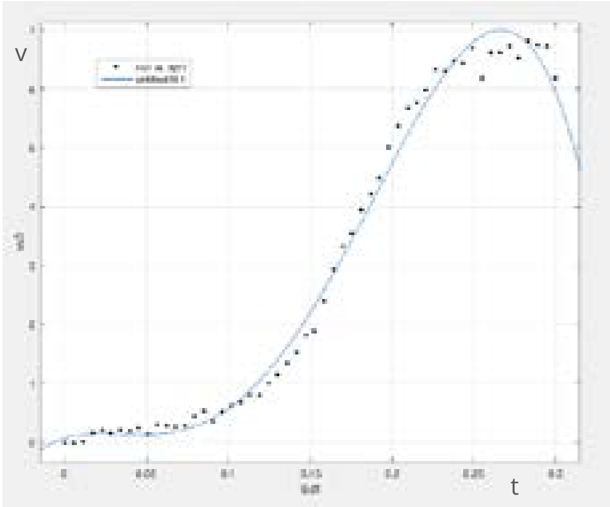


Figure 38: 4th degree polynomial curve fit of speed data

Angle calculations

To calculated the release angle, the angle between the current location of the center of gravity and the previous location of the center of gravity is calculated with a simple Pythagoras equation. The average angle between the 4 frames after the release is taken since the data is noisy.

To calculated the angle of attack, the angle between the front and back markers is calculated with the Pythagoras question again. This forms the angle with the horizontal plane. When subtracting the release angle, the angle of attack is found.

For the active tracker video, these calculations result in a release angle of -21.51 and an angle of attack of -1.49

4.3 SENSOR FUSION

Sensor fusion can be very beneficial to improve the data from the two sensors. The data for an IMU is known to be prone to drift while it is better at measuring the moment of release. The data from the visual tracking system is noisy, but it will always have to same noise no matter how long the recording takes. It also does not need to know the starting speed to calculate the current speed, something the IMU does need. Combining the two would be ideal for achieving the best accuracy.

After some reading, online a Kalman filter seems to be a good option. This filter would use the IMU data to follow its smooth speed curve while checking each time the visual tracking data comes in if the IMU reading has drifted. The filter would move the IMU data towards the readings from the visual system.

Unfortunately, due to the time it took to learn and build the two tracking systems, there was not enough time left to learn how to use a Kalman filter and use it with the collected data.

The best option is to use a curve fit on the visual tracking data to make it less noisy and use the IMU data to detect the moment of release (the moment where there is no more acceleration of the javelin in a standard throw). This approach gives a release speed of 6,61m/s, which can be seen in Figure 39. The previously named noise in the visual tracking and the drift of the IMU are visible in this figure.

When comparing the two systems to each other, they need to be synchronized. While testing, this is done, letting the prototype free fall for a second and catching it again. The catching moment is then used to align the data.

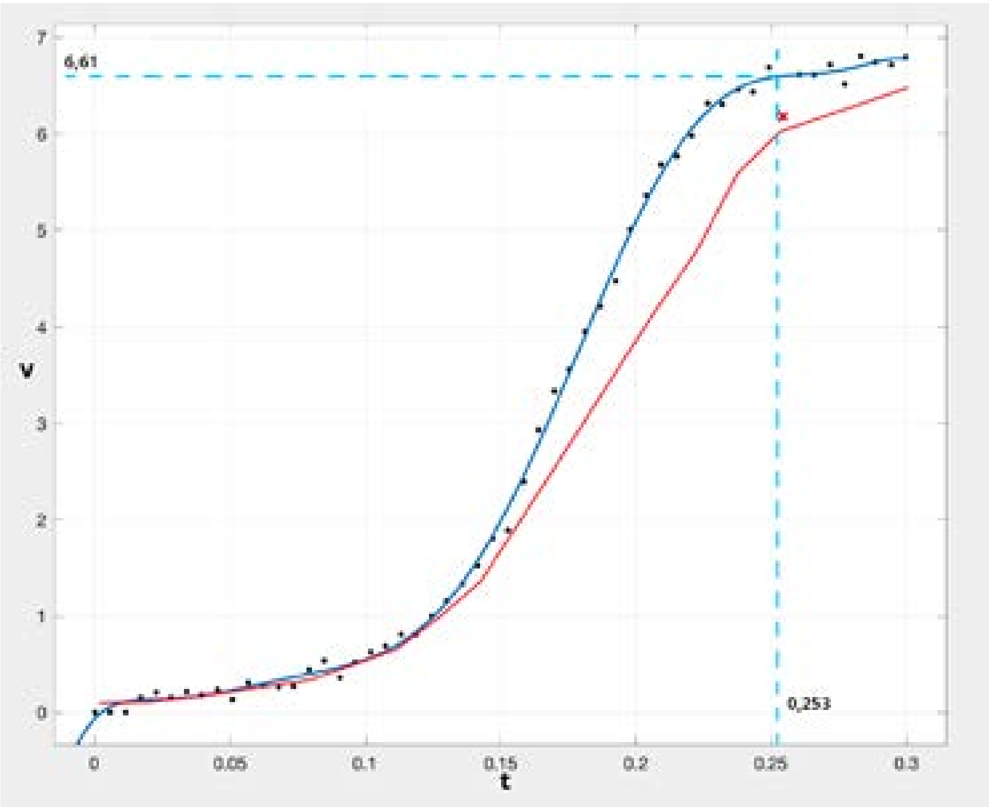


Figure 39: Velocity vs time plot. black dots are the visual tracking data points, the blue line is the curve fit to the data points. the red line is the imu velocity data.

5

PRODUCT

This chapter is going to take a closer look at how the speed and angles of the javelin can be measured. First, the current data collection for javelin throwing will be listed and explained why they are not sufficient enough. Then products in other sports that fulfill the same function are listed. Finally, the technology options for the data javelin are summarized.

Swedish javelin thrower Karl Åke Nilsson in 1968

Figure 40: Andreas Hoffman (1,95m) holding the prodon

5.1 PRODON: PRODUCT OVERVIEW

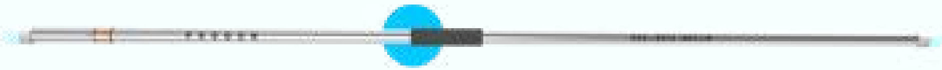
The Prodon is the first lower end javelin measuring tool. It provides athletes and coaches with valuable information about the release speed, release angle, and angle of attack of each throw and keeps track of their progress. The name PRODON comes from the Greek words **pró**vlepsi en **dón**isi, which means to forecast and javelin.

A stereo video of each throw is recorded to allow the PRODON to be tracked and provide the coaches with a playback of the throw in slow-motion so they can link the technique with the throwing performance.

The feel of the PRODON closely resembles the feel of a competition javelin, creating a smooth transition from indoor to outdoor javelin throwing.

