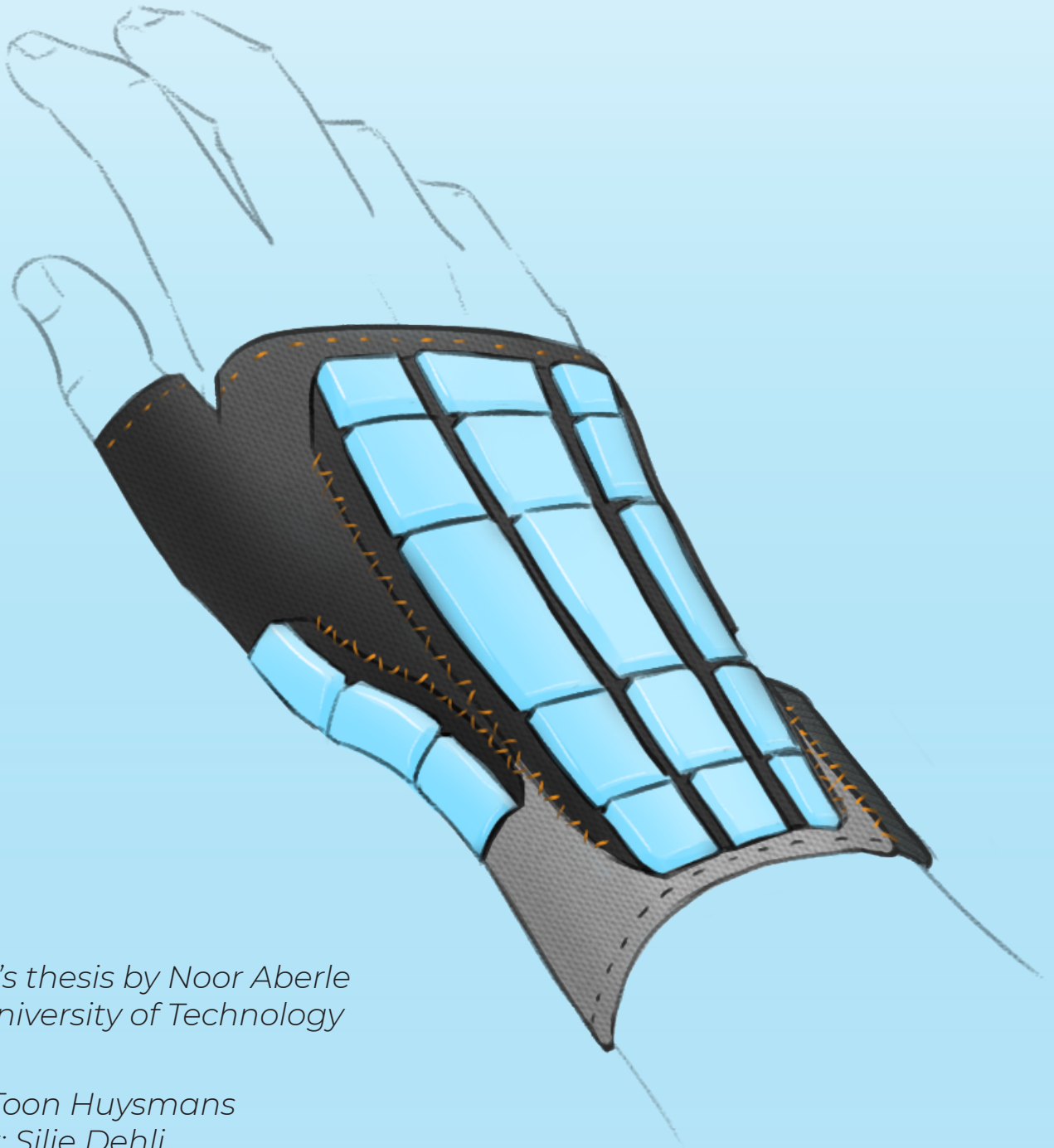


Wrist protection for professional goalkeepers

Master's thesis Integrated Product Design



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Commissioned by Norbert Alblas

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Summary

This report describes the design of a wrist protector for professional soccer goalkeepers. This project was part of the master's thesis for the TU delft and has been performed in collaboration with Norbert Alblas and the Fieldlab UPPS. Due to the increasing intensity of the game, injuries are becoming more common among goalkeepers. These include finger, hand and wrist injuries, which have a five times higher occurrence in goalkeepers than in any other player on the field.

The goal of this project was therefor to design a strong, comfortable and reliable form of wrist protection for the professional goalkeeper, that they can wear with their goalkeeping gloves. The wrist protector should limit the critical movements while still allowing enough range of motion for the goalkeeper to perform their tasks. On top of this, the wrist protector should be easily donned and doffed and should last the goalkeeper for at least two years.

Literature research, interviews with experts and tests were performed to learn more about the context, stakeholders and injuries. Through a survey (n=18) it was found that the majority of the goalkeepers had sustained a wrist injury before and tried to protect their wrists from further injuries. A range of motion test showed that goalkeepers need movement in the flexion direction to perform their tasks. Through literature research and interviews with a hand therapist it was found that the extension direction has to be obstructed to avoid hyper extension of the wrist as this the most common cause of wrist injuries.

After creating a current and envisioned use scenario as well as a program of requirements, many ideas were created through brainstorming, sketching and prototyping. Six concept directions were evaluated with a hand therapist, a professional goalkeeper and a list of wishes derived from the program of requirements.

The final concept is a personalized wrist protector that uses collision between protection pieces, positioned on the back of the hand, to limit movements in the extension direction.

The concept consists of four layers with the top layer being the protection pieces. The protection pieces are designed to create a smooth arc into the limited extension position. Using a parametric model and a 3D scan of the goalkeeper's wrist, a fully personalized wrist protector was made.

The protection pieces are connected to a non stretch fabric layer to allow for flexion of the wrist. Underneath the fabric layer is a thin rubber layer that dampens the movements. The last layer is an under-glove that ensures correct placement and easy donning and doffing of the wrist protector.

The design has been evaluated based on the use scenario and program of requirements as well as through testing with a professional goalkeeper and an interview with a hand therapist. The final concept was perceived as a wrist protector with great potential in its functionality. Especially the freedom of movement in the flexion and deviation directions was described as beneficial compared to other preventative techniques and wrist braces.

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Introduction

Soccer is the most popular sport in the world with around 3.5 billion fans from all ethnicities. It is one of the most accessible sports in the world (Sourav, 2020). Not only is it popular for professional play, there is also a vast group of amateur soccer players. Over the years the sport has become more intense, with the shots increasing in velocity and becoming unpredictable in their trajectory.

With the intensity of the game increasing the risk of injury is also increasing. For goalkeepers this includes the risk of wrist injuries. Because of his own history with wrist injuries Norbert Alblas, professional goalkeeper, wanted to develop a form of wrist protection that could be used during goalkeeping. In collaboration with the TU Delft and Fieldlab UPPS this graduation project was started.

During this design project the double diamond design method was used, see Image 1. This method starts with a discovery phase, researching goalkeepers, the techniques they use, the movements they make, how the wrist functions during these movements, what wrist injuries they are most likely to sustain and how they currently try to prevent those injuries.

The main insights were gathered and interpreted in the define phase. From this a program of requirements and a preferred use scenario was created.

With the requirements and use scenario as a basis, ideation was started to develop a solution. The ideas were developed through brainstorming, sketching and prototyping. Taking inspiration from plants, animals, material advancements and the human body, six concept directions were created and evaluated with experts.

A final concept was developed using a build - measure - learn approach. Through prototyping and testing the different aspects of the wrist protector were optimised. The final concept is explained in detail and evaluated with experts. Based on this evaluation and the insights gathered throughout the project, recommendations on further development of the wrist guard were made.

The final concept is a wrist protector that limits extension through the collision of so called "protection pieces" on the back of the hand. The final concept and this report can be used as a starting point for the embodiment of a wrist protector for professional goalkeepers.

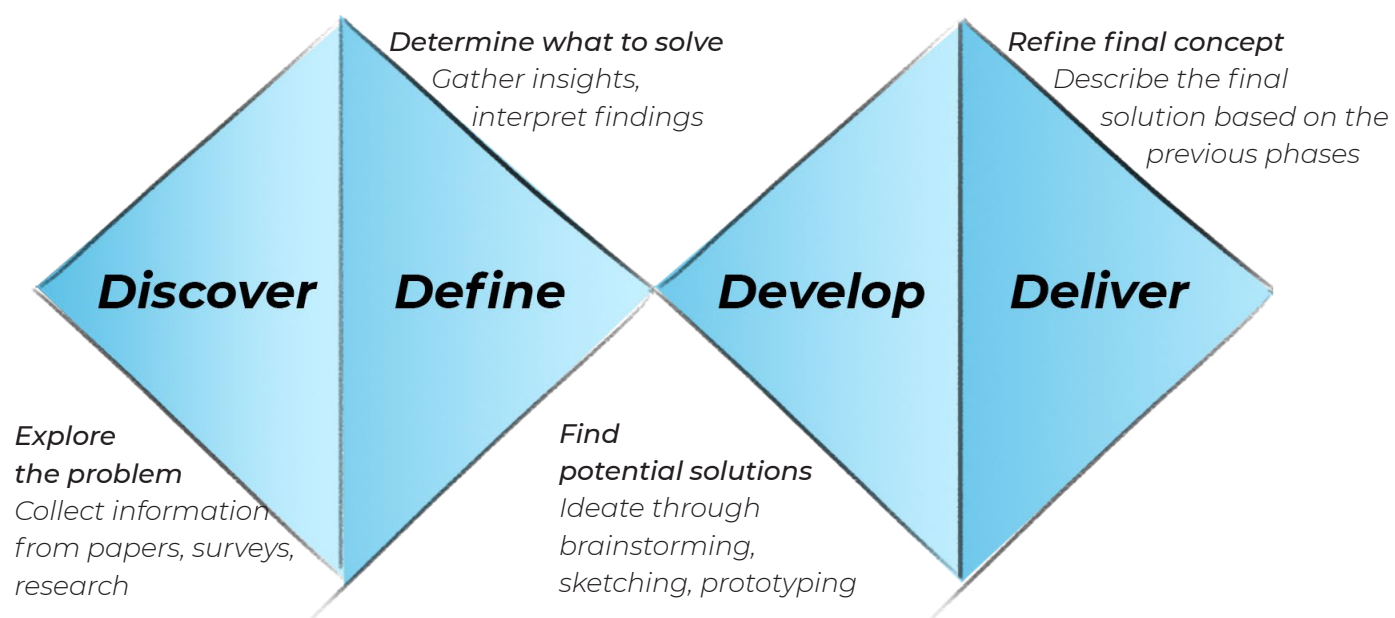


Image 1: Double diamond method

Problem definition

Professional soccer is becoming more and more intense. The shots fired on goals today are getting increasingly faster, with top speeds going up to 200 km/h (Agarwal, 2016). Not only are the balls going faster, they are also starting to swerve, resulting in unpredictable behaviour (Chandler, 2010). For the goalkeeper to catch these fast and unpredictable balls, he must be agile and his timing has to be precise. Due to the increasing intensity of the game, injuries are becoming more common.

Even though upper extremity injuries, such as of the wrists, hands and shoulders, are uncommon in elite soccer players, they have a 5 times higher occurrence in goalkeepers (Ekstrand, et al., 2012). When the ball is kicked directly at the goalkeeper, the ball can knock their fingers and hands back. Therefore, sprains, dislocations and fractures of the fingers, hands and wrists are common in goalkeepers (FIFA, 2010). Our hands are used to pinch, grasp, feel and even express ourselves. (Alpenfels, 1955) Therefore it is important to take good care of them and protect them from injury.

One of the solutions goalkeepers can use to prevent injury is taping. With taping the goalkeeper limits the range of motion of the taped limb and provides support to the joint. However, taping can be a nuisance when applying and taking off, cause skin irritations and get sweaty.

This project aims at designing a strong, comfortable and reliable form of wrist protection for the professional goalkeeper, that they can wear with their goalkeeping gloves. The wrist protector should limit the critical movements while still allowing enough range of motion for the goalkeeper to perform their tasks. On top of this, the wrist protector should be easily donned and doffed and should be durable enough to last the goalkeeper for at least two years.

The wrist, vocabulary

Basic terms that will be used throughout the report

The wrist is one of the most complex joints of the human body. It is comprised of multiple bones and articulations that together allow the hand to be positioned in a large number of orientations to pinch, grasp, hold or catch an object. (Werner & Plancher, 1998)

Movement of the wrist occurs in three planes: the sagittal, frontal and transverse plane, see Image 2.

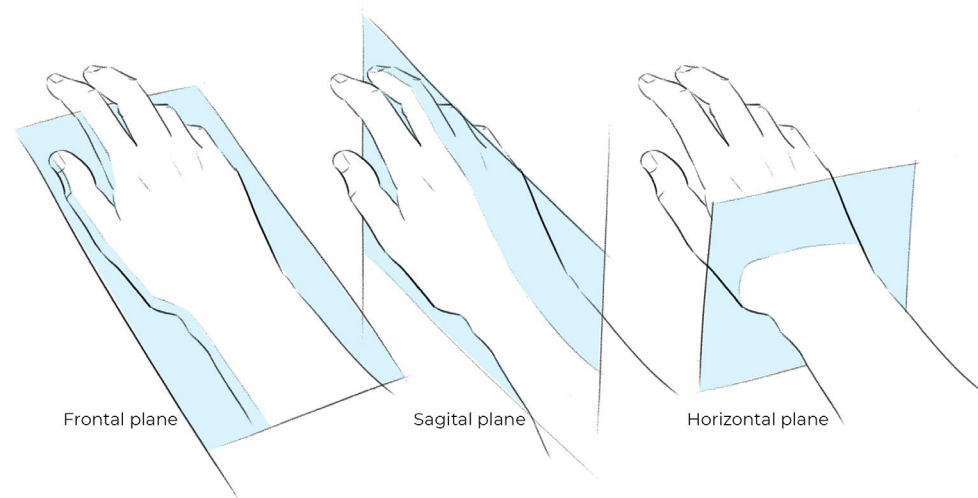


Image 2: Planes in the hand

In the sagittal plane the wrist can flex and extend, see Image 3, as an effect of movement in the midcarpal and radiocarpal joint. The wrist has an average maximum flexion of 74 degrees and an average maximum extension of 72 degrees. (DINED, Dutch adults 2004, 20-30, m+f, P50).

In the frontal plane the wrist can deviate from side to side, with radial deviation towards the body and ulnar deviation away from the body, see Image 3. The wrist has an average maximum radial deviation of 23 degrees and ulnar deviation of 45 degrees. (DINED, Dutch adults 2004, 20-30, m+f, P50).

In the transverse plane the wrist can pronate and supinate, see Image 3. (Werner & Plancher, 1998)
The wrist anatomy and functionality will be explained in depth in chapter "Anatomy of the wrist" and "Kinematics of the wrist".

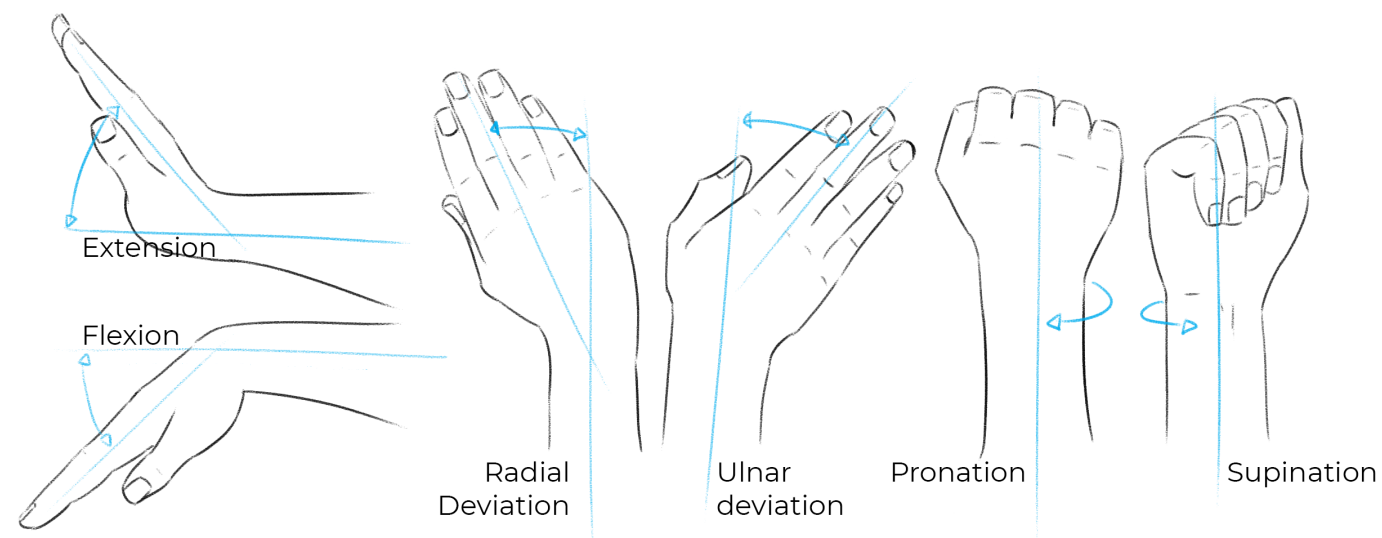


Image 3: Movements of the wrist

Glossary

Throughout the report several terms will be mentioned and explained. This chapter serves as a reference you can come back to when you are unsure of the meaning of a term that was mentioned before.

Proximal: Located close to the centre of the body

Distal: Located away from the centre of the body

Ulnar: The little finger (Dig V) side of the hand, towards the ulna

Ulnar deviation: Moving towards the little finger side of the hand

Radial: The thumb (Dig I) side of the hand, towards the radius

Radial deviation: Moving towards the thumb side of the hand

Flexion: Moving the hand down, towards the ground when the arms make a 90 degree angle with the body

Extension: Moving the hand up, towards the sky when the arms make a 90 degree angle with the body

Extension of the thumb: Moving the thumb away from the hand

Dorsal: Relating to the back of the hand

Palmar: Relating to the palm of the hand

TFCC: Abbreviation for Triangular Fibro Cartilage Complex. The TFCC is located at the ulnar side of the wrist.

FOOSH: Abbreviation for Fall On the Outstretched Hand

Frontal / coronal plane: The plane that cuts through the body from side to side

Sagittal plane: The plane that cuts through the body from back to front

Transverse / horizontal plane: The plane that horizontally cuts through the body

The sport

In soccer two teams of eleven players play against each other with the aim to score the most goals in the other teams' goal. The goalkeeper's task is to prevent these goals. The teams play on a field of real or artificial grass with a minimum dimension of 64 by 100 meters, see Image 4. (KNVB, 2018)

On the short sides of the field each teams' goal is located. The inner dimensions of this goal are 7.32 m wide by 2.44 m high by 1.5 m deep, see Image 5. The goal is made of goalposts, vertically, and a bar, horizontally, which have a width between 10 and 12 cm. Draped over the goalposts and the bar is a net to keep the balls inside the goal. The posts and bar are made of wood or metal and can be square, rectangular, round or oval. (KNVB, 2018)

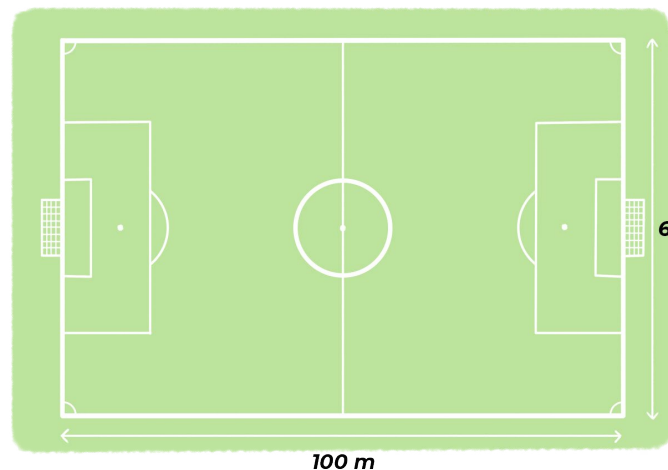


Image 4: Soccer field outer dimensions

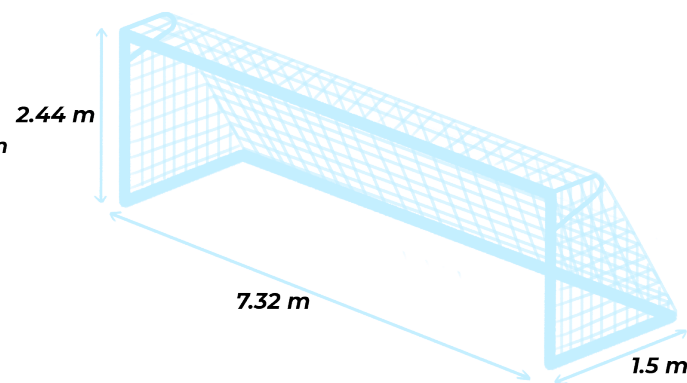


Image 5: Goal inner dimensions

To score a goal the players have to kick a ball into the goal. This ball is spherically shaped with a circumference of no more than 70 cm. It can weigh no more than 450 g and no less than 420 g. The ball is filled with air to a pressure between 0.6 and 1.1 atmosphere. (KNVB, 2020) The ball can reach speeds of up to 200 km/h (Agarwal, 2016).

Since soccer is an outdoor sport, there are variable conditions in which the players have to play. Matches can take place between 12:00 and 21:00, making the players play in daylight and in artificial light. Even during bad weather conditions, the matches are still played. There are two weather conditions due to which a match can be postponed (KNVB, n.d.). The first condition is a bad playing field; for example a slippery field, a damaged field, a frozen surface or loose grass. (KNVB, 2014) The second condition is an unsafe environment around the stadium; for example, due to code orange or red weather conditions. (KNVB, n.d.) On average a professional goalkeeper plays 6 days a week for 4 hours a day, this includes training and matches. In a year they have 6 weeks vacation. (De Nederlandse Federatie van Betaald voetbal Organisaties & Vereniging van Contractspelers, 2020)

The goalkeeper's apparel has to be able to cope with the different weather conditions, sweating and high activity movements. The standard apparel of a goalkeeper is a shirt with short or long sleeves, short or long pants, shin protectors, socks, soccer shoes and goalkeeping gloves. (KNVB, 2020) All of the apparel is washable or cleanable.

Goalkeeping gloves

Since the designed wrist protector should fit with the goalkeeping gloves it is important to know what type of goalkeeping gloves there are. Generally, there are four types of goalkeeping gloves, the flat cut, the roll finger, the negative cut and the hybrid cut. All goalkeeping glove types have a latex layer on the palm of the hand to provide extra grip on the ball. Next to the difference in type of glove, the closing mechanism can also differ, from elastic to velcro. The goalkeeping glove extends halfway up the forearm. What type of glove a goalkeeper uses is based on their personal preferences.

The sport



Image 6: Flat cut (Just Keepers, n.d.)



Image 7: Roll cut (Just keepers, n.d.-b)



Image 8: Negative cut (Just keepers, n.d.-c)



Image 9: Hybrid cut (Just keepers, n.d.-a)

Flat cut

The flat cut, see Image 6, is the most traditional glove cut. The flat cut can be identified by the flat palm and the stitches on the outside of the glove. It has a large contact area and therefore provides greater ball control. It has a loose fit around the fingers. (Unisport, 2017)

Roll finger

In the roll finger, see Image 7, the latex palm is wrapped all the way around the fingers from the palm of the hand to the side of the hand. Due to this wrapping the glove has a greater latex area, providing great catching security. (Kaliaaer, n.d.) This type of glove is more suitable for goalkeepers with thin hands and or fingers. (Just4keepers, n.d.)

Negative cut

The negative cut, see Image 8, can be identified by the stitches being on the inside of the glove. This creates a tighter fit around the hands. The flat palm surface gives the goalkeeper more feel on the ball (Kaliaaer, n.d.).

Hybrid cut

The hybrid cut combines two goalkeeping glove types in one goalkeeping glove. For example the roll finger and negative cut, see Image 9. The middle two fingers have the stitches on the inside, creating a tighter fit. The other three fingers have a rolled cut to provide more catching security. (Kaliaaer, n.d.)

Soccer is a sport in which two teams of eleven players play on a field of 64 by 100 with the aim to score the most goals in the other team's goal. The goalkeeper's task is to prevent these goals by catching the ball before it enters. Soccer matches can take place in light and dark conditions and all weather conditions. The players' apparel should be able to withstand these conditions. The goalkeeper's apparel consists of a shirt, soccer pants, shin protectors, soccer shoes and goalkeeping gloves. Since the wrist protector should fit with the goalkeeping gloves, an understanding of the types of gloves is necessary. There are four main types, the flat cut, the roll finger, the negative cut and the hybrid cut. Which type a goalkeeper uses is based on their personal preferences.

Goalkeeping

The goalkeeper is the last line of defence of the soccer team. Their most prominent task is prohibiting balls from getting into the goal. However, this is not their only task. Goalkeepers are also responsible for coordinating the defence, distributing the ball and facilitating communication. (Rizzardo, 2011) This means that the goalkeeper does not only have to be physically fit, but they also have to have a high understanding of the game. From their position on the field, the goalkeeper has an excellent view of the playing field.

Next to tactics regarding the game such as, positioning themselves on the field in relation to the goal and deciding when to move up to the ball, there are also several ball handling techniques goalkeepers use. The basic techniques are scoop, cup, W's and diving W's for catching the ball. Furthermore, goalkeepers can use several throwing techniques. As all these techniques involve movement of the hands and wrists, it is important to know how these techniques are executed.

Scoop

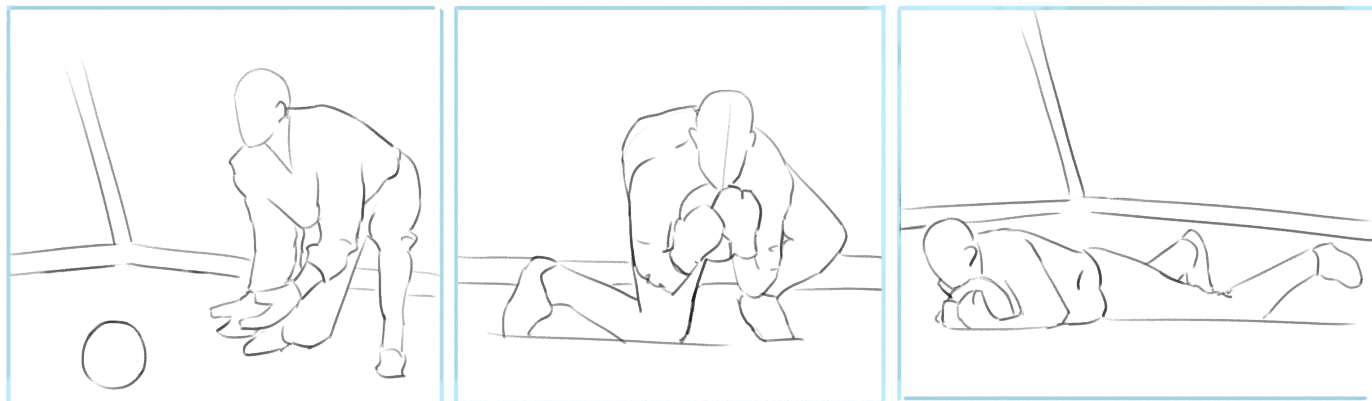


Image 10: Scoop technique

Scoops are used to handle shots below the knee. As the shot comes towards the goal, the goalkeeper's body should be in line with the direction of the ball. The hands should be lowered with slightly bent elbows. The fingers and palms of the hands are used to create a ramp for the ball to roll up into. The goalkeeper can lower their body to the ground by rotating down from the hip or by turning one foot out into a K position, see Image 10. (Rodden, 2013) Once the ball rolls up onto the hands, the arms should be moved towards the chest scooping the ball and holding it tightly to the chest. If the ball comes in with speed, the goalkeeper can collapse onto the ball. (Toby, 2019)

Cup

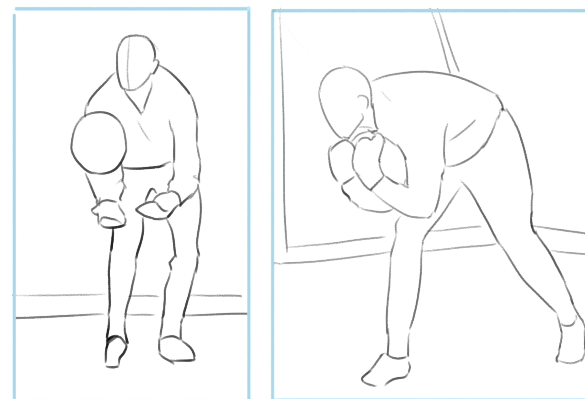


Image 11: Cup technique

The cup technique is used to handle shots around the midriff. Like in the scoop technique the goalkeeper should have their body in line with the ball. Their hands should be held towards the ball with little fingers touching, see Image 11. Their arms should guide the ball towards the chest as it comes in, locking the ball between the arms and chest. For fast shots it can be advised to collapse onto the ball. (Toby, 2019)

Goalkeeping

W's



Image 12: W technique

W's are used to handle shots at head height or higher. The goalkeeper should position their body to be in line with the ball. Elbows should be slightly bent, and hands raised to the height to catch the ball. The hands of the goalkeeper are positioned in a W position, see Image 12. As the ball hits, the thumbs and fingers should wrap around the ball. When catching using W's it is important to keep the wrists firm so that they do not get blown back. (Toby, 2019)

Hands leading

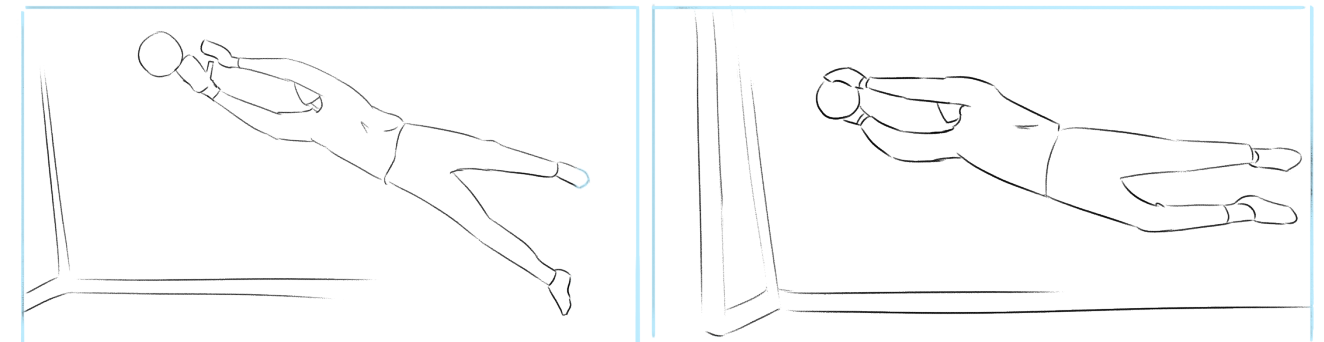


Image 13: Hands leading technique

Hands leading is used when the ball is too far from the goalkeeper to be handled while on their feet. The hands leading technique is also called diving W's. As the ball comes in, the goalkeeper drops down towards the ball to make the save. With hands in W positioning the ball should be pinned to the ground once caught, see Image 13. (Toby, 2019)

Deflecting

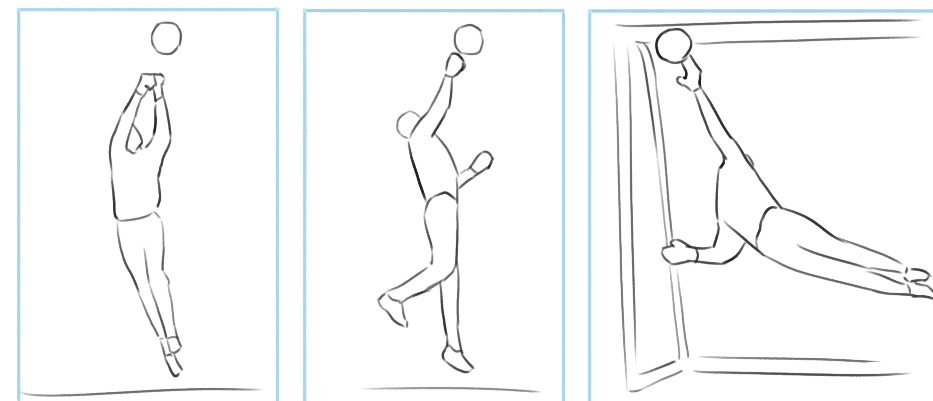


Image 14: Deflect technique

When the goalkeeper is not sure whether they can keep hold of the ball or when it is barely out of range, they can choose to deflect the ball, see Image 14. Deflection can be done with both hands or with one hand. The goalkeeper can choose to deflect the ball with an open palm or with a fist. With their hands the goalkeeper will try to deflect the ball out of goal trajectory. (FIFA, n.d.)

Goalkeeping

Next to the saving techniques, there are also several techniques that the goalkeeper can use to distribute the ball back into the field. Two main techniques involving the hands and wrist are rolling the ball out and the overarm throw.

Rolling the ball

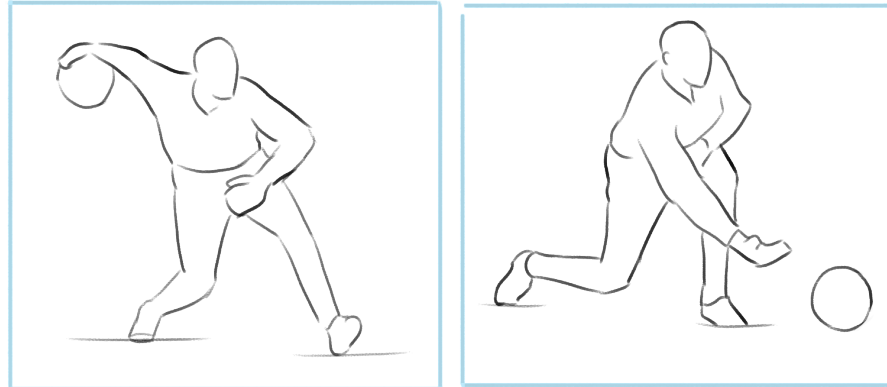


Image 15: Rolling the ball

The goalkeeper reaches their arm back while holding the ball like a pendulum and bends through one knee. As the goalkeeper's arm moves forward the ball is released to the ground, see Image 15. (FIFA)

Throwing the ball

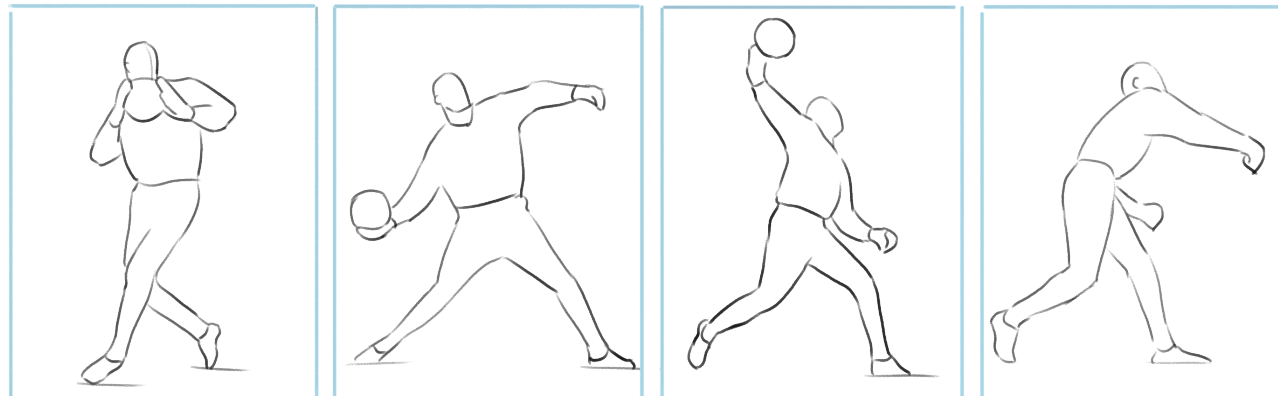


Image 16: Throwing the ball

The overarm throw has great accuracy and can be used for long distances. The goalkeeper throws the ball by angling his body backwards towards his throwing arm. The arm is extended and moves in a circular motion over the head. While their arm moves, their body weight is transferred to the front leg. Around the highest point the ball is released, see Image 16. (FIFA, n.d.)