Figure 42: Intel D435 Stereo camera

Figure 41: The prodon prototype



Shaft

The shaft of the PRODON is made from a standard 30mm round tube with a wall thickness of 1 mm. This is the same wall outer dimensions as a standard aluminum javelin. The tube stays the same size over the full length of the javelin in contrast to a standard javelin, which has tapered ends. This allows the PRODON to be made from a single piece of standard aluminum tubing while leaving space for the electronics to be housed. The tube is anodized to provide scratch resistants. Using a standard size of tubing that fits the needed dimensions keeps the cost for the shaft down.

Aluminum has been used in javelin manufacturing for a while in both indoor and outdoor javelins. This shows that the material is suitable to use for the PRODON.

The length of the shaft is dictated by the requirements found in 2.8 Requirements and wishes. The center of mass should be at least 900mm from the tip while the weight should be between 800-850 gr HR-4. The mass moment of inertia should also be close to that of a standard javelin. To meet all these requirements, the length of the shaft came out at 1.90m. A more in-depth explanation of the weight distribution can be found in paragraph 5.4

With a length of 1.90m, tho PRODON is also easier to transport than a standard javelin of 2.60m. It can lay flat inside a station wagon without having to poke almost through the windshield or having to be transported on the roof of the car. It also becomes more accessible to maneuver through doors and narrow hallways on the way to the indoor training location. The argumentation for te 2m shaft can be found in Appendix A.10

Grip cord

The achieve the same javelin feel as a normal javelin the grip cord is made from the same material as the grip cord on a standard javelin. The cord thickness of 3mm and grip length of 150mm are identical to what the athlete is used to. This creates a familiar feeling making it feel as if the athlete is holding a standard javelin.(HR-1)

Figure 43: Render of the grip cord

Rubber tip

The tips of the PRODON have two functions. First, the tip is the part that receives all the impact, so it needs to protect the PRODON and the indoor training location from damage. In the front, when the PRODON might accidentally hit a solid object and needs to reduce the impact on the shaft and electronics. Or when it falls from the net and lands on its back. The exposed part of the rubber tip can be squeezed in as sown in Figure 44
Second, the rubber tip acts as a light diffuser for the LED's that are inside of the shaft. Without the rubber tips, the light would not be visible from the side but shine straight out of the front and back.

The material that fits both functions is a SHORE A40 translucent silicon rubber. SHORE A40 means that it has the consistency of a pencil eraser. It can be squeezed in during impact but keeps its shape when that is not the case. A translucent silicone diffuses the light throughout the material, letting the material itself glow when light passes through it. The glowing tips are used to tracking the movements of the PRODON.
The rubber tips are held in place by friction, which is more than enough to keep them from moving during use while being able to remove them to turn on the device or access the micro USB port for charging.

Figure 44: The rubber tip in normal situation on the left and during impact on the right.

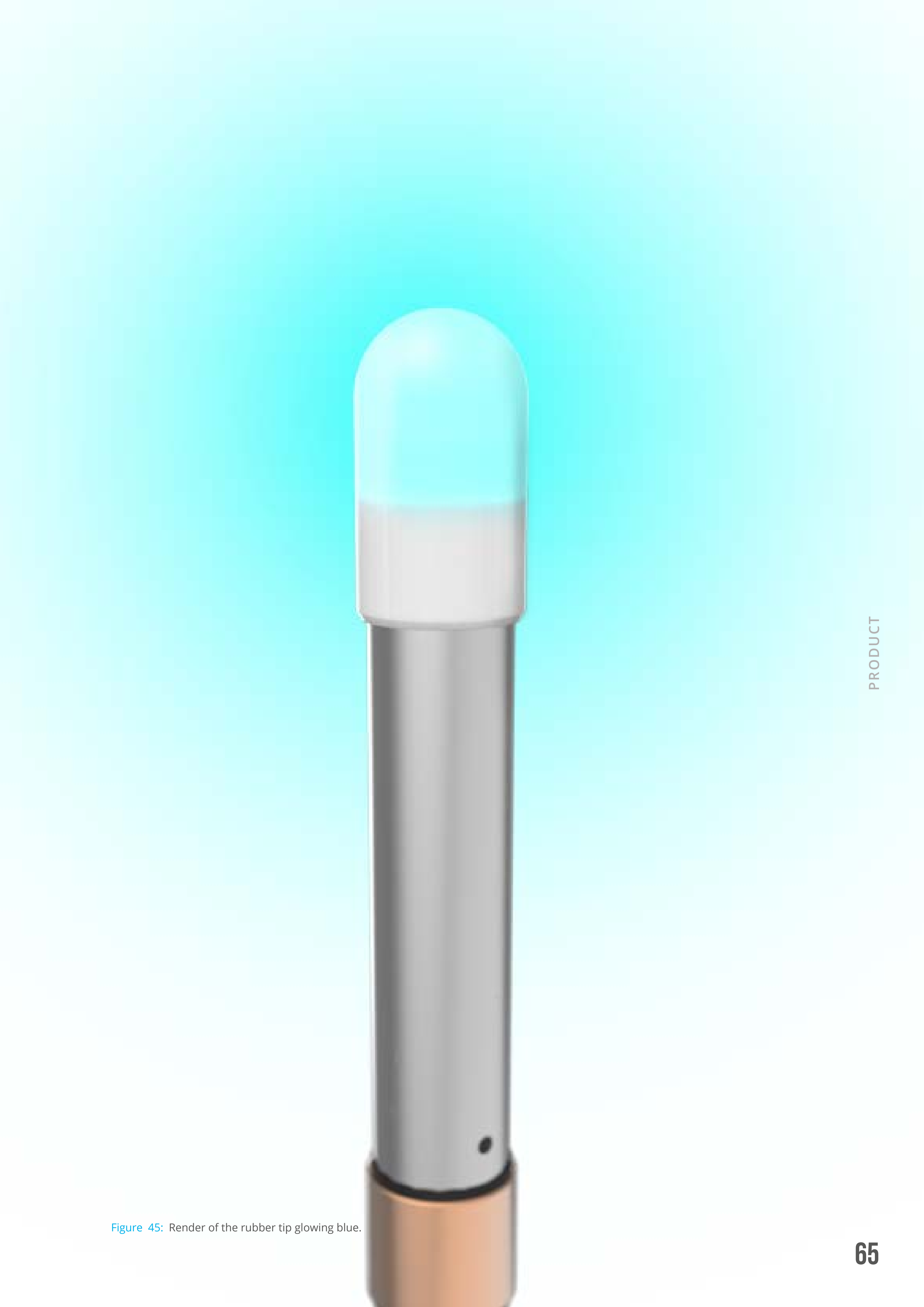
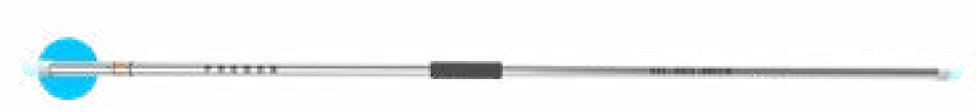


Figure 45: Render of the rubber tip glowing blue.