To perform their main task, saving from goals, goalkeepers can use different techniques. These techniques include, scoops, cups, W's, Hands leading and deflecting. On top of their main task, goalkeepers also have other responsibilities such as coordinating the defense, facilitating communication and distributing the ball back onto the field. To distribute the ball the goalkeeper can use different techniques. Two techniques that involve movement of the wrist are rolling the ball and the overarm throw. During the game goalkeepers should be able to perform all these techniques unobstructed by their gear or injuries.

The goalkeeper and injuries

To be able to create the wrist protector, an understanding of how the user handles wrist injuries and how they currently use wrist protection is necessary. A survey was conducted to gain insights into wrist injuries and wrist injury prevention amongst goalkeepers, see appendix "3. Survey goalkeepers". The survey was conducted amongst 18 male professional goalkeepers, with an average of 7 years playing in the premier or first league, between 21 and 31 years of age. An overview of the results can be seen in Image 17.

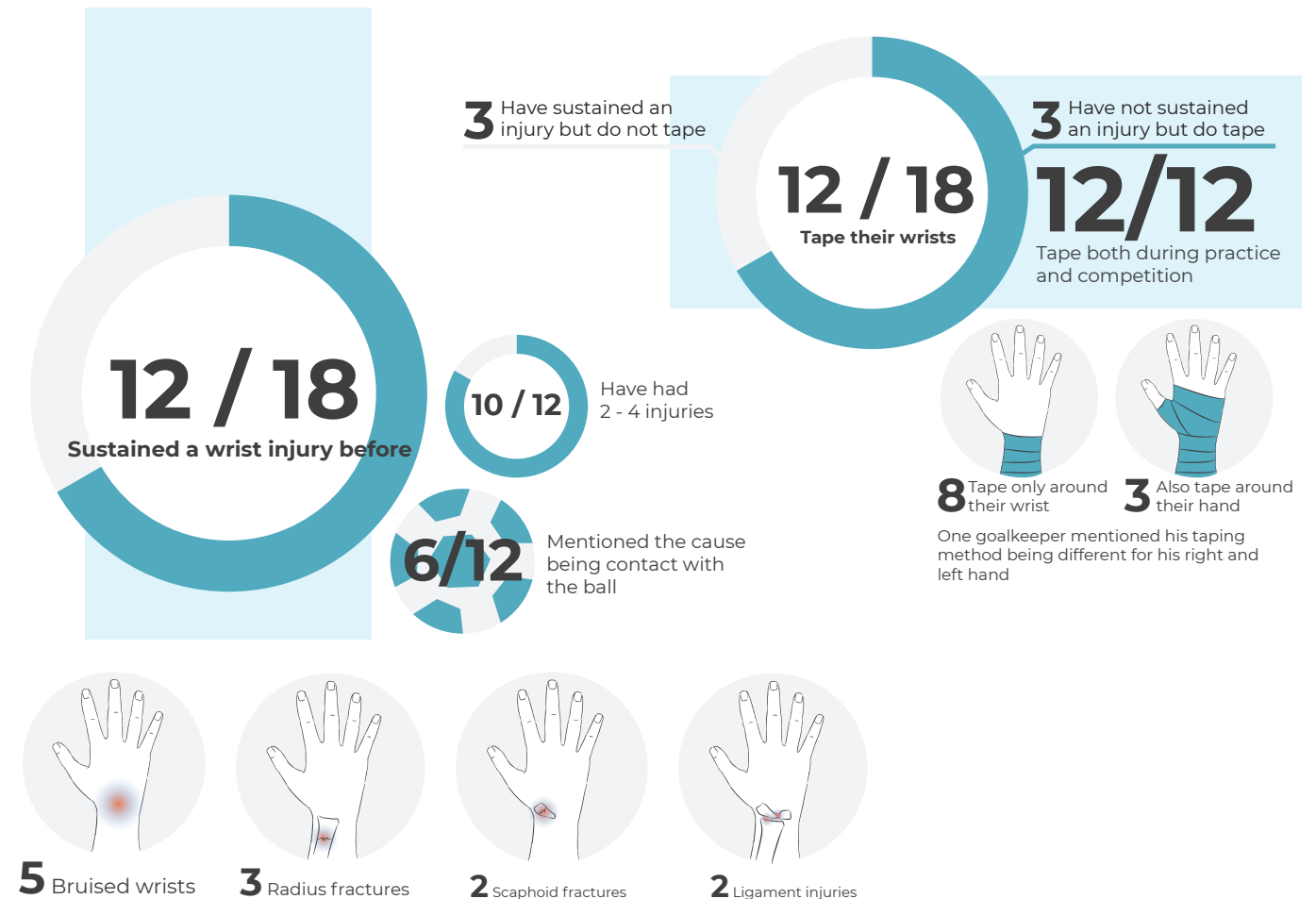


Image 17: Infographic survey results

The majority of goalkeepers who participated in the survey, 12 out of 18, have had a wrist injury before. Within the group of goalkeepers who have had injuries, 10 of them have had a wrist injury 2 – 4 times. Most injuries involve, in order of occurrence, bruised wrists (5), distal radius fractures (3), scaphoid fractures (2) and torn or ligament injuries (2). In 6 out of 12 instances the injuries occurred due to contact with the ball. Out of the 18 participants 12 taped their wrists. Of these 12 participants, 3 participants who did sustain a wrist injury do not tape there wrists, whereas 3 participants who had never sustained an injury do tape their wrists.

All the goalkeepers who tape their wrists do this during practice and competition. Tape is mostly used as a way to prevent injuries (11/12) and provide stability (10/12).

Eight out of twelve goalkeepers tape their wrists themselves. The most common way to tape is taping only around the wrist. A few goalkeepers (3/12) also tape around their hand to provide more support. The back of the wrist is the part that most goalkeepers (11/18) want more support at. Lastly, one goalkeeper mentioned that they tape their right and left wrist with a different technique. The full results of the survey can be found in appendix "4. Results survey goalkeepers".

The majority of goalkeepers that participated in the survey had sustained a wrist injury before. The most common wrist injury among them was a bruised wrist. Other injuries include radius fractures, scaphoid fractures and ligament injuries. Most goalkeepers that participated tape their wrists to try to prevent these injuries. The most common way to tape among the participants is by taping only around the wrist.

Range of motion

During the different goalkeeping techniques, the wrist moves into different excursion directions. To understand what these movements and their range of motion is, a test was performed using digital goniometers, see appendix “5. Wrist joint excursion”. In this test, three right handed, male, professional goalkeepers were asked to perform a series of tasks. The excursion of their wrists was measured using digital goniometers. The digital goniometers can measure angles in two planes. By placing the goniometers on the back of the hand and forearm, the excursion angles in ulnar deviation / radial deviation and flexion / extension can be measured.

The tasks the goalkeepers had to perform were; catching a low ball, cupping a medium height ball, catching a high ball using the W technique, rolling the ball and throwing the ball. The goalkeepers performed each task three times, each time without their goalkeeping gloves.

By analysing the results from the goniometers and the recorded video footage, the excursion during the different tasks was analysed. In this chapter the main insights from this test are discussed. The full analysis can be found in appendix “5. Wrist joint excursion”.

Wrist excursion when catching a low ball



Image 18: Participant 1 catching a low ball

For catching a low shot ball, the goalkeepers moved their arms and upper body towards the ground. The goalkeepers then turned their hands outwards to create a ramp or cup for the ball to roll into. When turning their hands, the goalkeepers hands were mostly relaxed. They either had a very slight extension or very slight flexion of their wrists.

One participant extended his wrists as he stopped the ball and moved them into flexion to pick the ball up from the ground. The other two goalkeepers kept their wrists in flexion while stopping and scooping the ball from the ground.

After the ball had been stopped by the goalkeeper, one goalkeeper locked it between their torso and arms to create a firm grip, see Image 18. This locking of the ball causes a more extreme flexion of the wrist. A faster ball or more difficult to catch shot might require the goalkeeper to lock the ball. Easier balls can be immediately distributed back into the field.

Range of motion

Wrist excursion when cupping a medium height ball



Image 19: Participant 2 cupping a medium height ball

For cupping a ball, see Image 19, all three goalkeepers moved their forearms up and turned the palms of their hands towards the ceiling. During this movement the goalkeepers moved their wrists into slight extension.

As the ball hit their arms and torso, they moved their forearms inwards to lock the ball between their arms and their torso. To lock the ball in place, the goalkeepers wrapped their hands around the ball, moving their wrists into flexion. Since the goalkeepers elbows were slightly outwards during this, their wrists are radially deviated. When the ball was shot more to one side, the goalkeepers face their body towards it. This can influence the deviation of the wrist.

During this task, all three goalkeepers had more radial and ulnar deviation in their non dominant hand than in their dominant hand. This can be explained by the goalkeepers first cupping the ball with their right hand around the ball and finishing the movement by placing their left hand slightly on top of their right.

Wrist excursion when catching a high ball



Image 20: Participant 3 catching a high ball

During the W technique, the goalkeepers moved their arms up, bringing their thumbs together. Their upper arms were almost perpendicular to their body, see Image 20. Their elbows were bent so that their hands were in front of their face. Their hands were in slight extension and radial deviation. As the ball hit their hands their wrists stayed in extension.

Range of motion

Wrist excursion when rolling a ball

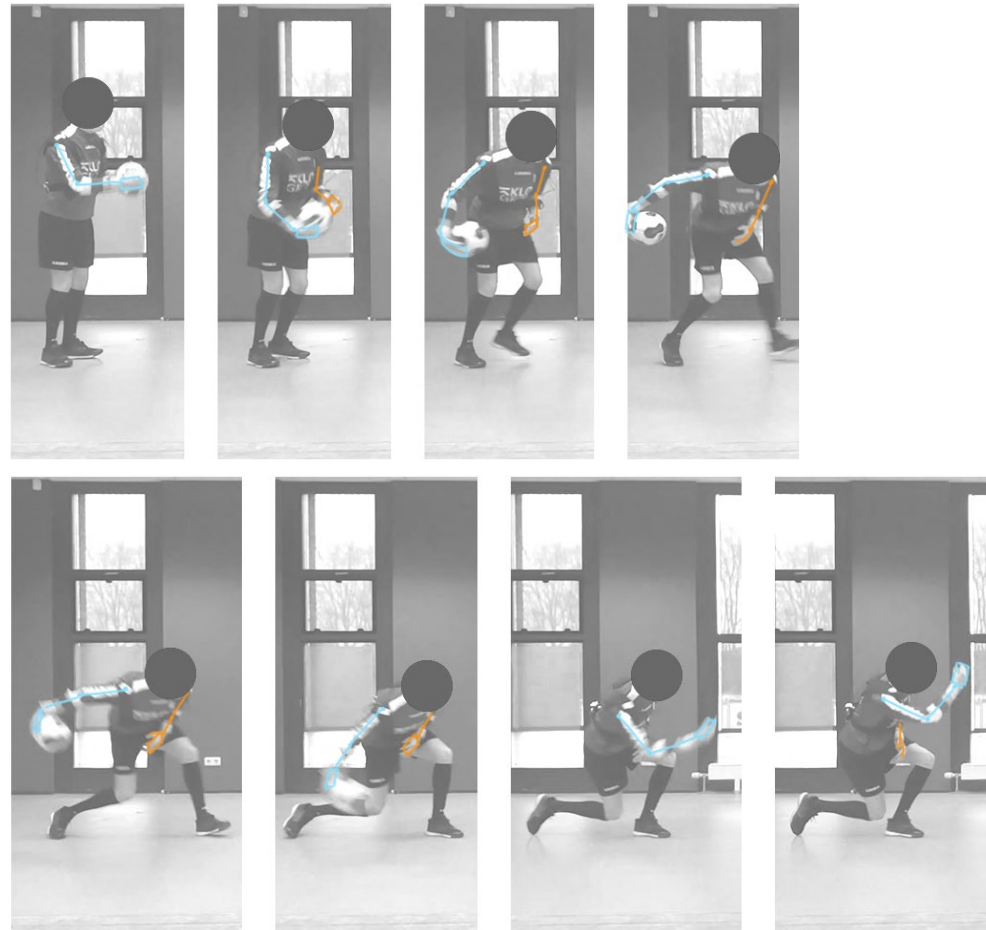


Image 21: Participant 1 rolling the ball

To roll the ball, the goalkeepers moved the ball into their right hand. They moved their arm backwards while keeping their hand underneath the ball. This resulted in a flexed wrist, see Image 21. When they moved their arm back, their wrist was radially deviated to create the correct trajectory for the ball.

They stepped their right foot backwards and bent through their left knee. They moved their arm forwards again decreasing the flexion in their wrist to release the ball.

Their left hand was not needed for this task. Two of the goalkeepers moved this hand in front of their torso in a relaxed, slightly flexed position. The third goalkeeper placed his left hand on top of his left knee, extending it.

Range of motion

Wrist excursion when throwing a ball

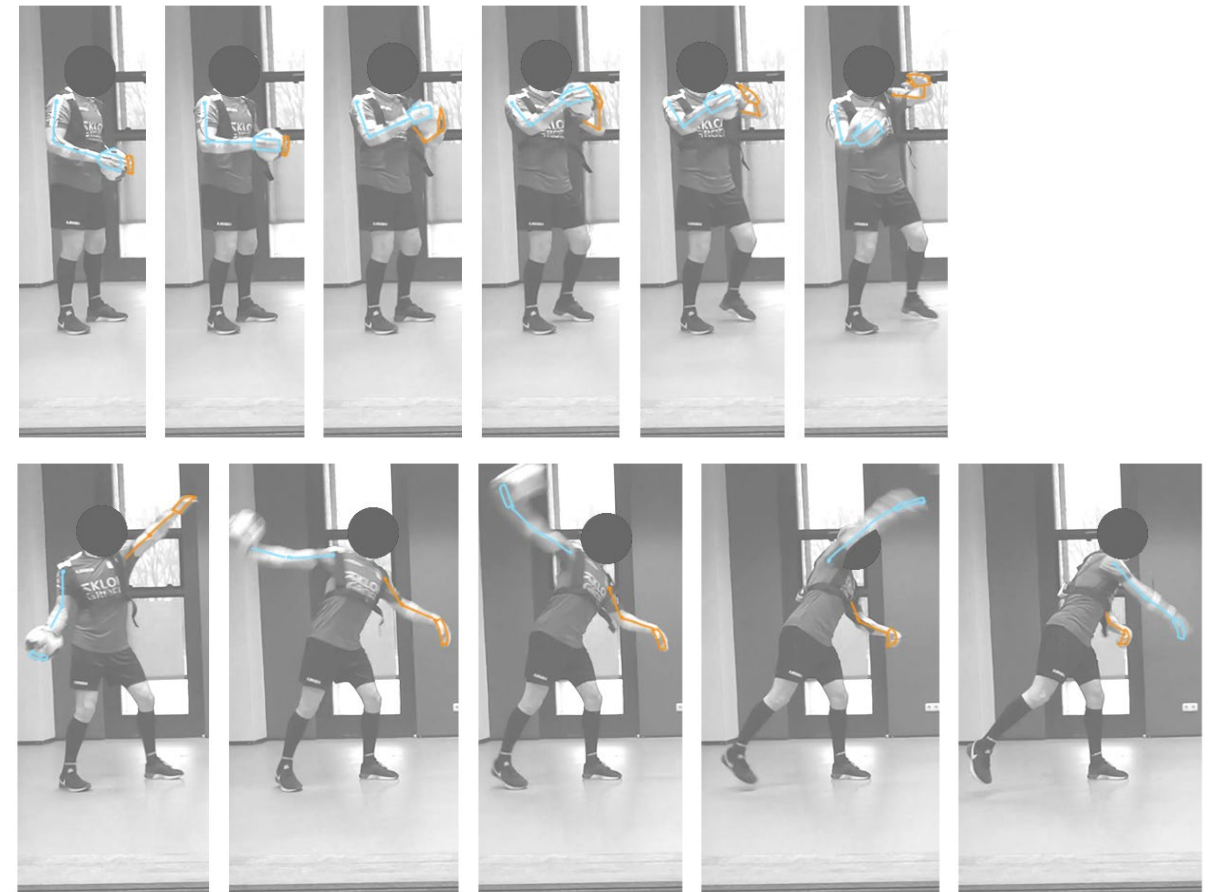


Image 22: Participant 3 throwing the ball

Similar to the previous task, the goalkeepers moved the ball into their right hand in order to start throwing it. They moved their right arm backwards while keeping their hand underneath the ball. This caused a flexed and slightly radially deviated wrist. They rotated their arm forwards and up, releasing the ball at the highest point by decreasing the flexion in their wrist, see Image 22.

The left hand was used to counter balance the movement. Two of the three goalkeepers moved their left arm up and rotated it down as their right arm rotated up. The third goalkeeper did not move his arm all the way up, but only to shoulder height. As they finished the movement the three goalkeepers moved their left hand towards their torso in a relaxed position.

From this test can be concluded that there are lot of factors that influence the joint excursion during the different tasks and between the different goalkeepers. However, there are still similarities in the joint excursion of the wrist.

During all the tasks the most prominent joint excursion was in the flexion and extension direction. Deviation took place in several instances mostly in the non-dominant hand. The test also showed that the goalkeepers needed free movement in the flexion direction in order for them to roll and throw the ball. These insights will be used to evaluate the functionality of the designed wrist protector and as a basis for the program of requirements.

Conclusion

In soccer two teams of eleven players play on a field of 64 by 100 with the aim to score the most goals in the other team's goal. The goalkeeper's task is to prevent these goals by catching the ball before it enters. A professional goalkeeper plays 6 days a week for 4 hours a day, this includes matches and training. In a year they have 6 weeks vacation. Soccer matches can take place during different light and weather conditions. The goalkeeper's apparel should be able to withstand these conditions. For the wrist protector this means that it should be able to withstand sweat and water from washing the wrist protector.

The goalkeeper's apparel consists of a shirt, soccer pants, shin protectors, soccer shoes and goalkeeping gloves. There are four main types of goalkeeping gloves, the flat cut, the roll finger, the negative cut and the hybrid cut. Which type a goalkeeper uses is based on their personal preferences. Some of the types provide a tighter fit around the hand, making it more difficult to fit something underneath. The wrist protector should be able to fit with these types of goalkeeping gloves. When the wrist protector is worn underneath the gloves this means that it should be as thin as possible.

A goalkeeper can use several techniques to defend the goal and distribute the ball onto the field. These techniques include scooping low balls, cupping medium height balls, catching high balls with the W technique, diving to catch balls, deflecting balls, rolling the ball onto the field and throwing the ball into the field. The goalkeeper has to use all these techniques in the same match. They should be able to perform these techniques unobstructed by the wrist protector.