Sensor probe

The sensor probe is the brain of the PRODON. Here most of the electronics housed. A custom PCB is fitted with a microprocessor, Bluetooth module, and an IMU to enable the javelin to capture the accelerations and rotations. The data is collected and transferred wireless by the Bluetooth module to the connected device.

Housing

The housing of the sensor probe consists of two parts. The main body is made of injection-molded ABS, which has excellent impact-resistant properties. The aluminum shaft protects it, so it will not be impacted directly. The snap-fit on the button keeps the probe in place. If needed, the probe can be taken out to perform a repair. The Battery is held in with a battery cover, and the custom PCB is incapacitated in epoxy resin to prevent the components from shock damage.

The second part of the housing is the impact cap. This aluminum end cap extruded out of the shaft so it is more exposed to semi direct impact. The 3mm sides of the rubber tip is the only thing protecting this part of the housing.

Battery

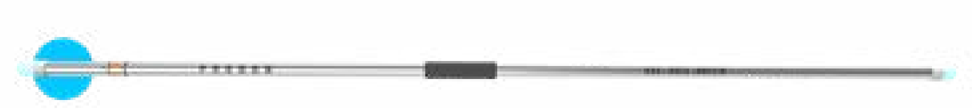
The battery cell is a 18650 lithium-ion cell. This type of battery is used a lot and tested a lot, so it is a reliable energy source. It has a capacity of 3500 mAh, which can power the system for 10 hours. The battery is charged via a micro UBS port located underneath the back rubber tip.

Communication

The Bluetooth chip on the custom PCB is responsible for the communication with a smartphone or tablet. Inside the aluminum shaft, the range of the signal is around 13 meters.

Figure 46: The back end of the PRODON without the rubber tip

Figure 47: An exploded view render of the sensor probe.



Back button

It usually is not possible to reach the back button because it is protected by the rubber tip and inside the shaft. Since it only needs to be used at the beginning and of the training, it is covered up during the training to prevent accidental activation or impact.

The PRODON is turn on by holding the button for 3 seconds. Upon activation, the LED lights will turn green and show the battery status. For every 1/8 of the battery capacity, one of the eight LEDs will go on one by one in a clockwise motion.

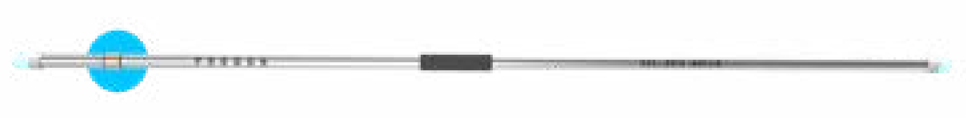
To turn on the Bluetooth, hold the button for 1 second until the lights start flashing blue.

Turn the PRODON off again is the same as turning it on. Just hold for 3 seconds. The Lights will again show the battery status in a reverse animation. So the amount of energy left, turning out one by one counterclockwise.

LED ring

The 26 mm LED ring in the front and back is fitted with 8 RGB LEDs. They are used both for communication to the athlete like explained in the part on the left as well as to provide an active marker for the stereo camera to track.

Figure 48: A render of the back of the PRODON



Capacitive touch ring

The athlete touches the ring whenever he wants to start a throw. When the ring is touched, a difference in capacity is measured, which lets the system know a throw is being initiated.

The ring is located at the back of the PRODON. This location keeps the mass far from the center, which is needed to get the right mass moment of inertia. The ring is connected at the bottom to the sensor probe that analyses the signal. In the resting position with the front of the PRODON on the ground, the ring can be easily reached.

The ring is made from brass, which is an excellent conductor. The color of the brass stands out from the rest of the aluminum tube, making it easy the locate. The brass ring is isolated with the use of shrink wrap, to prevent making the whole javelin into one big capacitive touch tube.

Separating the back button and touch ring keeps the throw initiation with the touch ring as simple as possible.

Figure 49: Overview drawing of the inside of the prodon

Figure 50: A render of the capacitive touche ring and the led ring

5.2 JAVELIN TRACKING

The Prodon uses a combined tracking system of an internal measurement unit and video motion tracking. The data from both systems are combined to fill in the disadvantages of the inertial measurement unit and video tracking on its own. Combined, they are making for more accurate and reliable tracking.

A BNO080 IMU is housed inside the sensor probe at the back of the javelin. It is providing the system with information about the rotation and acceleration of the prodon. Since an inertial measurement unit is only able the proved information about changes in acceleration, it needs the information of the camera system to know its orientation and rotation. Upon activation, the inertial measurement unit needs to be calibrated. During the throw, the IMU will measure with 500Hz. The data is sorted before it is sent over Bluetooth, the monitoring device. This way, there is no bottleneck in sending the data in real-time.

For the video motion tracking, a stereo camera is used that captures the position of two active markers placed on the front and the back of the prodon. Having two lenses enables the camera to create a 3D image of the position of the markers, proving more accurate tracking then one camera can. The Intel D435 stereo camera (Figure 51) has a frame rate of 90 FPS.

The camera is placed on a tripod perpendicular to the release location around five meters away. It is connected to a tablet or smartphone via a USB-c cable. The device can be held on the tripod with a tablet or smartphone stand. The setup can be seen in Figure 52

The two systems are synced with each other when the throw is initiated. The athlete starts the throw by pushing the brass ring. When the device is set to zero, the video starts recording although the athlete might be at the end of the approach out of sight, the camera will know how long the system has been running for.

Figure 51: Intel D435 Stereo camera

Figure 52: Illustrating the camera setup tracking during the throw

PRODUCT

5.3 PRODON APP

This paragraph will go over the functions the app of the PRODON has to offer.

The prodon app allows the athlete and coaches to playback the video of the record throw and lets them see the measured parameters at the same time. The app is the place where the two tracking systems come together and are processed to get a more accurate measurement. The app is not fully developed and tested. It is only the give an impression of what functions the app might offer.

The functions of the app are:

- Connecting and calibrating the PRODON.
- Displaying the data and video of the throw after it happened.
- Analyzing throws afterward.
- Keeping track of progression by comparing to previous trows

Figure 53: Home screen of the PRODON app.

Connect

When the PRODON is turned on, it automatically starts looking for a Bluetooth network. Selecting the PRODON in the Bluetooth menu is the only thing that needs to be done is.

Figure 54: Bluetooth connection screens of the PRODON app.