Wrist injuries occur quite frequently among goalkeepers. From a survey with 18 goalkeepers it was found that 12 of them had sustained an injury before. These injuries were most of the time caused by impact of a ball on their hand, causing the hand to hyper extend. Most commonly their hands got bruised, their radius broke or they injured the bone or ligaments of the scaphoid. The majority of goalkeepers in the survey taped their wrists to try to prevent these injuries. From this survey it seemed that hyper extension is the most crucial movement in causing wrist injuries. This is investigated in part 2 "The wrist, wrist injuries & wrist injury prevention".

During the different goalkeeping techniques, goalkeepers move their wrists into different excursion directions. A test to find which directions the goalkeeper needs during the previously mentioned goalkeeping tasks was performed. This showed that goalkeepers need to be able to freely flex their wrists to accurately perform the different techniques. Ulnar and radial deviation takes place mostly in the non-dominant hand and only to a certain degree. Extension of the wrist is needed to some degree when catching a ball using the W technique. This means that the wrist protector can obstruct the extension direction to some degree, however, movement in the flexion direction should not be obstructed.

Not all movements need to be obstructed, some directions might be less likely to cause injury than others. To find out which directions cause injury, research into the wrist, wrist injuries and wrist injury prevention was performed. The results from this research can be read in part 2 "The wrist, wrist injuries & wrist injury prevention."

Requirements from part 1

- The wrist protector should be able to withstand moisture from sweating and cleaning.
- The wrist protector should be washable / cleanable.
- The wrist protector should fit with the standard goalkeeping cuts.
- The wrist protector should allow movement in the flexion direction.
- The wrist protector should withstand an average use of 6 days a week for 4 hours a day for a duration of 90 weeks, 2 years with a total of 12 weeks vacation.
- The wrist protector should have minimal influence on the goalkeeper's performance

Anatomy of the wrist

Although the wrist is most often described as a single joint, it actually consists of two joints that, together, add two degrees of freedom to the movement of the hand. This chapter will explain the anatomy of the wrist. The explanation of the movement of the hand is described in chapter "Kinematics of the wrist".

Bones

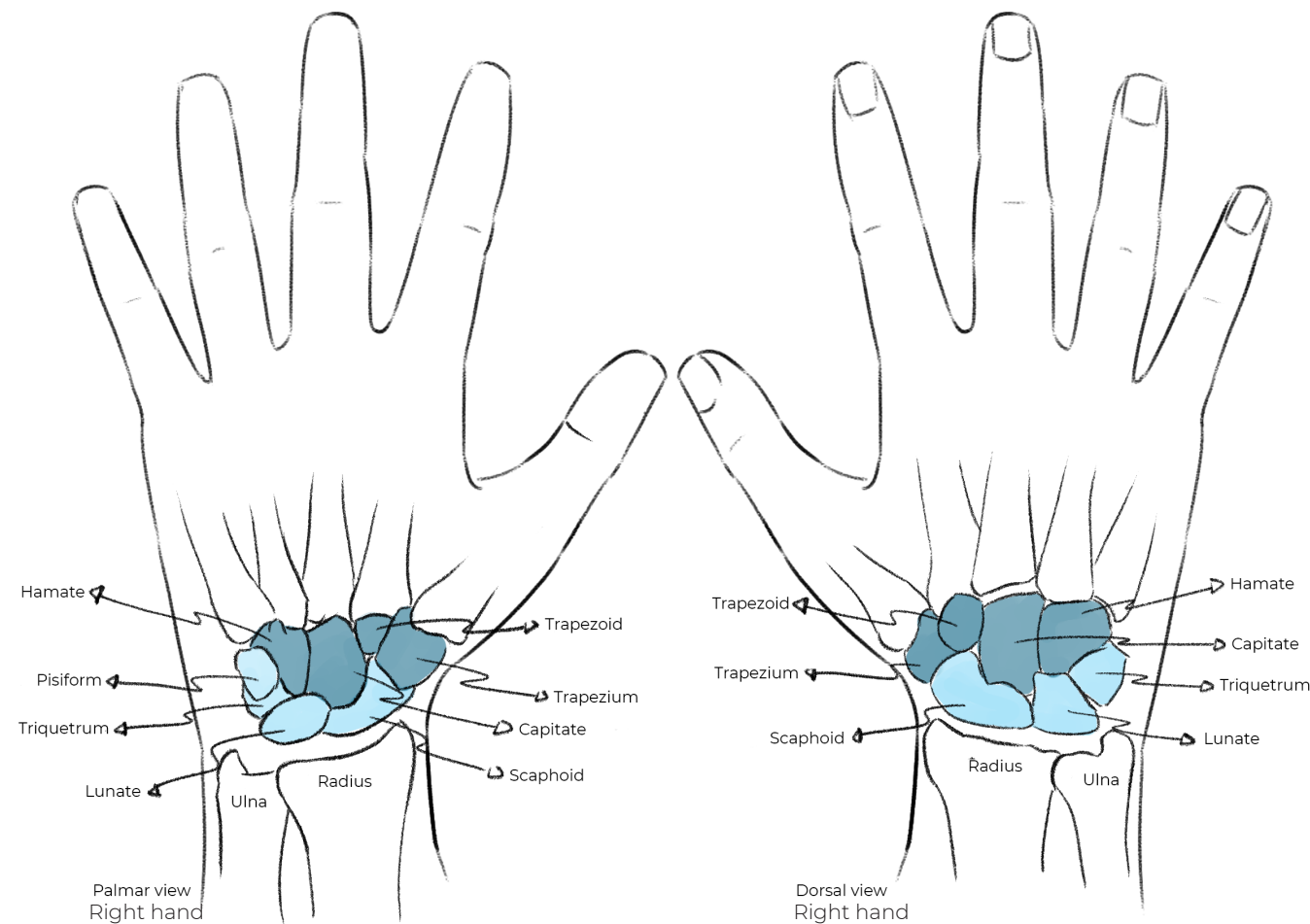


Image 23: Bones of the wrist: Dark bones are part of the distal row, Light bones are part of the proximal row

The wrist is composed of eight carpal bones and the distal ends of the two bones of the underarm. Movement of the wrist is facilitated by muscles located in the under arm that are connected to the wrist through tendons.

The eight carpal bones can be classified into two rows, the proximal and distal rows. The proximal carpal bone row consists of the scaphoid, lunate, triquetrum and pisiform. The distal row consists of the trapezium, trapezoid, capitate and hamate, see Image 23. The proximal carpal bones are connected to the bones of the underarm, the radius and ulna. They can all move independently and need to be stabilized to create the wrist joint. The bones of the distal row are tightly connected to the bones running towards the fingers, the metacarpals, creating an almost solid block of bone. (Hirt, Seyhan, Wagner, & Zumhasch, 2017)

Ligaments

Stabilization of the wrist is done through various ligaments that run over top and in between the carpal bones. There are in total 33 different ligament structures that connect the bones of the wrist. These ligaments are largely responsible for stabilization during extension and flexion. The ligaments can be classified into three layers: superficial, middle and deep ligaments. (Hirt, Seyhan, Wagner, & Zumhasch, 2017)

Anatomy of the wrist

Superficial wrist ligaments

The flexor retinaculum and extensor retinaculum are part of the superficial layer, see Image 24. They are responsible for the positioning and guidance of the tendons. The flexor retinaculum centers the pisiform on the triquetrum, preventing it from sliding towards the ulna. This ligament does not greatly influence the stability of the wrist joint. The extensor retinaculum however does contribute to the stability of the carpal bones. (Hirt, Seyhan, Wagner, & Zumhasch, 2017)

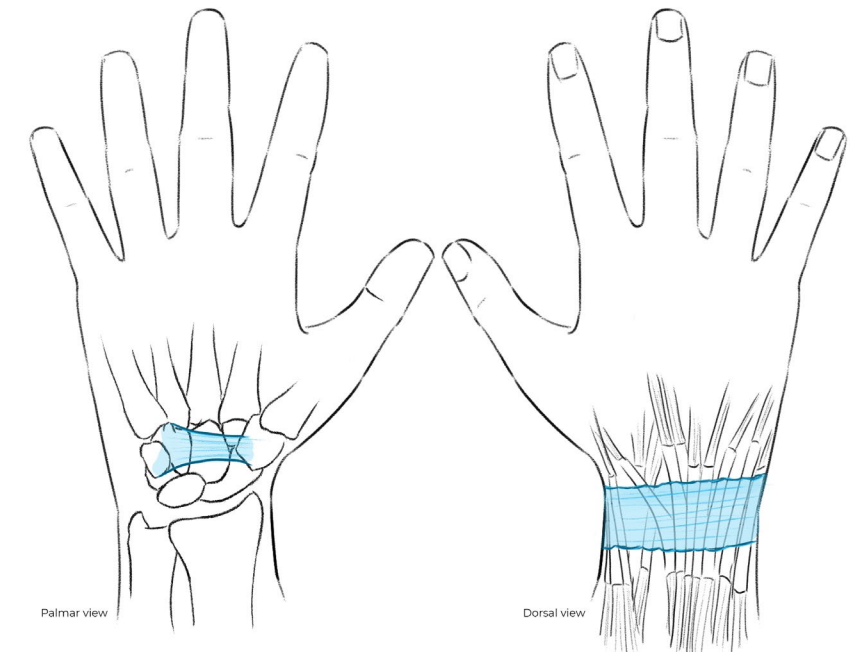


Image 24: Superficial wrist ligaments: Flexor retinaculum (Left) and extensor retinaculum (Right)

Middle wrist ligaments

The middle ligament layer consists of the radial collateral carpal ligament, the triangular fibrocartilage complex (TFCC), the dorsal intercarpal ligament and the palmar and dorsal radiocarpal ligaments, see Image 25. These ligaments stabilize and limit the movement of the wrist in deviation, flexion and extension. The triangular fibrocartilage complex or TFCC is a key element in the stabilization of the radioulnar joint and the wrist. It serves to regulate pressure in the carpus and acts as a decelerator of radial deviation. (Hirt, Seyhan, Wagner, & Zumhasch, 2017)

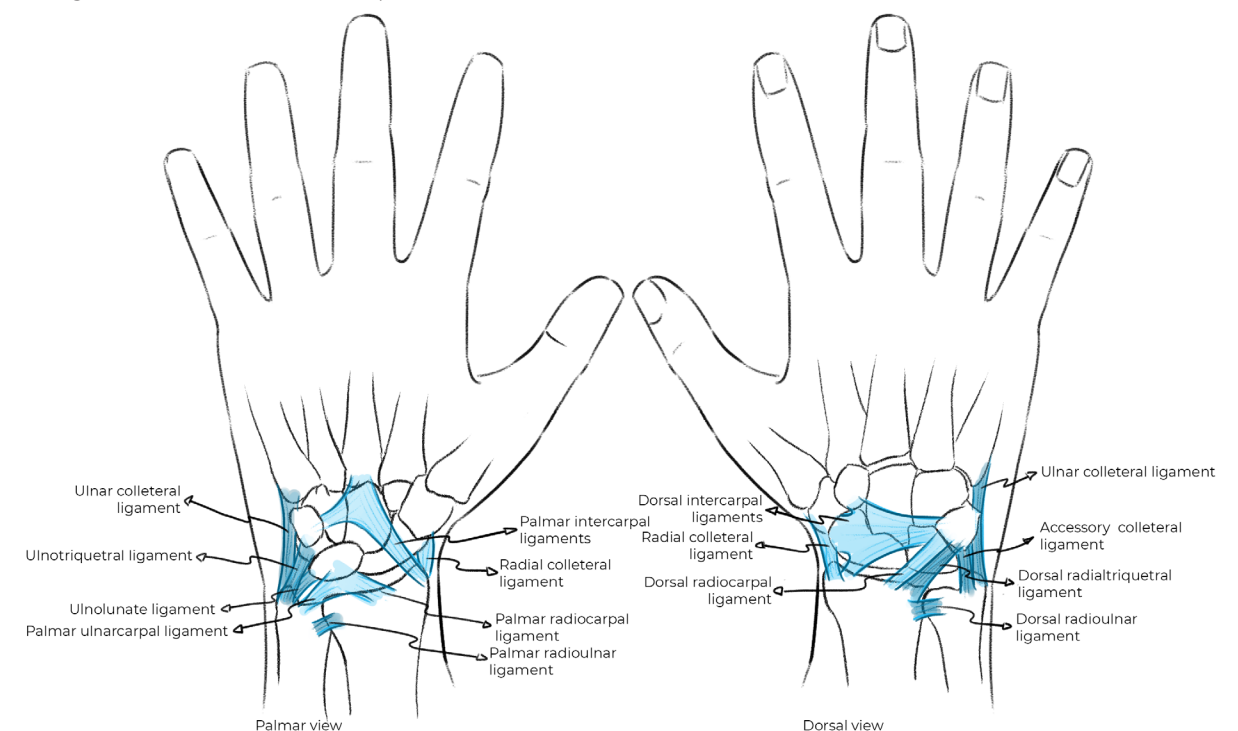


Image 25: Middle wrist ligaments: Dark ligaments are part of the TFCC

Anatomy of the wrist

Deep wrist ligaments

The deep ligament layer connects the carpal bones into a functional unit, see Image 26. These ligaments stabilise the wrist and limit extreme movements. The most important ligaments are explained below.

The trapeziotrapezoid and capitotrapezoid ligaments connect the trapezoid to the trapezium and capitate. The ligaments only allow for minimal freedom of movement between these carpal bones.

The hamatocapitate ligaments connects the hamate and capitate. The ligaments between these carpal bones allow for the greatest freedom of movement of the distal carpal bones.

The lunotriquetral ligament connects the lunate and the triquetrum. This connection allows the triquetrum to displace from proximal to distal during ulnar deviation.

The scapholunate ligament is one of the most important components of the carpal complex. The connection between the scaphoid and lunate enable the movements of extension, flexion, radial deviation and ulnar deviation. The scapholunate ligament allows gliding and torsional movement of the two bones against each other.

The scaphotrapezial ligament connects the scaphoid to the trapezium. The trapezium glides on the distal surface of the scaphoid and allows the scaphoid to move palmarward during radial deviation.

The radioscapolunate ligament runs from the radius to the scaphoid and lunate. It stabilizes the bones during extension and radial deviation. (Hirt, Seyhan, Wagner, & Zumhasch, 2017)

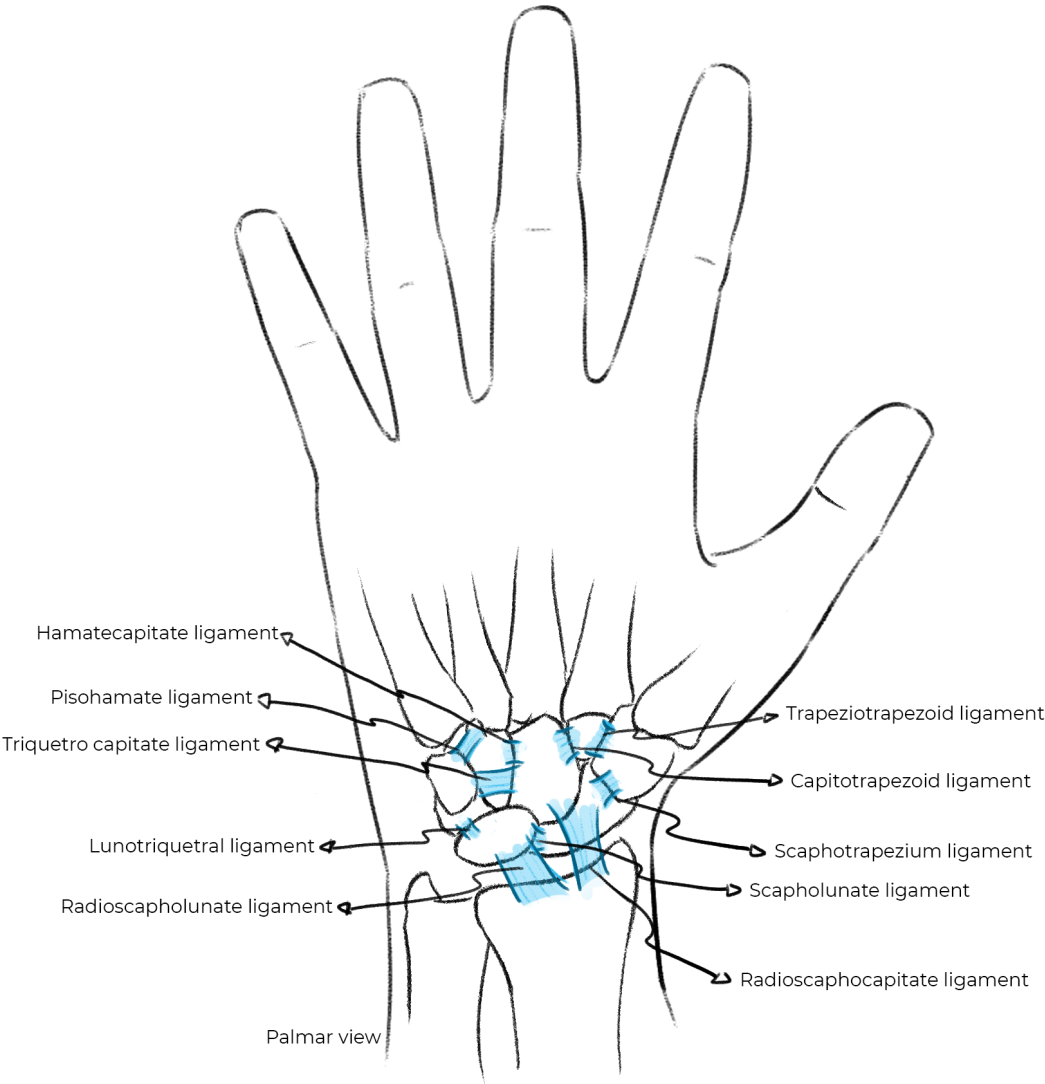


Image 26: Deep wrist ligaments

Anatomy of the wrist

Joints

As previously mentioned, the wrist consists of two joints. The first joint, the radiocarpal joint, is located between the radius and the carpal bones and the second joint, the midcarpal joint, is located between the proximal and distal carpal bones, see Image 27. The range of movement of the wrist is due to a combination of movement in the radiocarpal and midcarpal joint. (Norris, 2011)

The radiocarpal joint is made up of the head of the radius and the proximal surfaces of the scaphoid, lunate and triquetrum. It is ellipsoidal in shape, providing movement in two directions. The ulna is not part of this joint. (Werner & Plancher, 1998) The extension and ulnar deviation range of the wrist is mostly due to movement in the radiocarpal joint. (Norris, 2011)

The midcarpal joint can be seen as having a medial and lateral part. The lateral part consists of the trapezium and trapezoid in contact with the scaphoid. The medial part consists of the capitate and hamate fitting into the proximal carpal bones. (Werner & Plancher, 1998)

On top of the two joints, the carpal bones can also move independently to adapt the shape of the wrist joint to specific space and force requirements. This movement is controlled by the alignment of the surfaces of the carpal bones and the carpal ligaments. The distal carpal bone row has a relatively small range of movement between them due to tight ligaments. The proximal carpal bones however have a relatively large freedom of movement between them. (Hirt, Seyhan, Wagner, & Zumhasch, 2017)

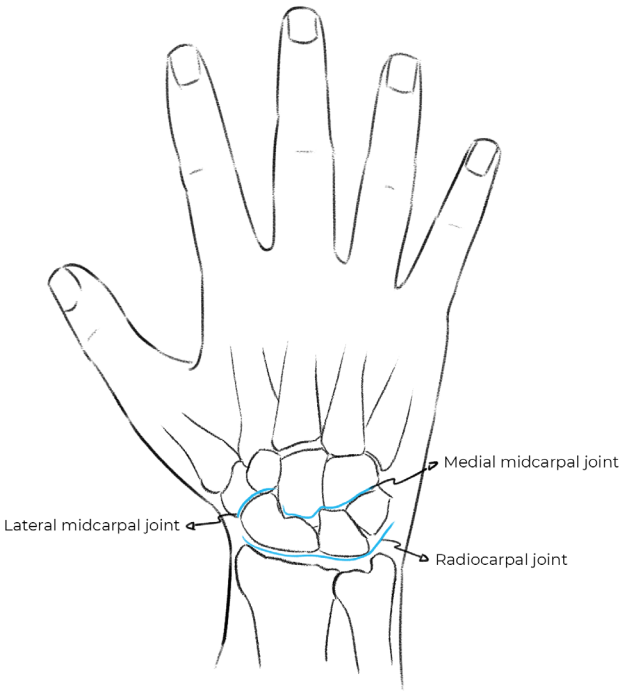


Image 27: Joints of the wrist

The wrist consists of 8 carpal bones, the distal radius bone and the distal ulna bone. The carpal bones can be divided into a proximal and distal row. The proximal row is connected to the radius and ulna and the distal row is connected to the metacarpal bones. To facilitate movements between the separate bones, they need to be stabilized. Stabilization is done by the ligaments in the wrist. The deepest ligament layer connects the carpal bones to each other. They stabilize the carpal bones and limit extreme movements. The middle ligament layer connects the carpal bones to the bones around them. They also stabilize the wrist and limit movements of the wrist. In the middle layer ligaments the TFCC functions as a key element in the stabilization of the radioulnar joint of the wrist. The superficial ligament layer is responsible for guiding and positioning of the tendons that run across the hand.

The connected bones and ligaments together create the two wrist joints, the radiocarpal joint and the midcarpal joint. Movement of the wrist occurs due to a combination of movement in both joints.

The carpal bones can also move independently to adapt to the space and force requirements during different movements of the wrist. The ligaments between the distal row are tight, limiting their movement. The proximal carpal row has more freedom in the ligaments giving them a larger range of motion.

Kinematics of the wrist

To explain the kinematics of the wrist, the carpal bones should be divided into three columns. The radial column consists of the scaphoid, the central column consists of the trapezium, trapezoid, capitate, hamate and lunate and the ulnar column consists of the triquetrum and pisiform. The central column is connected to the radius through the capitate and lunate. (Hirt, Seyhan, Wagner, & Zumhasch, 2017) Flexion, extension and deviation are all centered around the central column with the proximal end of the capitate as rotational axis. The axis is oriented from radial to ulnar for flexion and extension and from palmar to dorsal for ulnar and radial deviation. (Neumann, 2017)

Flexion and extension

Movements of flexion and extension occur mostly within the central column of the carpal bones.

Extension is facilitated by the lunate rolling dorsally on the radius and sliding palmarly. Simultaneously the proximal end of the capitate rolls dorsally on the lunate and slides in a palmar direction as well, see Image 28. During wrist extension the palmar radiocarpal ligaments are elongated. The wrist is capable of bearing loads when extended. The average maximum joint excursion for extension is 72 degrees (DINED, Dutch adults 2004, 20-30, m+f, P50).

The scaphoid makes a similar movement on the radius as the lunate. Due to their different shapes and sizes there is a difference in speeds of the movement. This causes the lunate and scaphoid to slightly move away from each other. This displacement is minimized by the scapholunate ligament.

During wrist flexion the joints move in the opposite direction as with extension, see Image 28. The wrist is unstable during flexion and is not suited for bearing loads. (Neumann, 2017) The average maximum joint excursion for flexion is 74 degrees (DINED, Dutch adults 2004, 20-30, m+f, P50).

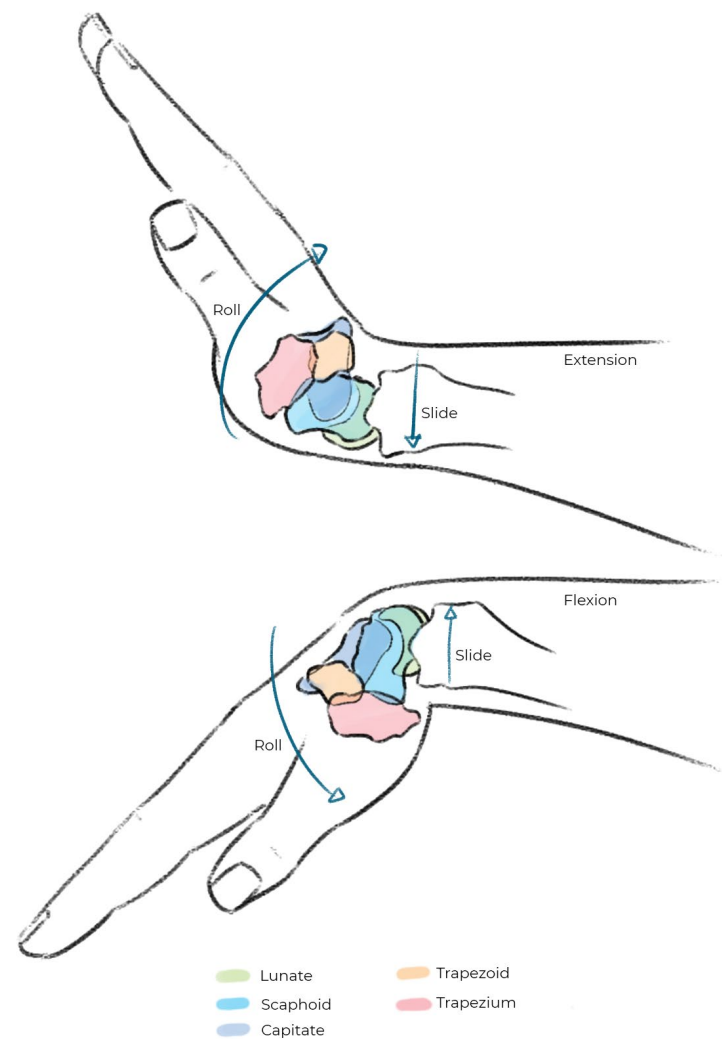


Image 28: Movement of the carpal bones in flexion and extension

Kinematics of the wrist

Ulnar and radial deviation

During ulnar deviation, the proximal row of carpal bones roll ulnarly and slide radially. This radial movement can best be seen by the displacement of the lunate in relation to the radius. The capitate also rolls ulnarly and slides slightly radially, see Image 29. The average maximum joint excursion for ulnar deviation is 45 degrees (DINED, Dutch adults 2004, 20-30, m+f, P50).

Radial deviation is facilitated through the same principles as ulnar deviation only in the opposite direction, see Image 29. The overall movement of radial deviation is limited at the radiocarpal joint by the styloid process of the radius colliding with the scaphoid. The average maximum joint excursion for radial deviation is 23 degrees (DINED, Dutch adults 2004, 20-30, m+f, P50).

Where ulnar deviation is facilitated in both the radiocarpal and midcarpal joint, radial deviation is mostly facilitated in the midcarpal joint. (Neumann, 2017)

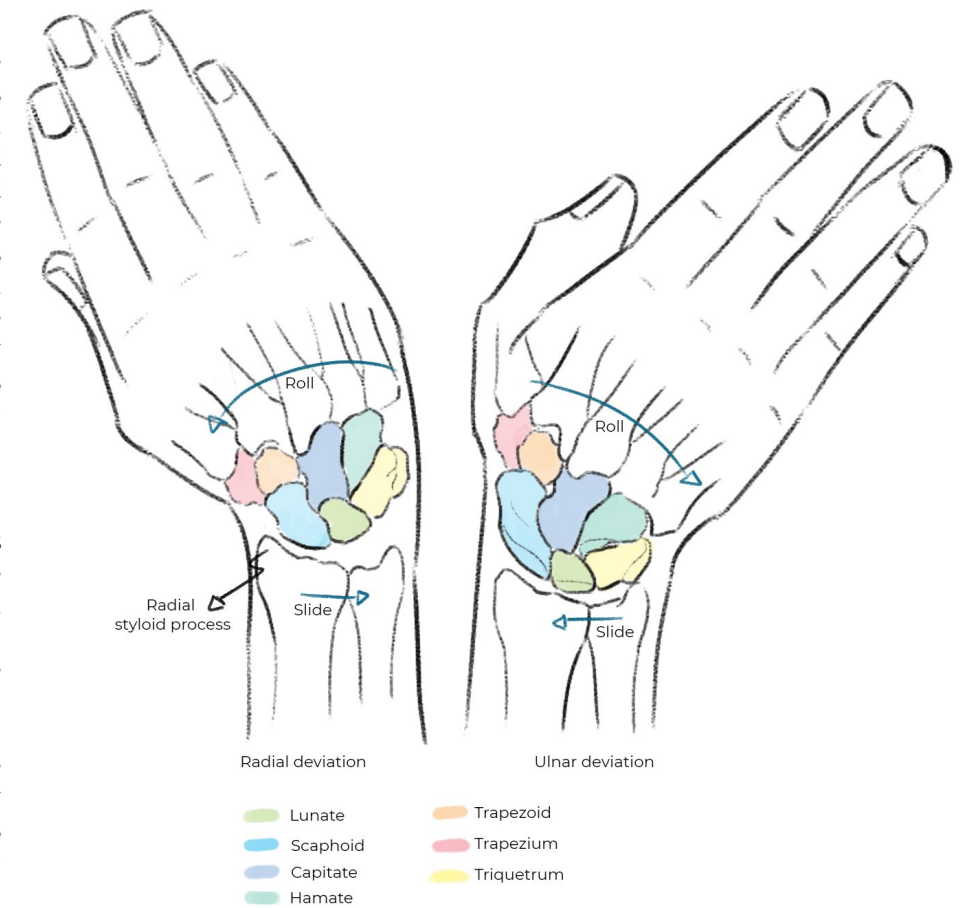


Image 29: Movement of the carpal bones in ulnar and radial deviation

Within the wrist joints, the proximal end of the capitate can be seen as the rotational axis for flexion, extension, ulnar deviation and radial deviation. Flexion and extension mostly occur in the central column of the carpal bones. In extension the palmar ligaments between the radius and the carpal bones are elongated. The wrist can bear loads in extension. During deviation the carpal bones rotate and slide over the radius. Radial deviation is limited by the styloid process of the radius hitting the scaphoid.

Force transmission

During goalkeeping, a wrist injury can occur in different instances. A common cause of wrist injuries in contact sports is a fall on the outstretched hand, also known as FOOSH. (Werner & Plancher, 1998) According to dr. Videler, this is the most common cause of wrist injuries in goalkeepers. (Videler, 2020) When a keeper is diving for a ball or has a collision with another player they may fall on an outstretched hand, resulting in injury. Furthermore, trying to catch a full speed ball using the W technique can also cause the wrist to hyper extend and in its turn cause injury to the wrist. The biomechanical principle behind this hyper extension can be compared to the biomechanics during a FOOSH. (Videler, 2020)

When impact occurs on an outstretched hand, a force is transmitted along the length of the hand and arm. This force is transmitted through the carpal bones to the distal end of the radius. (Majima, Horii, Matsuki, Hirata, & Genda, 2008) According to dr. Videler, forces during a FOOSH are mostly transmitted through the radial side of the wrist, towards the thumb (Videler, 2020). The injury occurs at the part of the wrist that is weakest at that time.

Majima and Horii found that in an extended wrist more loads are transmitted through the scaphoid, with 62% of the force transmitted from the scaphoid to the radius. This force is concentrated on two parts of the scaphoid, one on the proximal pole and the other on the distal pole, see Image 30. During load bearing the tension in the palmar capitatehamate ligament and scaphocapitate ligament as well as the flexor retinaculum increases. (Majima, Horii, Matsuki, Hirata, & Genda, 2008)

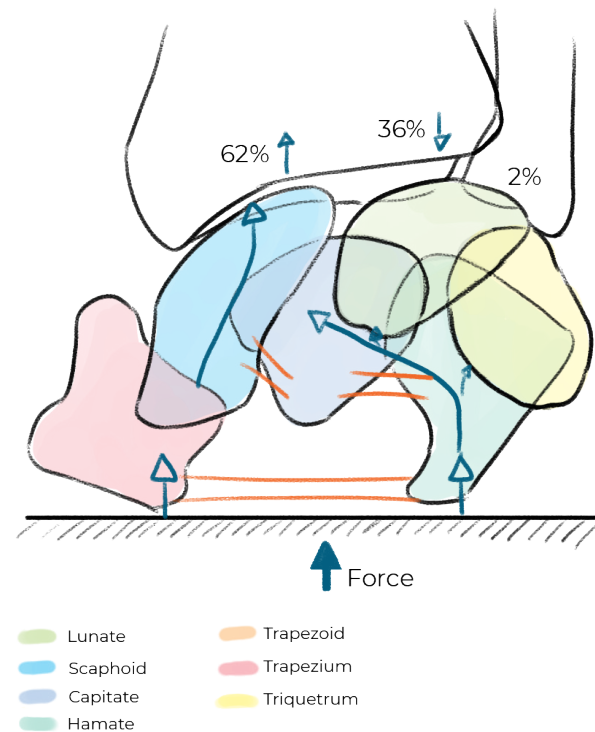


Image 30: Load transmission through the extended wrist

When the wrist joint hyperextends, as can happen during a fall or ball against the hand, most of the force is transmitted through the scaphoid and towards the radius. Tension in the palmar ligaments increases. The increase in force and tension are the main causes for the most common wrist injuries amongst goalkeepers that are explained in chapter "Wrist injuries in goalkeepers".

Wrist injuries in goalkeepers

In contact sports wrist injuries such as a FOOSH are characterized by direct impact on the wrist. (Werner & Plancher, 1998) Although the ball can also cause the wrist to be forced into other directions, such as extreme flexion, ulnar deviation or radial deviation, the focus of this chapter will be on the injuries caused by hyperextension of the wrist.

Dr. Videler stated that the most common hyperextension injuries at the radial side of the wrist are distal radius fractures, scaphoid fractures and scapholunate tears. These injuries correspond to the injuries mentioned by goalkeepers in the chapter "The goalkeeper and injuries". On the ulnar side of the wrist the most common injuries are related to the Triangular fibrocartilage complex such as a TFCC ligament tear.

Distal radius fracture

A fracture of the distal end of the radius is very common in contact sports. (Werner & Plancher, 1998)

Distal radius fractures are most often caused by a FOOSH. During impact onto a hyper extended wrist, the dorsal rim of the radius hits the dorsal rim of the scaphoid. Radial deviation on top of the extension of the wrist can increase the chance of a fracture (Werner & Plancher, 1998).

Distal radius fractures can be classified according to the AO / ATO classification system, see Image 31 (AO Foundation; Orthopaedic Trauma Association, 2018). The higher the impact on the wrist the more likely it is to cause severe fractures such as a multi fragmentary fracture (Dr. Videler).

A distal radius fracture is treated by putting the broken pieces back into position and preventing them from moving out of place until healed. Depending on multiple factors, such as the severity of the fracture, this can be done by simply splinting the arm or by surgically fixating the bones. (OrthoInfo, 2013)

After the distal radius fracture is healed, most people can return to all their former activities. However, this can depend on the nature of the injury and the body's response. Stiffness is common during the first month or two after treatment but is in some cases permanent. Vigorous activities such as soccer can be resumed 3 to 6 months after the injury. (OrthoInfo, 2013)

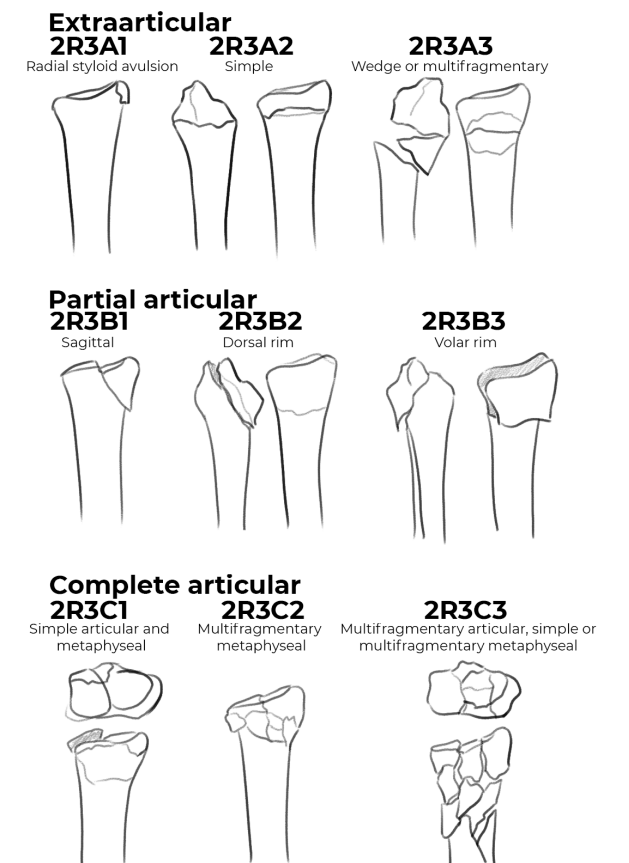


Image 31: Distal radius fracture classification (AO/ATO classification system)

Wrist injuries in goalkeepers

Scapholunate ligament injury

The scaphoid and lunate are tightly connected through the scapholunate ligament. This causes them to move together (Bedi, n.d.) Damage can occur as the scaphoid and lunate spread due to compression from the capitate. (Werner & Plancher, 1998) When the scapholunate ligament tears, the scaphoid bends forwards while the lunate bends backwards, creating a gap between the two bones which results in instability of the wrist. (Bedi, n.d.)