Calibrate

When the PRODON is connected, the IMU needs to be calibrated. The app will should the steps that need to be taken

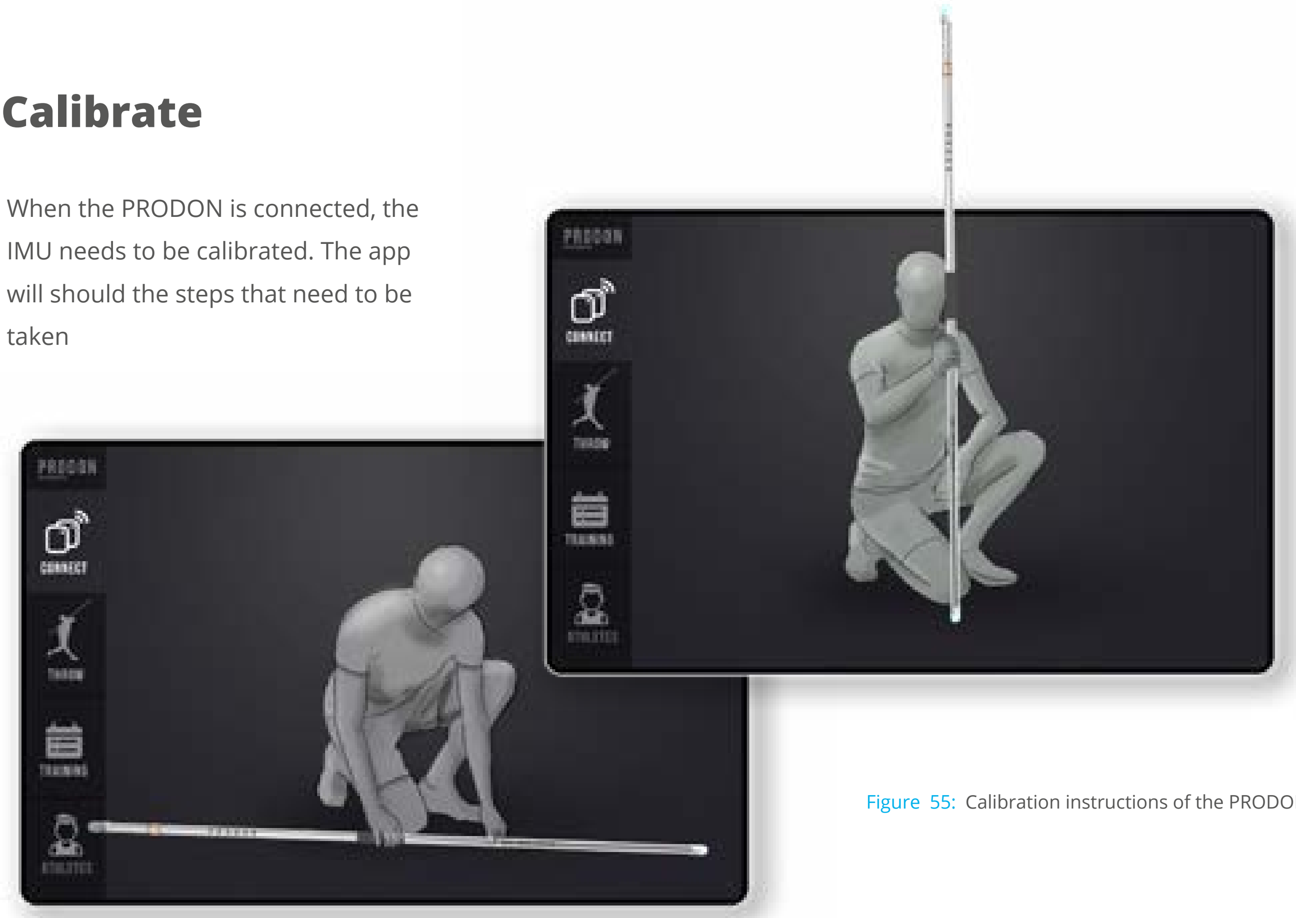


Figure 55: Calibration instructions of the PRODON app.

Display throwing parameters

Right after a throw, the video recording is available to playback. The release velocity, release angle, and angle of attack are displayed at the side of the video.

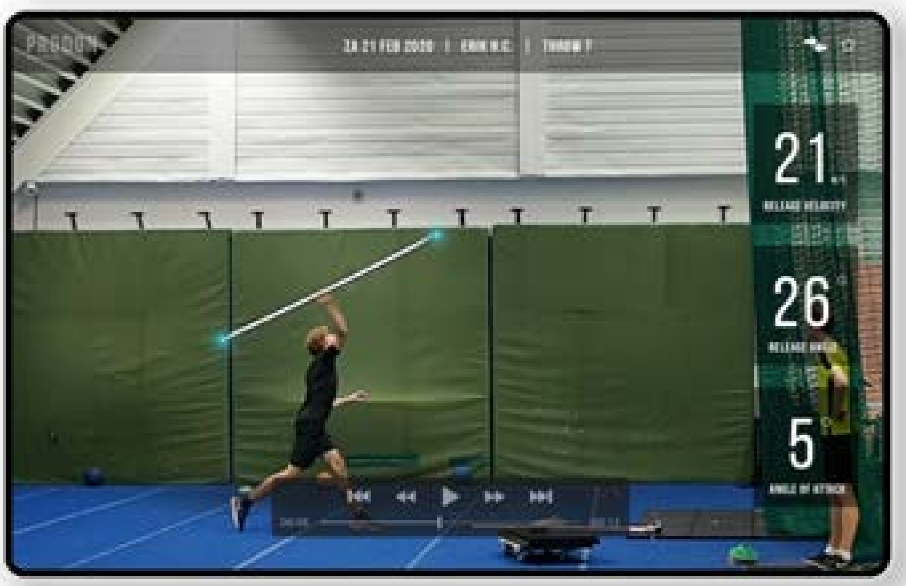


Figure 56: Video and performance parameters in the PRODON app.

Analyze throws

Each throw can be watched back afterward to analyze the training.

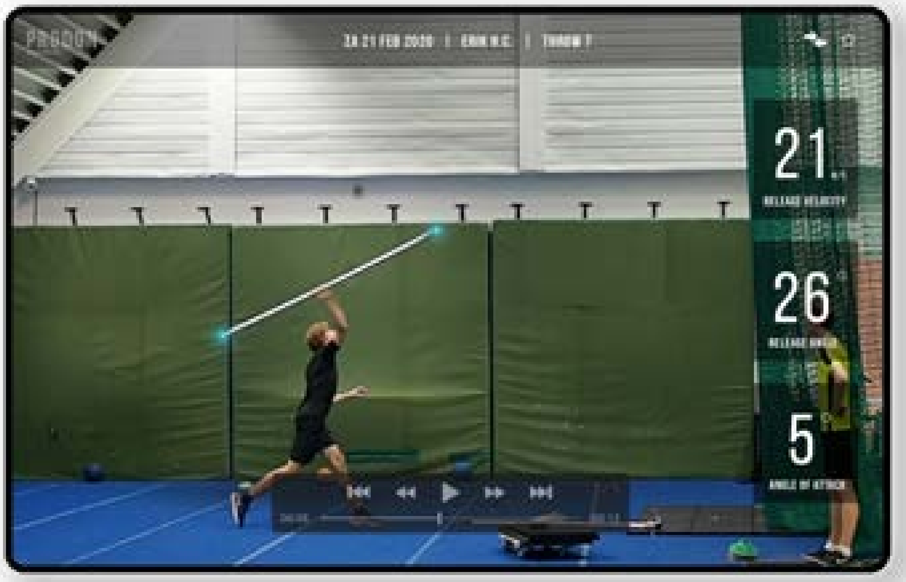
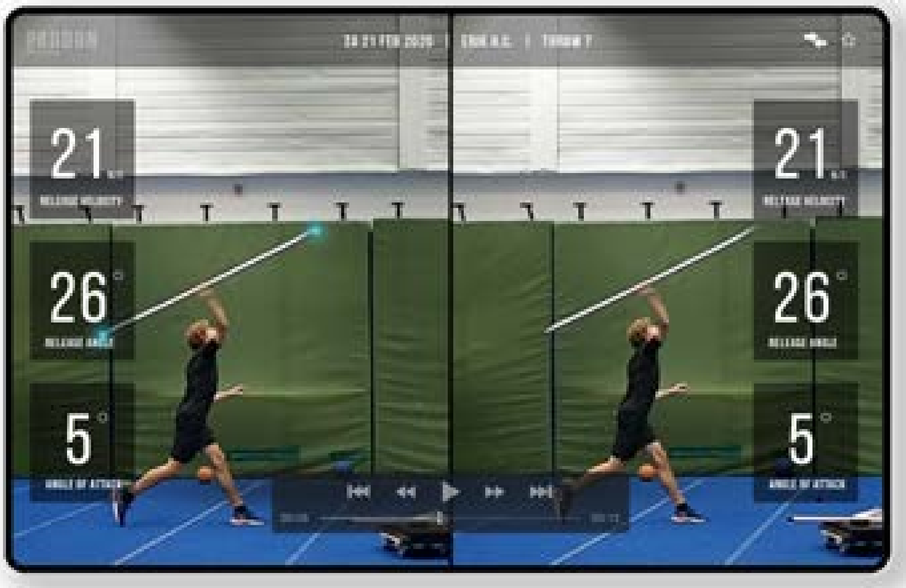


Figure 57: Video and performance parameters in the PRODON app.

Record progress

Compare to previous throws to see the progress made



5.4 PRODON FEEL

As described in paragraph 2.5 Javelin characteristics, the feel of a javelin has two sides. First, there is the shape sizes and material of the handle, which is described in 5.1 Prodon: product overview. Second, there is the behavior of the javelin, which is dependent on the weight and weight distribution. In this paragraph, these two factors will be evaluated for the PRODON design.

Weight

An estimate of the weight for each component is made to calculate the weight of the PRODON design. These estimates are based on weight indications for products found only as well as weight calculations in modeling software when assigning the right material to the modeled shape. The overview of the weight can be found in Table 2. The total weight of the PRODON is 837g, which well within limits set by the requirement HR-4.

Weight distribution

All the added components of the PRODON are placed the far ends of the shaft to get the weight distribution and thereby the mass moment of inertia right. The combined weight of the components in the back is 150g. This weight needs to be compensated to get the center of mass in the right position. The components in the front have a combined weight of 50g, which is not enough to get the center of mass in the right position. The LED holder in the front is therefore made of 80g steel to get the center of mass in the right position and keep the weight under 850g (HR-4). The compensation in the front does not have to be the same as the weight in the back since the back portion of the shaft is slightly smaller than the front portion (90cm and 100cm), making the moment around the center of mass equal.

Mass moment of inertia

With the weight distribution as described previously, a mock-up of the PRODON is made, which can be put to the test. The test described in appendix A.4 shows that the mass moment of inertia of the PRODON mock-up is 0.32 kg.m^2 where a standard javelin scored 0.34 kg.m^2ion the same test. According to a 3d model simulation, the mass moment of inertia of this mock-up is 0.422 kg.m^2, which is the same as found by Best et al. (1995)—feeling both the PRODON mock-up and a standard javelin in both hands at the same time relieve as similar feeling as the test results show. The PRODON mock-up has a lower mass moment of inertia, but it is very close to the mass moment of inertia of a standard javelin. This complies with the requirement HR-6.

Part	Weight	Amount
Anodized aluminum tube[REF-17]	550g	1.9m
BNO080 IMU[REF-61]	4g	1
18650 ION battery cell[REF-55]	45g	1
Sensor probe [(3d model)]	25g	1
LED holder[(3d model)]	5g	1
PU end caps	36g	2
Grip cord[REF-30]	10g	1
5050 LED ring[REF-23]	2g	2
Push button[REF-66]	8g	1
Epoxy[REF-59]	14g	1
Brass ring and isolation [(3dmodel)]	10g	1
Wiring and connectors	10g*	1
Compensation weight [(3d model)]	80g	1
TOTAL	837g	

Table 2: Weight estimation

5.5 COST ESTIMATION

The know if the PRODON will be affordable for athletics clubs, a cost price estimation is made. Which will indicate the price.

For each component of the PRODON, a price indication is found online. Adding the prices together gives a total material cost of €338.14. This price is tax included on a lower scale. The actual price for the material will be lower if taxes are subtracted, and the PRODON is made on a larger scale. The overview of the cost can be found in Table 3.

In Figure 58 the prices of comparable products are shown to give an indication of what is paid for a high-end javelin or a data collection device.

Based on the comparable products and adding assembly and a profit margin of around 50% to the material cost. The PRODON will cost around €1000

Part	Price	Amount
Anodized aluminum tube[REF-17]	€20	1
BNO080 IMU[REF-61]	€35	1
18650 ION battery cellREF-55	€3.50	1
Sensor probe [(P3Dmail)]	€45	1
LED holder	€5	1
PU end caps	€4.10	2
Grip cord[REF-30]	€4.60	1
5050 LED ring[REF-23]	€5.80	2
Push button[REF-66]	€6.74	1
Intel D435 stereo camera[REF-18]	€164	1
Tripod[REF-51]	€35	1
Epoxy[REF-59]	€3	1
Brass ring and isolator	€1.40	1
Wiring and connectors	€5	1
TOTAL	**€338.14**	