Mild scapholunate ligament injuries can be treated without surgery. Treatment can involve a wrist brace that has to be worn for 2 to 6 weeks. Afterwards the ligaments should be gradually strengthened and stretched. Full activity in sports depends on the symptoms and type of sport. Return to contact sports without a brace can be considered after 6 months. When bracing is not successful, surgery might be needed. (Bedi, n.d.)

TFCC injury

On the ulnar side of the wrist the most commonly injured part is the TFCC. (Hayton, Ng, Funk, Watts, & Walton, Chapter 12 - Injuries to the Triangular Fibrocartilage Complex, 2019) The TFCC is compressed during ulnar deviation. Pronation and supination of the wrist result in an additional rotation of the TFCC. Excessive movements in these directions can result in TFCC injuries. (Werner & Plancher, 1998) The TFCC is most commonly injured through a combination of rotation and compression.

There are different types of TFCC injuries ranging from small perforations to complete tears. The TFCC is responsible for load distribution between the ulna and radius. On top of that it also functions as a stabilizing factor of the radioulnar joint. TFCC injuries also commonly occur together with distal radius fractures. (Hayton, Ng, Funk, Watts, & Walton, Chapter 12 - Injuries to the Triangular Fibrocartilage Complex, 2019)

TFCC tears may be treated with a cast or splint and physical therapy. TFCC tears that are not healed after rest and physical therapy may need to be surgically treated with a minimally invasive surgery in which the surgeon repairs the damage using only a few small incisions. After surgery a cast for about 6 weeks is necessary. Recovery from a TFCC injury involves physical therapy to rebuild strength in the TFCC. Non-surgically healed TFCC injuries usually take about 4 to 6 weeks to heal. (Adcox, 2018)

Scaphoid fracture

As mentioned in chapter “Kinematics of the wrist”, the scaphoid bears a great concentration of the load during extension. This can be seen as one of the reasons why scaphoid fractures are the most frequent type of fracture of the carpal bones. (Majima, Horii, Matsuki, Hirata, & Genda, 2008) On top of that, the scaphoid is the only bone that bridges both the proximal and distal carpal rows, making it more likely to injure. (Werner & Plancher, 1998) When a scaphoid fracture goes undiagnosed it can carry a risk of several chronic wrist injuries, such as bone necrosis, due to a lack of blood supply to the bone. (Hayton, Ng, Funk, Watts, & Walton, Chapter 9 - Scaphoid Fractures, 2019)

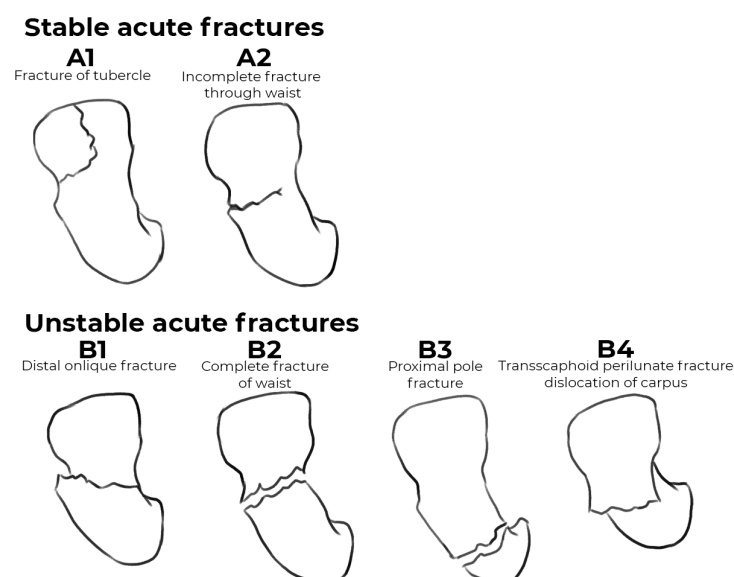


Image 32: Scaphoid fracture classifications (Herbert classification)

Wrist injuries in goalkeepers

The scaphoid can fracture at different locations. The most common scaphoid fracture is that of the waist of the scaphoid. (Majima, Horii, Matsuki, Hirata, & Genda, 2008) Waist fractures occur in a hyperextended and ulnarly deviated wrist. This forces the scaphoid against the distal end of the radius, resulting in a scaphoid fracture. (Werner & Plancher, 1998) The high occurrence of fractures at the waist can be linked to the structural properties of the bone. The internal structure of the scaphoid is the least densely packed at its waist. (Sendher & Ladd, 2013) The most commonly used classification of scaphoid fractures is the Herbert classification, see Image 32. (Ten Berg, Drijkoningen, Strackee, & Buijze, 2016)

Scaphoid fractures can also occur due to repetitive stresses on the wrist, although it is uncommon. This injury occurs with wrist extension and repeated compressive loads. The dorsal rim of the radius and scaphoid impact each other with the scaphoid most affected by these loads. (Werner & Plancher, 1998)

Depending on the location of the break and type of fracture, different treatments are recommended. When the fracture is closer to the thumb it can heal in a matter of weeks when splinted because of the good blood supply to this part of the bone. Fractures closer to the forearm have a lesser blood flow. These fractures can still be treated with a cast of the wrist, thumb and forearm up to the elbow. For breaks at the waist, breaks at the proximal pole and displaced breaks surgery might be needed. (OrthoInfo, 2016)

Recovery of scaphoid fractures can take up to 6 months even for minor fractures. Due to the poor blood supply to the scaphoid they tend to take longer to heal and complications are not uncommon. Scaphoid fractures can cause longterm physical restrictions. (OrthoInfo, 2016)

The most common injuries caused by hyper extension are distal radius fractures, scaphoid fractures, scapholunate ligament injuries and TFCC injuries.

Distal radius fractures are caused by the dorsal rim of the radius hitting the dorsal rim of the scaphoid during extension. Radial deviation on top of extension can increase the chance of a distal radius fracture. There are different types of distal radius fractures which can be classified according to the AO / ATO classification system. Recovery can take three to six months.

Scapholunate ligament injuries are caused by the scaphoid and lunate spreading apart due to compression from the capitate. A tear of the scapholunate ligament causes a gap between the two bones resulting in instability of the wrist. Full return to contact sports without a brace can be considered after 6 months.

TFCC injuries occur on the ulnar side of the hand. It is most often injured due to compression and rotation of the wrist. Compression of the TFCC occurs during ulnar deviation of the wrist. Different types of injuries can occur in the TFCC such as ligament tears and perforations. TFCC injuries commonly occur together with distal radius fractures. TFCC injuries usually take four to six weeks to heal.

During extension the scaphoid bears the greatest concentration of the load. The scaphoid most often fractures at its waist since this is the thinnest part. Scaphoid fractures occur in a hyper extended, and ulnarly deviated wrist during which the scaphoid is forced against the distal end of the radius. Scaphoid fractures are classified according to the Herbert classification. Recovery can take up to six months with a possibility of longterm physical limitations.

Taping

To prevent wrist injuries, it is common practice among goalkeepers to tape their wrists. Taping provides support, limits excessive range of motion, and protects against forces that can cause injury. (Norris, 2011) There are several different tapes that can be used separately from each other or in combination with each other.

Pre-wrap or underwrap is used as an under layer for the rest of the tape. Pre-wrap protects the skin from damage due to the adhesives on the tape. (Macdonald, Chapter 1 - Introduction, 2010)

Elastic tape can conform to the shape of the body. It allows for tissue expansion and is therefore used around muscles and to support soft tissue. Elastic tape will not give mechanical support to ligaments. It can be used in combination with non-elastic tape for added support. (Macdonald, Chapter 1 - Introduction, 2010)

Non elastic tape has a non-yielding cloth backing. It provides high support to the ligaments and joint capsule. Non elastic tape is used as support for the body part as well as to limit joint movement. It can be used to reinforce elastic tape. (Macdonald, Chapter 1 - Introduction, 2010)

Before the tape is applied, the area that it will be applied to should be clean and preferably free of hairs. (Macdonald, Chapter 1 - Introduction, 2010) After use, the tape is cut away from the wrist and discarded.

Taping techniques

The taping starts by applying a layer of underwrap to protect the skin. Afterwards non – elastic supportive strips are applied following a set of basic techniques. Lastly the taping is finished by locking strips that are taped over the whole tape job with non – elastic tape. (Macdonald, Chapter 1 - Introduction, 2010) This closes the gaps where the skin is still visible and secures the rest of the tape. The different taping layers and how they are applied can be seen in Image 33.

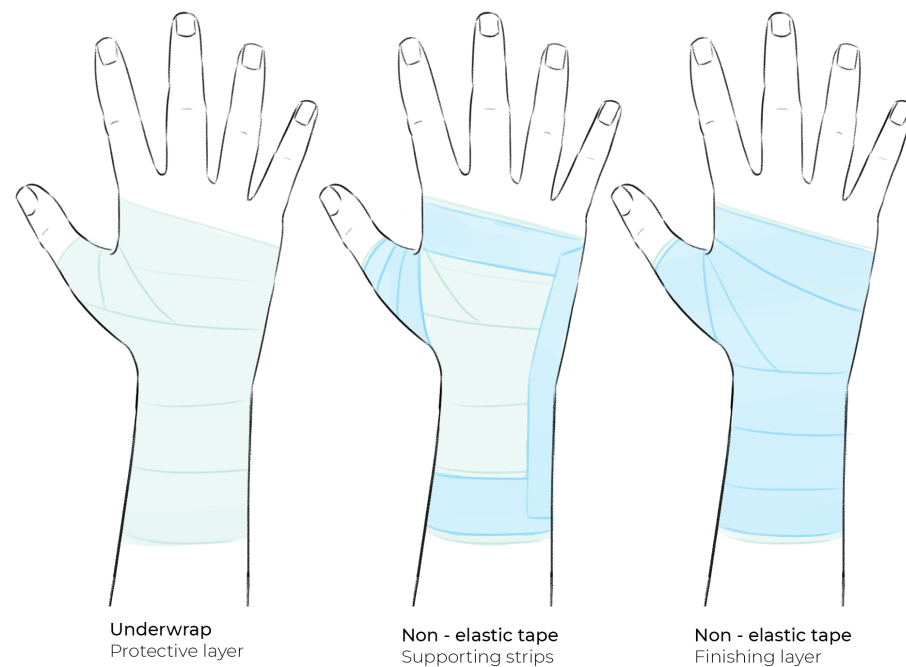


Image 33: Taping layers

Anchors

Anchors are the first strips applied during the tape job. They are placed above and below the place of injury, see Image 34. Anchors are used to minimize skin drag and should be applied without tension. (Macdonald, Chapter 1 - Introduction, 2010)

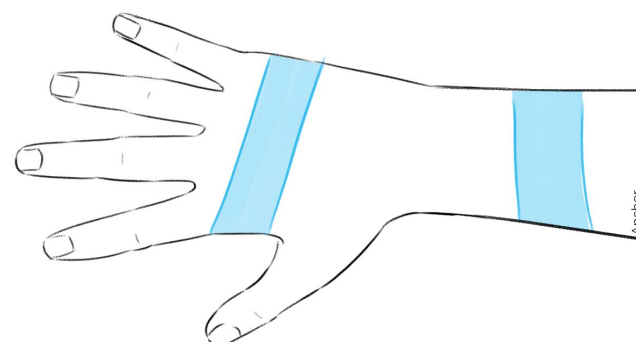


Image 34: Anchors

Taping

Horizontal strips

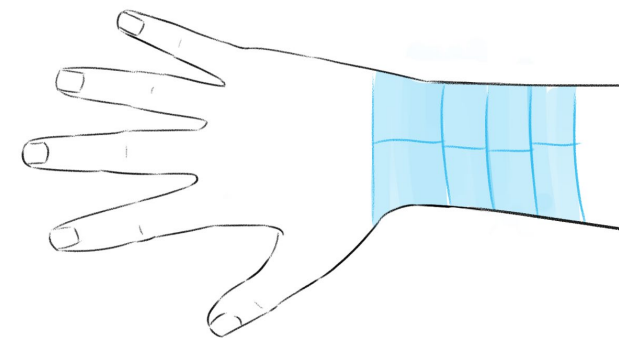


Image 35: Horizontal strips

Gibney or horizontal strips are used to add stability to a joint, see Image 35. (Macdonald, Chapter 1 - Introduction, 2010)

Vertical strips

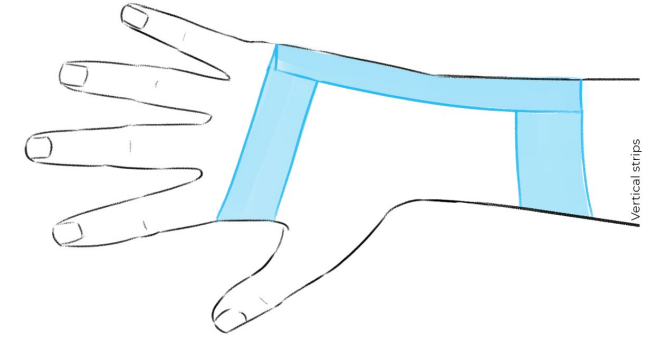


Image 36: Vertical strips

Vertical strips are applied from anchor to anchor, see Image 36. They limit mobility by drawing the distal part of the injury towards the proximal part. (Heweton, Austin, Gwynn-Brett, & Marshall, 2010)

Check reins

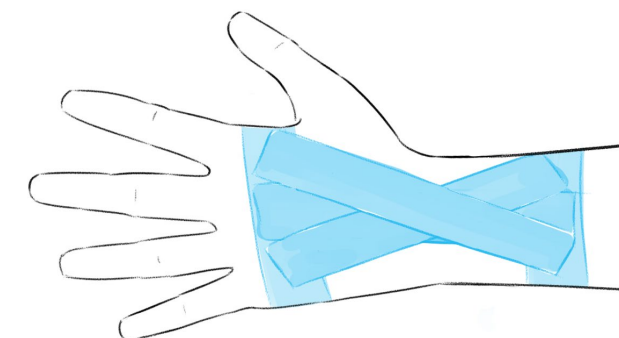


Image 37: Check reins

Check reins or butterflies are used to restrict range of motion. They can resist stresses in multiple directions as well as torsional stresses. It consists of three or more strips applied at angles between 10 to 45 degrees, see Image 37. They are placed over the axis of rotation of the joint. (Heweton, Austin, Gwynn-Brett, & Marshall, 2010) When applied to the palm of the hand check reins restrict hyper extension. When applied to the back of the hand check reins can restrict hyper flexion.

Spica

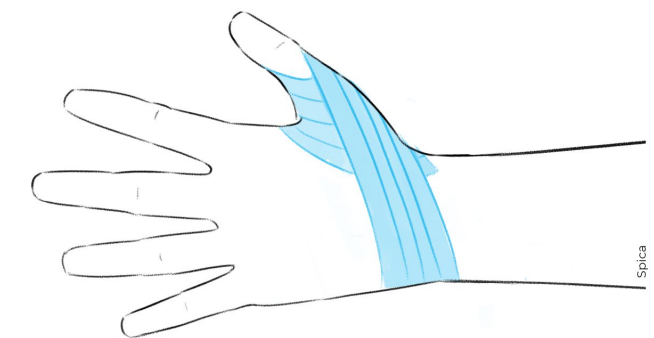


Image 38: Spica

Spicas or figure eight bandages are used to restrict range of motion and minimize swelling. (Macdonald, Chapter 13 - Spicas and triangular bandages, 2010) They are mostly used to prevent the thumb from folding back, hyper extension, see Image 38.

As a preventative measure, goalkeepers can tape their wrists. Taping provides support, limits extreme motions and protects against harmful forces. There are several types of tape that can be used. A standard tape job includes a protective layer of underwrap, non-elastic tape strips to provide the needed support and a non-elastic top layer to fill all the gaps and secure the tape in place. The support strips can be placed according to different techniques to provide different types of support. Combining the different techniques provides personalized support to the goalkeeper.

Wrist protection

Next to taping there are also other products to prevent wrist injury. For goalkeepers there are a few wrist protectors on the market, most of which are made of a soft material and are used purely to stimulate recovery. For other sports where the FOOSH is more common, such as skate- and snowboarding, wearing wrist protection is more common. For these sports there are more wrist protectors on the market. Most of these wrist protectors are very rigid and stop the movement of the wrist all together. Other wrist protectors on the market are made for injuries due to repetition, such as a tennis elbow. These wrist protectors provide support through compression and stimulate healing. In images 39 - 46 an overview and analysis of different types of wrist protectors can be seen.



Image 39: Push sports wrist protector (Merkala, n.d.)

Push sports €19,95

Tennis / Golf / Badminton

- Only covers wrist
- Soft support
- Only supports with compression
- One handed application
- Velcro to tighten
- Can be used with goalkeeping gloves



Image 40: Reusch GK wrist protector (Pro Direct, n.d.)

Reusch GK €13,00

Goalkeeping

- Covers the palm of the hand
- Provides minimal support
- One handed application
- Made for goalkeepers



Image 41: Atom palm wrist protector (Skatepro, n.d.)

Atom Palm €14,95

Skateboarding

- Will not fit with goalkeeping gloves
- Rigid support
- Bulky cover on the palm
- One handed application
- Velcro to tighten



Image 42: Mc David wrist protector (Korfbalshop.nl, n.d.)

Mc David €19,50

Multi-sport use

- Only supports with compression
- One handed application
- Velcro to tighten
- Can be used with goalkeeping glove
- No material on the palm of the hand

Wrist protection



Image 43: Wed'ze wrist protector (Decathlon, n.d.)

Wed'ze €14,99

Snowboarding

- Covers palm of the hand
- Does not fit with goalkeeping glove
- Rigid support on back of hand
- One handed application
- Velcro to tighten
- Soft support on palm of hand
- Slits in rigid support for extra movement



Image 45: Mc David wrist protector (McDavid 451, n.d.)

Mc David €19,95

Multi-sport use

- Only supports with compression
- One handed application
- Velcro to tighten
- Promotes healing
- Can be used with goalkeeping glove



Image 44: Novamed wrist protector (podobrace, n.d.)