Table 3: Cost estimation

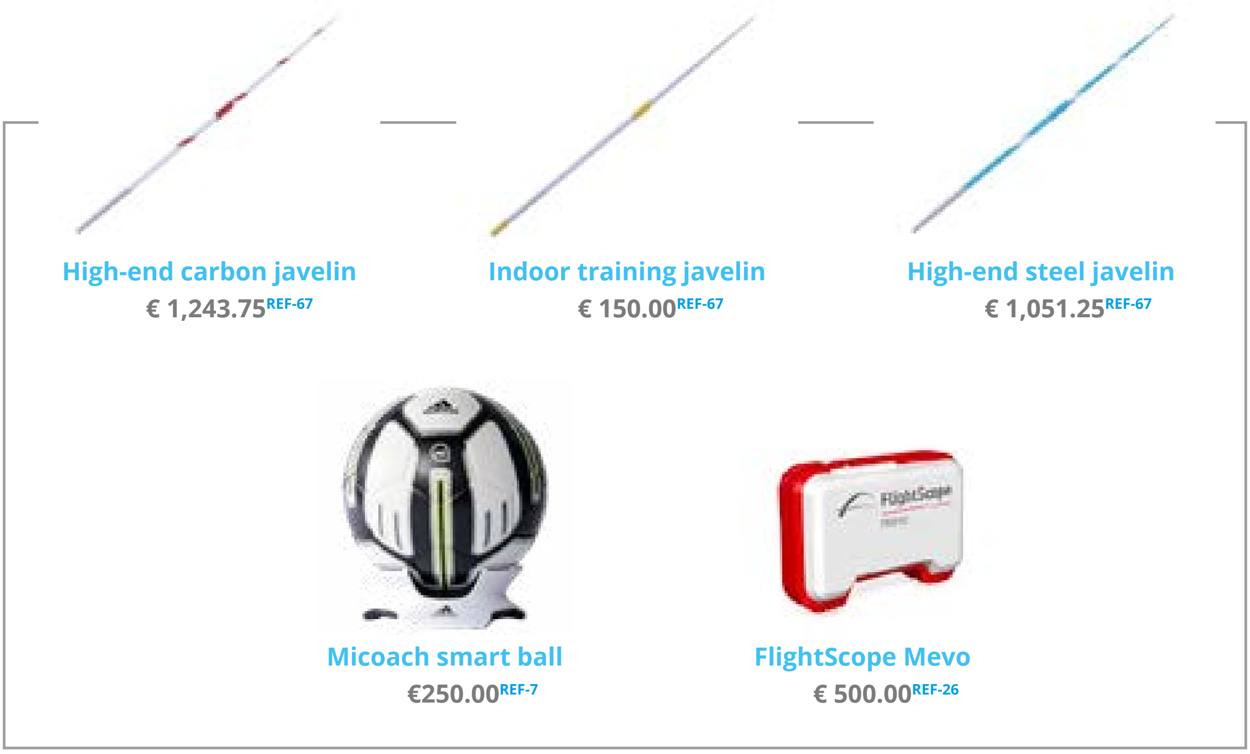


Figure 58: Prices of comparable products

5.6 INTERACTION SCENARIO

The user interaction illustrates the use of the PRODON during the training. The interaction starts with the set-up of the system. The camera needs to be placed perpendicular to the throwing direction at the release location The Prodon is turned on and will show the current battery status turning on the LED lights one by one in a clockwise motion . After 5 seconds, the PRODON will start searching for a Bluetooth device.

A blue light will go round until a Bluetooth network is connected . On the device, PRODON needs to be selected. When the Bluetooth pairing is complete, the lights will turn a solid blue. On the device to start training, the sensors need to go through a short calibration process. Click the calibrate sensor and follow the calibration instructions on the screen. The device is now ready to use for training.

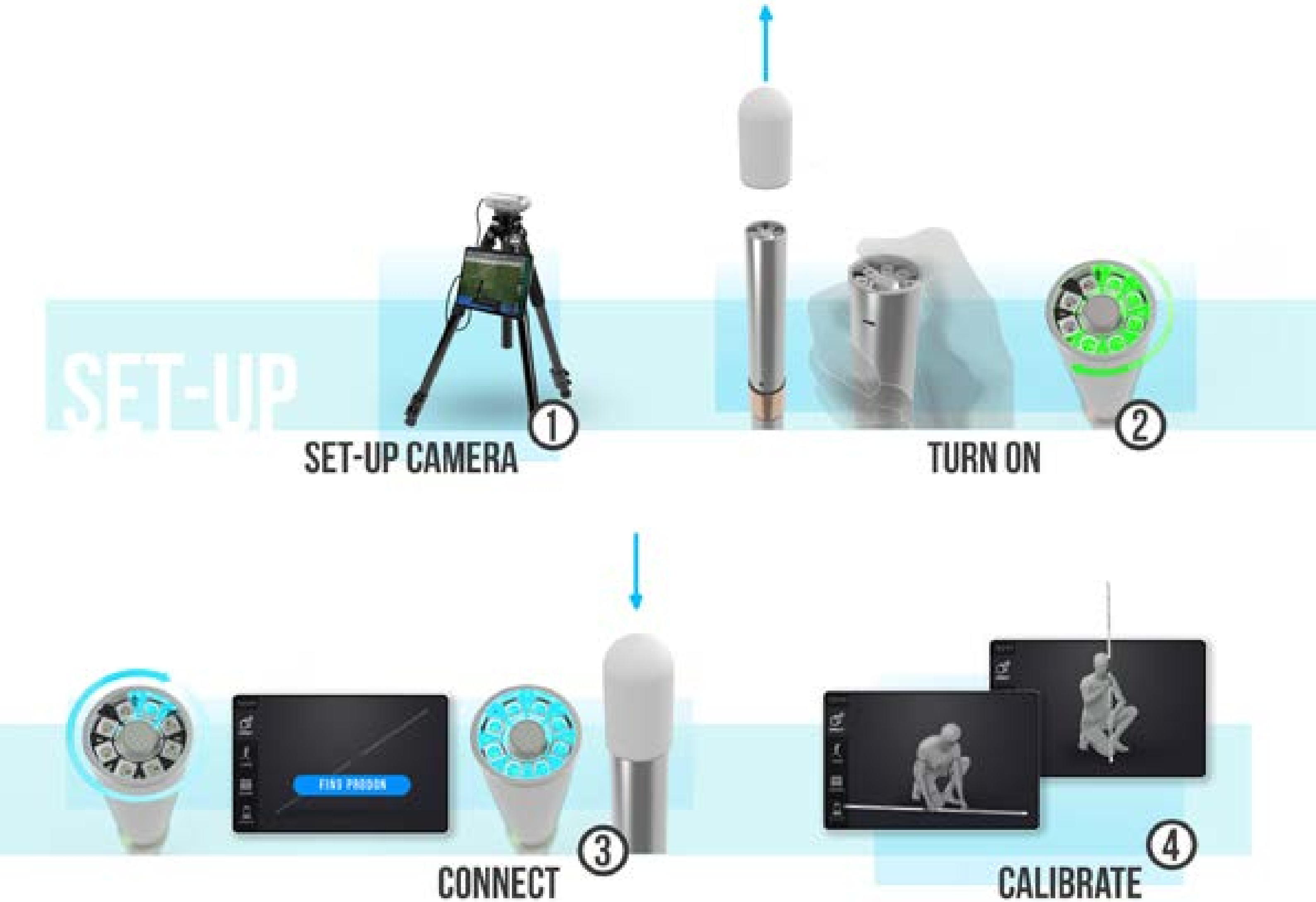


Figure 59: Set-up interaction

In training, when an athlete wants to start his throw, he touches the brass ring to let the product know. The lights will He needs to hold the device still for 3 seconds

In training, the IMU needs to be set to zero before each throw, as will be explained in 5.2 Javelin tracking. The recording of the throw can be re-watched, and the throwing parameters are available to watch.

Figure 60: Training interaction

5.7 MOCK-UP

Sensor probe

A mock-up is made of the final design. Here the mock-up of the sensor probe is displayed. It helped with defining the lay-out of the sensor probe.

LED insert

This LED insert has to functions. First, it probes the light that represents the active markers. Second, the insert is weighted, so the mass distribution of the mock-up is the same as the mass distribution of the final design. This also allowed the mass moment of inertia to be tested

LED insert

The brass capacitive touch ring is added. This allows the placement of the ring to be tested.

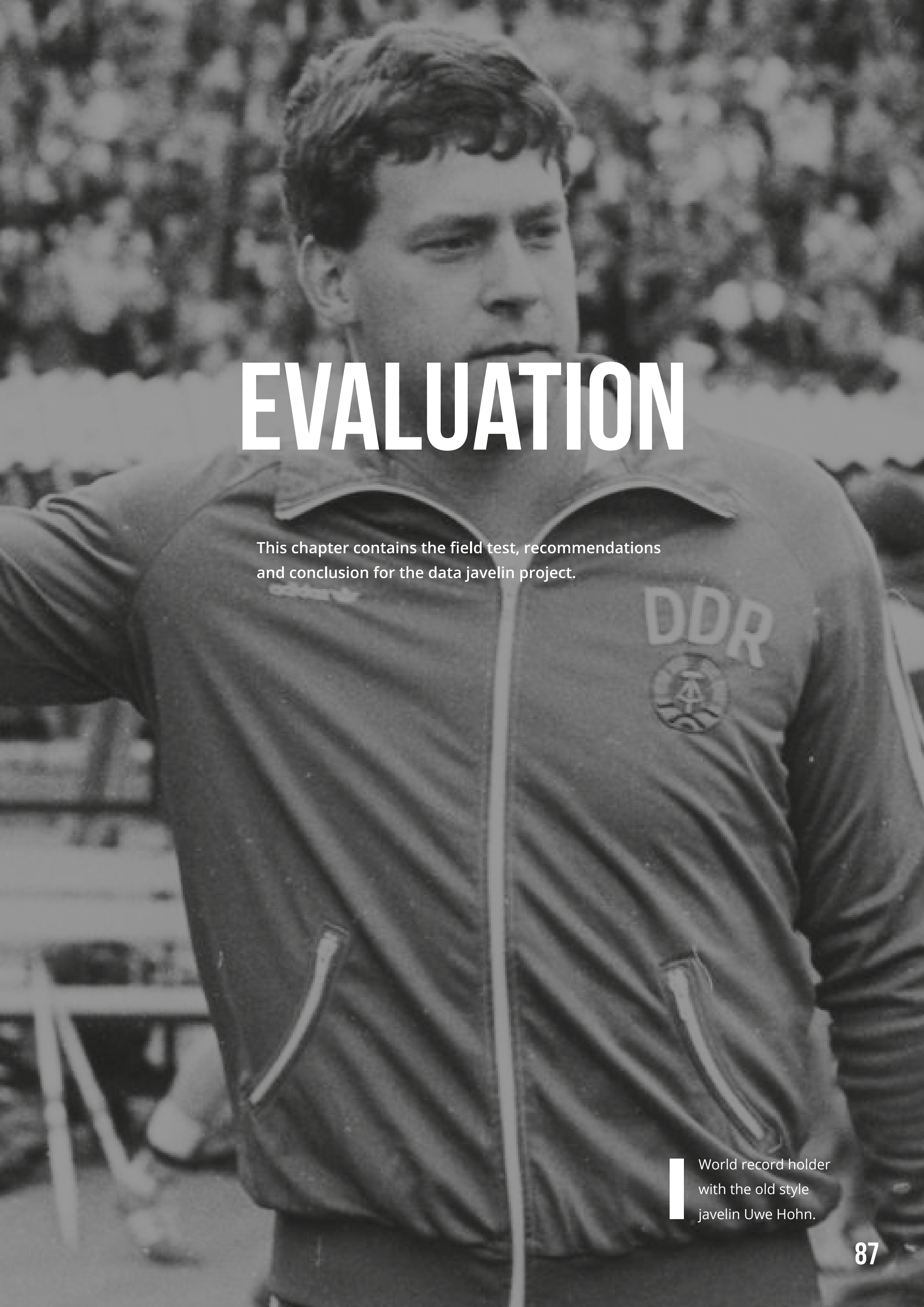
Light diffuser

To finish off the look of the mock-up, a light diffuser is placed over the LEDs that glow when the LEDs are turned on.

6

EVALUATION

This chapter contains the field test, recommendations and conclusion for the data javelin project.



World record holder with the old style javelin Uwe Hohn.

6.1 OVERVIEW

To evaluate if the PRODON can reach the requirements for paragraph 2.8, some requirements need to be tested. These requirements are:

ER-2 A sensor must be able to measure the release velocity with an accuracy of 0,25 m/s

ER-3 A sensor must be able to measure the angle of attack and the release angle with an accuracy of 1,5 degrees.

HR-6 The mass moment of inertia of the design should be within 10% of the mass moment of inertia of a standard javelin. which is between 0.378 and 0,462 kg.m^2

Where HR-6 is already explained in paragraph 5.4, the other two still need to be tested. A prototype is made with two lights markers on the ends for tracking and an imu inside to record accelerations and orientations at the same time.

In paragraph 4.3, both the active marker tracking as the IMU data is tested with a similar prototype. In the test, it was not clear what the accuracy of the measurements is.

6.2 PROTOTYPE

The testing prototype needs to be able to do two things. First, it needs to have markers that can be tracked by a camera, and second, it needs to have an imu inside with a refresh rate of at least 67Hz (ER-5).

In the prototype, a set of lights front and back function as markers. The lights are made by putting a light-diffusing ping pong ball over two bicycle lights at either end. Since the ball emits light as well as a color, it can be easily disguised from the surroundings when recorded. The testing prototype can be found at the left of Figure 61.

The inertial measurement unit part of the prototype can be seen on the right of Figure 61. A probe is placed in the back where it does not receive direct impact. An Arduino with Bluetooth capabilities, a battery with a charging circuit, and a BNO055 IMU are integrated into the prototype sensor probe. The IMU has a theoretical refresh rate of 100Hz, which is in practice lower. In this prototype, it is brought down to 67Hz to get a more stable data flow. 67 Hz is the minimum required refresh rate (ER-5). The Bluetooth receiver is placed outside the aluminum tube to achieve the best possible data transfer.

Figure 61: Testing prototype. left the overview right the probe that is inside with the battery, inertial measurement unit and arduino

6.3 TESTING AND RESULTS

Tracking testing

The two systems are tested in a steady state. For requirement ER-2, the prototype is placed on a caliper with the two systems running. The calipers are moved 150mm in one direction, after which the recording is stopped. The recorded displacement of the prototype should be equal to 150mm. Any discrepancy in the distance will point to the accuracy of the tracking system. The camera is placed 4m from the prototype perpendicular to the movement direction.

The test for ER-3 is similar. Instead of moving the prototype 150mm in one direction, the prototype is rotated 90 degrees. From laying flat to standing on one end. This is done by attaching it to a square object, rotation it over one side. The prototype is moved eight times from 0 to 90 degrees and back.

Velocity results

In the first test, the IMU measurement proved to be unusable. There is too much unfiltered noise in the measurements. Integrating the acceleration measurements twice to get the displacement amplifies the noise to a level at which it is not usable.