Novamed €34,95

Multi-sport use

- Rigid support on both sides of hand
- Covers palm of the hand
- Does not fit with goalkeeping glove
- One handed application
- Velcro to tighten



Image 46: Mc David wrist protector (McDavid Wrist Brace, n.d.)

Mc David €11,95

Multi-sport use

- Only supports with compression
- Localised support around wrist
- One handed application
- Velcro to tighten
- Can be used with goalkeeping glove

From the assortment of wrist protectors shown can be concluded that the wrist protectors that would fit with a goalkeeping glove are mostly made of soft materials. They provide support by adding compression to the wrist. The wrist protectors that provide more support do this with a rigid plate on the back or on the palm of the hand. These protectors are bulky and stiff making them less ideal for goalkeeping. The common way to tighten the wrist protector is by using Velcro, only one of the wrist protectors shown does not use this.

Conclusion

The wrist is a complex body part consisting of multiple joints, bones, ligaments and tendons. The intrinsic structure of the wrist allows it to move in four directions: flexion, extension, radial deviation and ulnar deviation. Together with movement of pronation and supination of the two bones in the under arm and the movements of the fingers, the hand can be positioned to allow for movements such as pinching, grasping, holding, catching and throwing objects.

The wrists consists of the radiocarpal joint and the midcarpal joint which together are responsible for the movements of the wrist. The joints are made up of the 8 carpal bones, the radius bone and the ulna bone. The 8 carpal bones can all move separately. They are stabilized by the various ligaments running in between and over top of them.

Most goalkeeping injuries are related to a FOOSH or fast ball against the hand causing the wrist to hyper extend. During hyper extension, the forces applied to the wrist are more concentrated through the scaphoid and towards the radius. This can be seen as one of the explanations of why the scaphoid fracture is the most common carpal bone fracture. The scaphoid is not the only part of the wrist prone to injury. Distal radius fractures, scapholunate ligament tears and tears of the TFCC are also common injuries in contact sports such as soccer. As the injuries are for the largest part caused by hyper extension of the wrist, the wrist protector should limit this movement. The other directions can be left unobstructed.

To prevent injuries, goalkeepers can tape their wrists. Taping reduces the range of motion of the wrist and increases the forces needed to cause injury to the wrist. There are different types of tape, pre-wrap, elastic and non-elastic tape, that are used to tape the wrist. For different injuries and uses the wrist should be taped differently. The tape is discarded after use.

Another way to prevent wrist injuries is by wearing a wrist protector. In other sports, in which a FOOSH is more common such as snowboarding, wearing wrist protection is also more common. The wrist protectors used during those sports provide support by adding rigid plates. Goalkeepers, however, do not use these types of wrist protectors as they do not fit underneath their goalkeeping gloves and obstruct the movement too much. The types of wrist protectors that would fit underneath a goalkeeping glove are made of soft materials and only rely on compression to provide support.

With the research of parts 1 and 2, the full context of the wrist protector has been made clear. This results in boundary conditions within which the wrist protector should function. In part 3 “Synthesis” the insights from parts 1 and 2 are translated into a use scenario and the boundary conditions for the wrist protector are summarized in a list of requirements.

Requirements from part 2

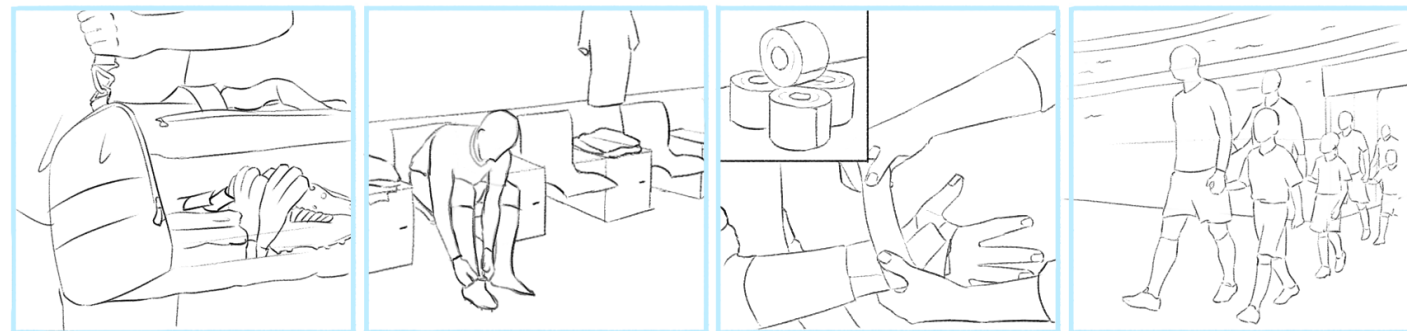
- The wrist protector should limit extension while not obstructing the goalkeepers' performance
- The wrist protector should allow movement in the other directions, mainly flexion
- The wrist protector should be able to provide protection for the left and right hand
- The wrist protector should provide a personalized fit for the goalkeeper
- The wrist protector should be able to compete with the price of 3 rolls of tape a week (Alblas, 2020), used over a period of 90 weeks for a total of (€5,70 x 3 rolls of tape x 90 weeks) €1539 (LEUKOTAPE CLASSIC 3,75 CM X 10 METER, n.d.)

Current scenario

As explained in chapter “Taping”, goalkeepers can tape their wrists to prevent injuries. Taping has a few negative sides which makes it an unideal solution. The current scenario for goalkeeping with tape can be seen in Image 47. In this scenario there are a few scenes that the designed wrist protector can improve upon.

Firstly, tape takes a few minutes to apply, scene three, and sometimes has to be done by a physical therapist. This takes up valuable time of the goalkeeper and makes them dependent on someone else to help them. Secondly, the tape stretches during the game, scene 5, and eventually loses its supporting functionality. Thirdly, the feeling with the ball is obstructed by the tape crossing over the palm of the hand, scene 7. This influences the goalkeepers’ capabilities. Fourthly, to remove the tape it has to be cut away from the arm, scene 9, which takes time and can be precarious. Afterwards, the tape is discarded. Lastly, the tape can cause irritation to the skin of the goalkeeper, scene 10.

The designed wrist protector should improve on these scenes. In the requirements, chapter “Requirements”, these insights have been included.

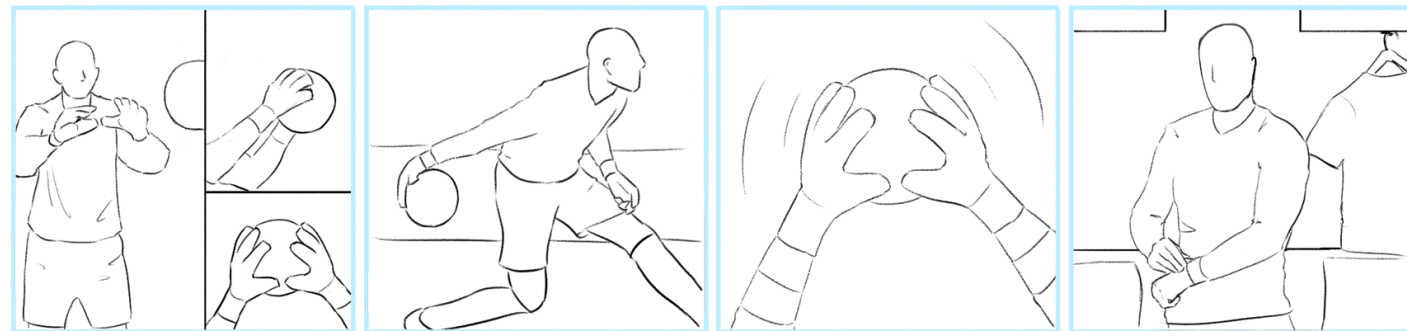


The goalkeeper takes their soccer gear with them in a sports bag.

The goalkeeper puts on their soccer gear.

The goalkeeper gets a roll of tape from the physical therapist. The goalkeepers' wrists are taped by the physical therapist or themselves.

The players walk onto the field for the match or training.

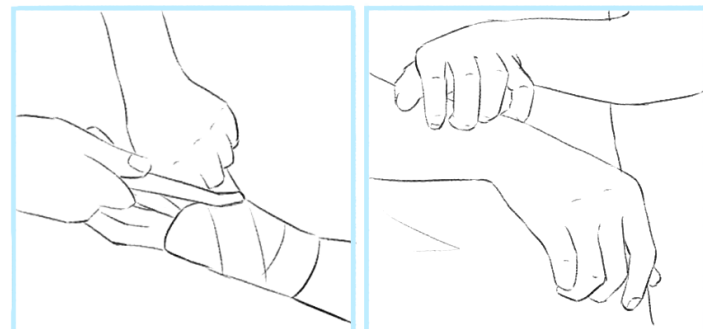


The goalkeeper has to make a save against a hard shot ball. With every save, the tape gets less tight.

The goalkeeper distributes the ball back onto the playing field, they are not obstructed by the tape.

The goalkeeper has a hard time catching one of the ball since the palms of their hands are covered in tape, obstructing the contact with the ball.

Afterwards, the goalkeeper takes off their soccer gear.



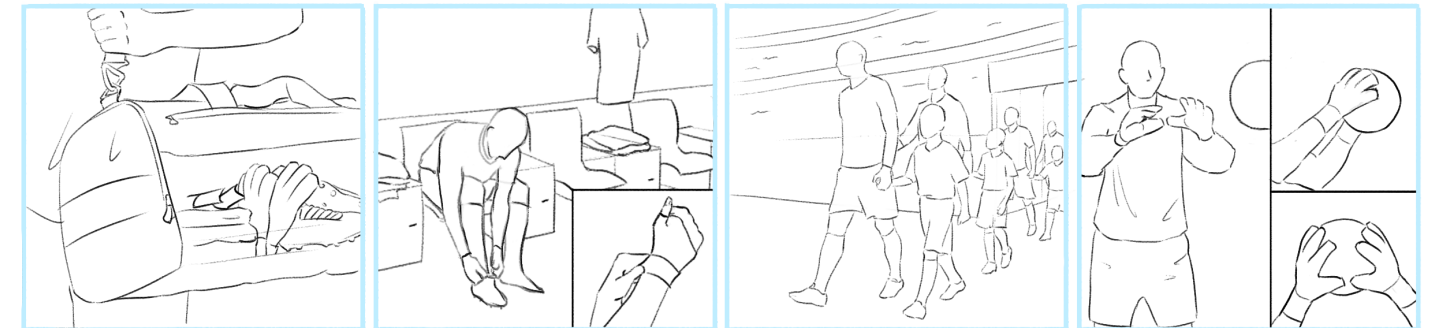
The goalkeeper has to cut away the tape to get out. The used tape is discarded.

The tape has irritated the goalkeepers' skin and removed some of the hairs on their arm.

Image 47: Current scenario

Envisioned use scenario

Based on the research into goalkeepers, their wrist injuries and the different goalkeeping techniques a scenario has been created that shows the different situations in which the wrist protector will have to function, see Image 48. This not only includes preventing injuries during practice and competition but also allowing the goalkeeper to perform other goalkeeping tasks, clean the wrist protector and to store the wrist protector. This scenario, together with the research, will form a basis for the in chapter “Requirements” described requirements for the product.

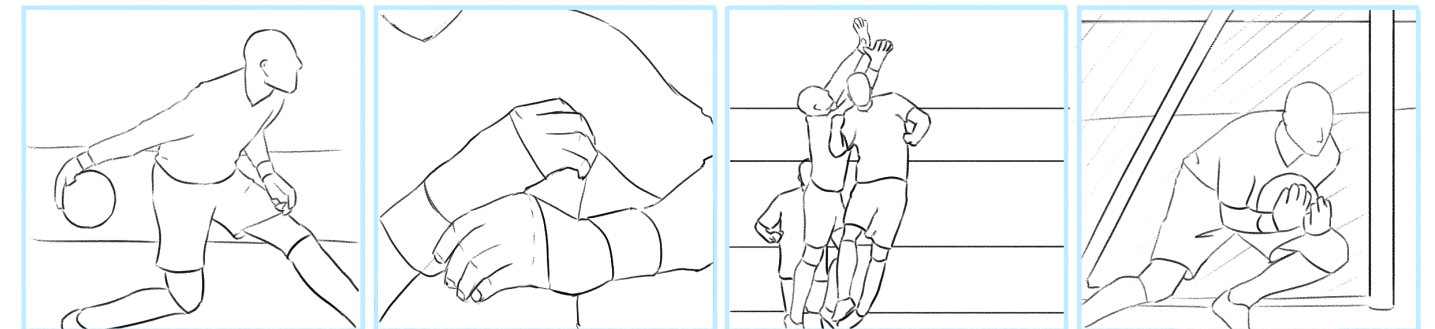


The goalkeeper takes their soccer gear, including his wrist protection, with them in a sports bag.

The goalkeeper puts on their soccer gear and wrist protection. The wrist protection fits tightly and secure around his wrist. The wrist protection fits within his goalkeeping gloves.

The players walk onto the field for the match or training.

The goalkeeper has to make a save against a hard shot ball. The wrist protector keeps their wrists from overextending, preventing injury.



The goalkeeper distributes the ball back onto the playing field.

During the practice or match the goalkeeper makes some slight adjustments to the fit of the wrist protection.

Due to the intensity of the game the goalkeeper collides with an opponent when trying to save a ball. The wrist protector does not harm the other players.

During another save the goalkeeper catches the ball and locks it between his arms and upper body.



The opponents have gotten a penalty in their favour. The wrist protector makes the goalkeeper feel confident in his abilities.

Afterwards, the goalkeeper takes off their wrist protection and soccer gear.

The goalkeeper cleans and washes the wrist protection.

The wrist protection is put away into his sports bag.

Image 48: Envisioned use scenario

Requirements from the envisioned use scenario

- The wrist protector should store away neatly
- The wrist protector should not cause harm to the user or to other players (KNVB, 2020)
- The wrist protector should be made of lightweight materials (KNVB, 2020)
- The wrist protector should be made of soft materials (KNVB, 2020)
- The user should be able to apply the wrist protector with one hand

Requirements

Based on the research shown in the previous chapters a list of requirements was constructed. The list of requirements was used during the ideation phase to set a boundary for the brainstorm. On top of the set of requirements, a list of wishes was constructed to help with the concept selection process. The list of requirements was also used to finalize and evaluate the final design.

1. Performance

- 1.1 The wrist protector should limit extension while not obstructing the goalkeepers' performance
- 1.2 The wrist protector should allow movement in the other directions
- 1.3 The wrist protector should be able to provide protection for the left and right hand
- 1.4 The wrist protector should have minimal influence on the goalkeeper's performance
- 1.5 The wrist protector should provide a personalized fit for the goalkeeper
- 1.6 The wrist protector should not cause harm to the user or to other players (KNVB, 2020)

2. Environment

- 2.1 The wrist protector should be able to withstand moisture from sweat and cleaning

3. Life in service

- 3.1 The wrist protector should withstand an average use of 6 days a week for 4 hours a day for a duration of 90 weeks (2 years with 6 weeks of vacation per year)

4. Maintenance

- 4.1 The wrist protector should not need any maintenance during life in service
- 4.2 The wrist protector should be washable/ cleanable

5. Costs

- 5.1 The wrist protector should be able to compete with the price of 3 rolls of tape a week (Alblas, 2020), used over a period of 90 weeks for a total of (€5,70 x 3 rolls of tape x 90 weeks) €1539 (LEUKOTAPE CLASSIC 3,75 CM X 10 METER, n.d.)

6. Size and weight

- 6.1 The wrist protector should be usable with the standard goalkeeping gloves
- 6.2 The wrist protector should be made of lightweight materials (KNVB, 2020)
- 6.3 The wrist protector should be able to store away neatly

7. Materials

- 7.1 The material used in the wrist protector should allow the goalkeeper's skin to breathe
- 7.2 The wrist protector should not cause skin irritation
- 7.3 The wrist protector should be made of soft materials (KNVB, 2020)

8. Ergonomics

- 8.1 The wrist protector should not cause discomfort to the user
- 8.2 The user should be able to apply the wrist protector with one hand
- 8.3 The user should be able to apply the wrist protector by themselves

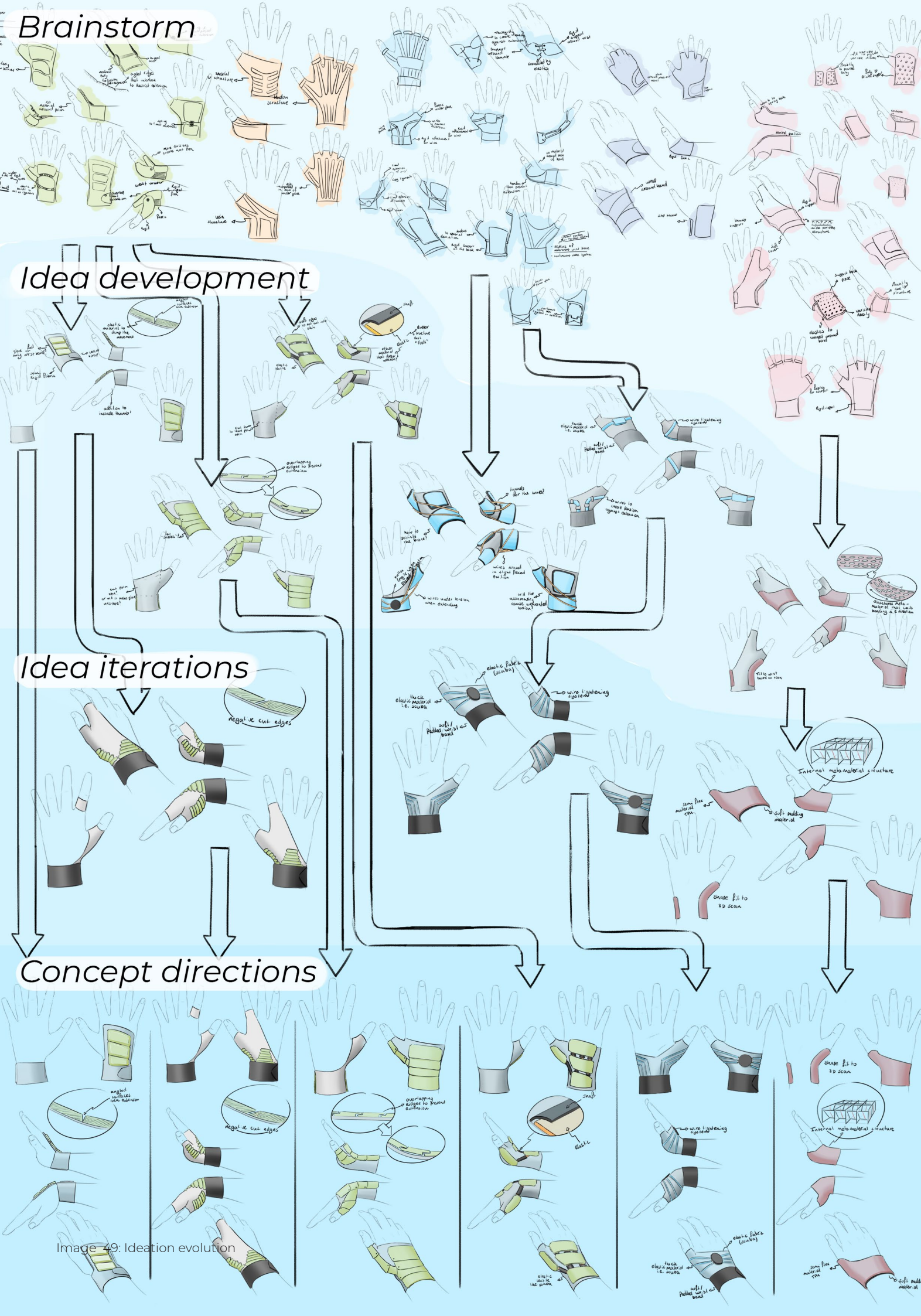
9. Reuse/ recycling

- 9.1 When a part of the wrist protector breaks it should be replaceable to increase the protectors life in service

List of wishes

Next to the list of requirements there are also certain wishes that the final concept should comply to, to some degree. These wishes are based on the research performed as well as discussions with the professional goalkeeper. With these wishes a ranking of the developed concept directions will be performed, chapter "Direction".