The visual tracking results on the other hand look promising. The results are illustrated in Table 4. The average error is only 0,25 mm, with the highest error at 0,52 mm.

When a javelin travels at 28 m/s, and the max refresh rate of the intel D435 of 90 FPS is used. The javelin will travel 0,3111m per frame. Adding the highest measured error of 0,52 mm to that distance will give 0,3136 meter per frame, which is 28,023 m/s. the increase of 0,023 m/s is nearly 1/10th of the 0,25m/s requirement in ER-2. However, this test is performed under controlled conditions. The error of a real javelin throw would most likely be higher.

IMU displacement	Visual tracking displacement	Error
-	150,1 mm	0,1 mm
-	150,12 mm	0,12 mm
-	150,09 mm	0,09 mm
-	149,85 mm	0,15 mm
-	149,58 mm	0,42 mm
-	150,35 mm	0,35 mm
-	150,52 mm	0,52 mm
		0,25 mm

Table 4: Test results for the first test where the prototype is moved 150mm. The IMU data is not usable.

Angle results

In the angle test, the results for both the IMU measurements as the visual tracking look promising. The errors are 1,385 degrees and 0,625 degrees, respectively, which is below the requirement set in ER-3. The results are visualized in Figure 62. The IMU data in blue is consistently less the visual tracking data in green by about 1 degree in both directions. The measurements for both data are consistent.

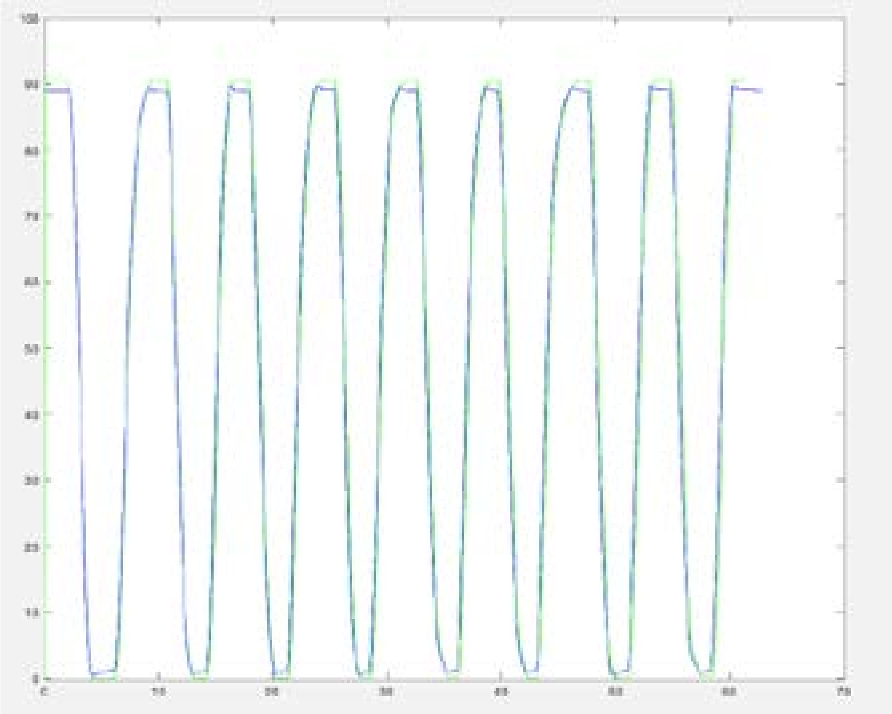


Figure 62: Plot of the measured angles of both the IMU and the visual tracking. IMu data in blue and the visual tracking in green.

90 degree measurement	0 degree measurement	Angle
89,06	0,37	88,69
89,37	0,75	88,62
89,44	0,69	88,75
89,37	0,56	88,81
89,44	1,00	88,44
89,50	0,94	88,56
89,37	0,69	88,68
89,37	1,00	88,37
		88,615

Table 5: Test results for the rotation test of the IMU where the prototype is rotated 90 degrees . an average error of 1,385 degrees is found in the IMU tracking

90 degree measurement	0 degree measurement	Angle
90,77	-0,12	90,89
90,70	0,01	90,69
90,68	0,02	90,66
90,65	0,06	90,59
90,65	0,08	90,57
90,65	0,01	90,64
90,66	0,2	90,46
90,70	0,2	90,50
		90,625

Table 6: Test results for the rotation test of the visual tracking where the prototype is rotated 90 degrees . An average error of 0,625 degrees is found in the visual tracking.

6.4 ASSESSMENT

At first sight, the PRODON seems to meet most of the requirements set in paragraph 2.8. The feel of the product is close to the feel of a standard javelin. The weight is identical; The grip is the same. Only the mass moment of inertia is slightly off. Combined, this creates a similar feeling.

The cost of the PRODON is kept low. The estimated price of 1000 euro is way more affordable than its only real competitor, the FlightScope Athletics.

The tests showed that the accuracy of the velocity and angle measurements in the controlled test set-up falls way below the required accuracy from ER-2 and ER-3.

The Bluetooth communication achieved a transfer distance of 13 meters when tested inside an aluminum tube. The data speed was actually not tested, so an antenna might need to be added.

But there are some side notes to make. My initial vision of creating a stand-alone device proved not the be technically possible yet. Further study in the 3D object tracking domain is needed to facilitate this.

The current system also requires more testing. The concept of it is proven, but the real-world test is needed to say with certainty. The sensors should be fused correctly and developed further. This, on the other hand, requires much more specific knowledge than is being taught in the field of industrial design or could be learned in the span of this 100-day project.

In the design of the PRODON, the impact resistance is kept in mind. However, requirements ER-4 and HR-5 are not tested, so the impact resistance is still uncertain.

For the app which communicates the performance measurements, only the basic functions are designed. Developing a complete can be a graduation project on its own, so this falls outside the scope of this project but still needs to be done to get a productive product.

6.5 NEXT STEP

If the PRODON is developed further, the priority should be real-world testing. The results for such a test can be useful for bringing defects to light. The sensors need to be fully fused before a real-world test is done.

If the test results meet all the requirements, the data transfer and processing need to be automated. In the prototypes, this is all done by hand to safes time, but in the product, it would have to go automatically.

Then the impact resistance needs to be tested thoroughly. Although not in regular use, a javelin throwing performance measurement tool would need to be to withstand hitting a solid object.

The charging is now done with a micro usb port. The charging interaction could be imporved by wireless charging. A beginning is made in the ideation for the wireless charging in appendix A.11

6.6 CONCLUSION

tracking and IMU system. The system can measure the release velocity, release angle, and angle of attack. These parameters influence the performance of the throw the most.

The PRODON is an affordable option for javelin data collection that provides the athlete and the coach with meaningful performance parameters. The video playback that is already used a lot is incorporated in the app, which allows for a seamless transition from the current state.

An added benefit of the PRODON is that it can provide the athlete on its own with feedback, given him more autonomy. The recorded throws can later be discussed with the coach.

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