- 1. The wrist protector does not need to be adjusted during the game
- 2. The movement of the wrist should be brought to a stop in a progressive way (Dampening)
- 3. The wrist protector should be as easy as possible to put on and take off
- 4. The wrist protector should fit as comfortably around the goalkeeper's hand as possible
- 5. The wrist protector should leave the palm of the hand open
- 6. The wrist protector should be as thin as possible
- 7. The wrist protector should be as light as possible
- 8. The wrist protector should take up minimal space when stored



Ideation

Using the insights gathered from the research, ideation was started. During ideation, the solution direction was focused on limiting extension since hyper extension injuries are the most common. Limiting this extension will be the main purpose of the wrist protector.

During the brainstorm phase inspiration was taken from several sources. These sources include structures found in nature, advancements in material technology, the workings of the wrist and existing types of wrist protection.

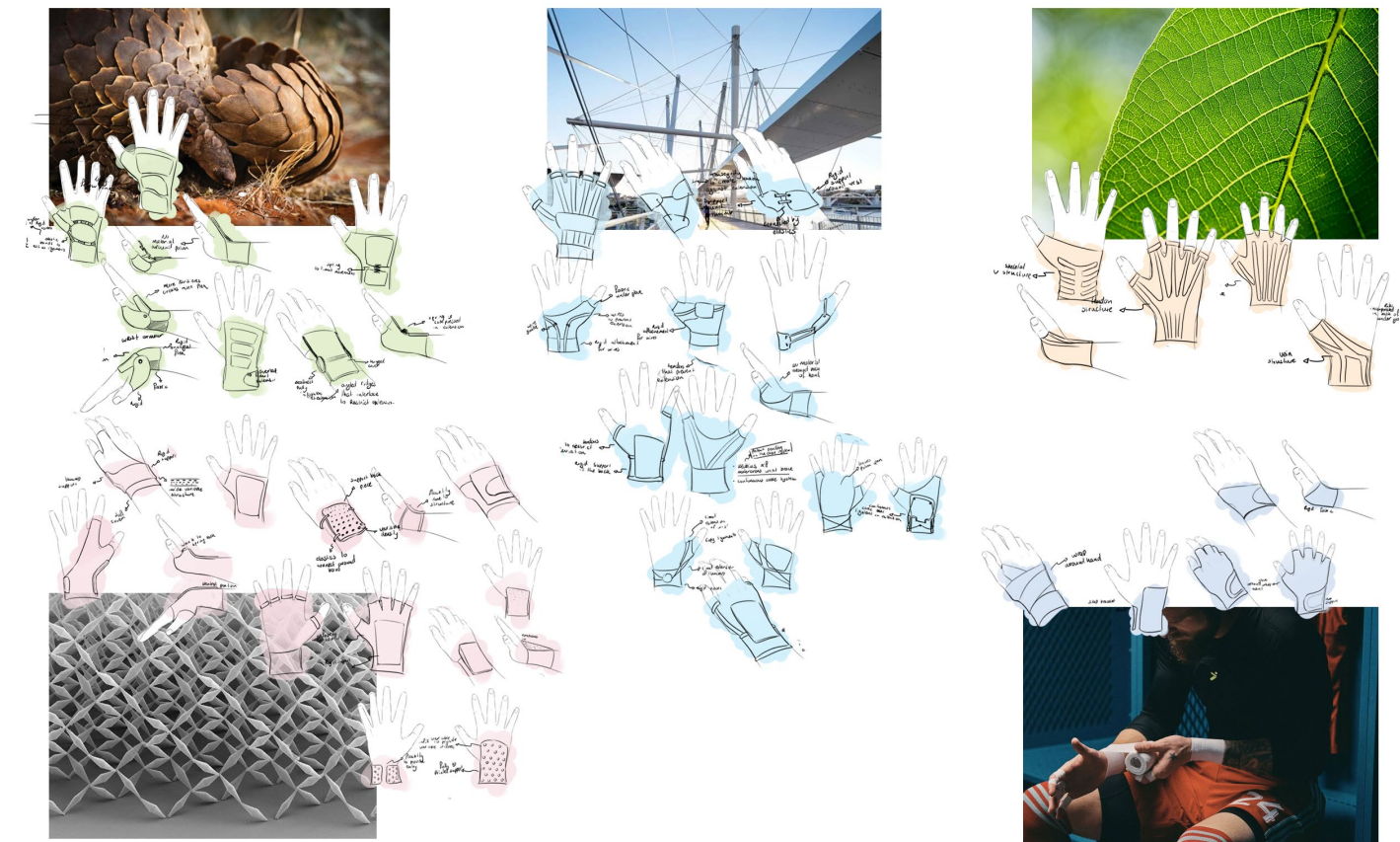


Image 50: Ideation clusters (Arjun, n.d.) (Just keepers, 2020) (Fratt, 2020) (Fischer, Thiel, & Wegener, 2020) (WWF, 2020)

The ideas were clustered into five groups based on their working principal, see Image 50.

The following clusters were created:

- Green: Plated structures, inspired by pangolins and medieval armor
- Blue: Wired structures, inspired by tensegrity and pulley systems
- Orange: Skeletal like structures, inspired by veins of a leaf and the tendons in the hand
- Red: Material based protection, inspired by advancements in material technology
- Purple: Wrapping based protection, inspired by taping and existing wrist protectors

From the initial brainstorm, six ideas that had the most potential were selected. Their potential was based on innovativeness versus feasibility. To evaluate the feasibility of the ideas, the expertise gathered in the research phase was combined with small proof of concept prototypes.

Three of the selected ideas originated from the green cluster, two ideas originated from the blue cluster and one originated from the red cluster. No ideas were selected from the purple and orange clusters since the ideas in these clusters did not seem to be able to limit extension enough. These clusters did help as a source of inspiration during the brainstorm and further development of the concept directions. The evolution from ideation to concept directions can be seen in Image 49.

Through further development of the selected ideas, new ideas were generated and the selected ideas were further developed. In this stage one of the ideas from the blue stage turned out not to be feasible and was abandoned. The other ideas were iterated on and turned into concept directions.

Image 49: Ideation evolution

Concept directions

The ideation phase resulted in six concept directions. Four of the concept directions are based on plated structures, one concept direction is based on creating tension and the last concept direction is based on the material structure. All concept directions would be a solution to the problem definition however, some concept directions have more potential than the others. To evaluate the concept directions a professional goalkeeper and hand therapist were consulted.

Concept direction 1

Concept direction 1, see Image 51, limits extension of the wrist through rigid plates on the back of the hand. When the wrist is moved into extension the plates lock together and limit the movement. By changing the angle between the plates, the amount of allowed extension can be adjusted. The plates will only lock the extension direction, leaving the flexion direction free for the goalkeeper to perform their tasks.

Professional goalkeeper

- Only limits extension.
- Leaves the palm of the hand open.
- Visible protection.
- Looks comfortable.
- How will it move with the hand?

Hand therapist

- Does not include the thumb.

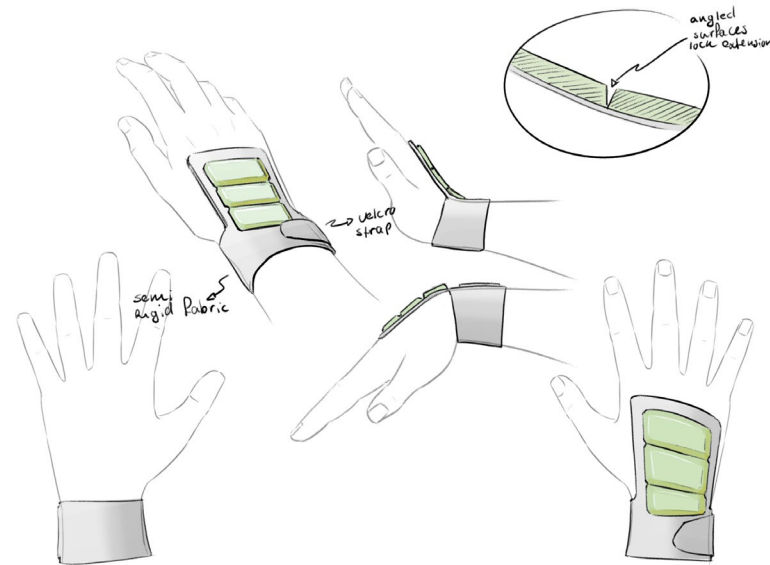


Image 51: Concept direction 1

Concept direction 2

Concept direction 2, see Image 52, limits extension of the wrist and thumb through rigid strips at the back of the hand. Since the strips are slim, they can be incorporated into the fabric. When the wrist is moved into extension the plates lock together and limit the movement. By changing the angle between the strips, the amount of allowed extension can be adjusted. The strips will only lock the extension direction, leaving movement in the flexion direction unobstructed.

Professional goalkeeper

- Less surface area covered.
- Only a small part of the back of the hand is fortified

Hand therapist

- The short fortification could result in pressure points, causing irritation.

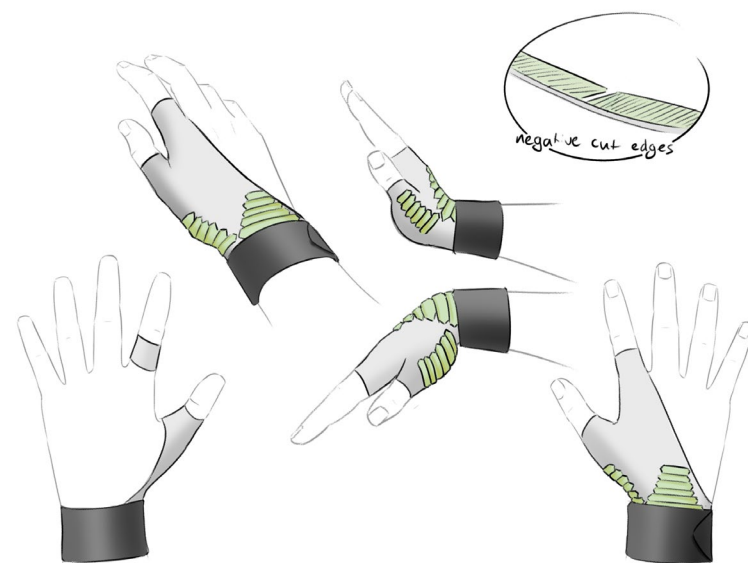


Image 52: Concept direction 2

Concept directions

Concept direction 3

Concept direction 3, see Image 53, limits extension of the wrist and thumb through overlapping plates at the back of the hand. When the wrist is moved into extension the plates collide with each other, limiting the extension. The flexion direction is not restricted.

Professional goalkeeper

- Only limits extension.
- The principle of protection looks promising.
- Looks like an abrupt stop.
- Comfort leaves something to be desired.

Hand therapist

- Looks promising

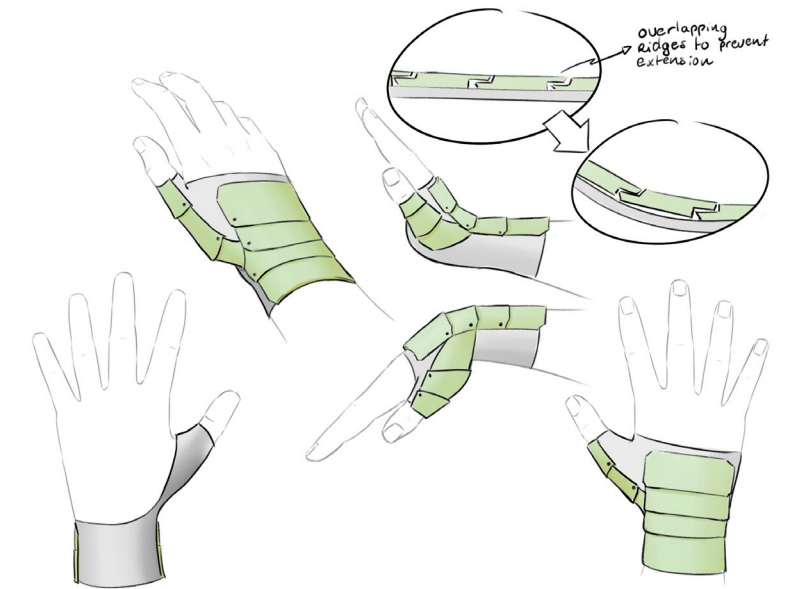


Image 53: Concept direction 3

Concept direction 4

Concept direction 4, see Image 54, limits extension and flexion of the wrist and thumb through plates at the back of the hand that are connected with elastic bands. The elastic bands are connected to a fabric glove that fits tightly around the hand. Because of this the elastic band can only extend and retract. When the wrist moves into flexion or extension the elastic bands are stretched, putting tension on the movement. This restricts the wrist from moving into hyper flexion or -extension.

Professional goalkeeper

- Free movement of the hand in the other directions.
- Gradually limits the movement.
- Clearly visible which part is fortified.
- Looks uncomfortable at first glance because of the size of the plates.

Hand therapist

- Looks promising

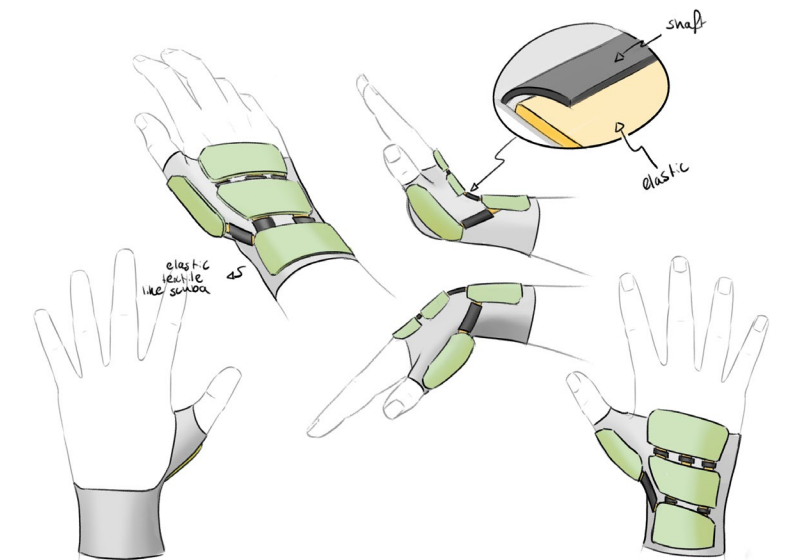


Image 54: Concept direction 4

Concept directions

Concept direction 5

Concept direction 5, see Image 55, limits extension of the wrist and thumb through cables that run from the palm of the hand to the back of the hand. As the wrist moves into extension the cables tighten, limiting the movement. With the button on the back of the hand the tension of the cables can easily be adjusted as needed.

Professional goalkeeper

- Provides support across the whole back of the hand.
- You can tighten it as you please.
- Button on the back of hand can cause irritations.
- Does not look as comfortable, especially on the inside of the hand.

Hand therapist

- Looks promising
- Wires could cause unwanted adduction of the thumb

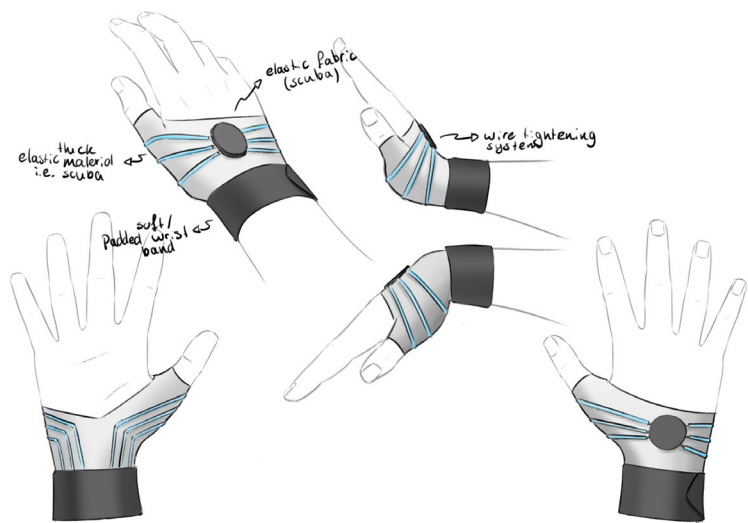


Image 55: Concept direction 5

Concept direction 6

Concept direction 6, see Image 56, limits extension of the wrist and thumb through the material's internal structure. The internal structure will lock during extension, limiting the movement, and unlock during flexion, not prohibiting the flexion movement. The brace will sit on the hand with a layer of protective foam in between the hand and brace.

Professional goalkeeper

- Only limits extension.
- Very solid yet very flexible at the same time.
- You can clearly see which part is fortified.
- Limits the movement gradually instead of abruptly.
- Leaves the palm of the hand open.
- Looks like it will be very thick.
- Will it stay in place?

Hand therapist

- Does not look suitable for this application

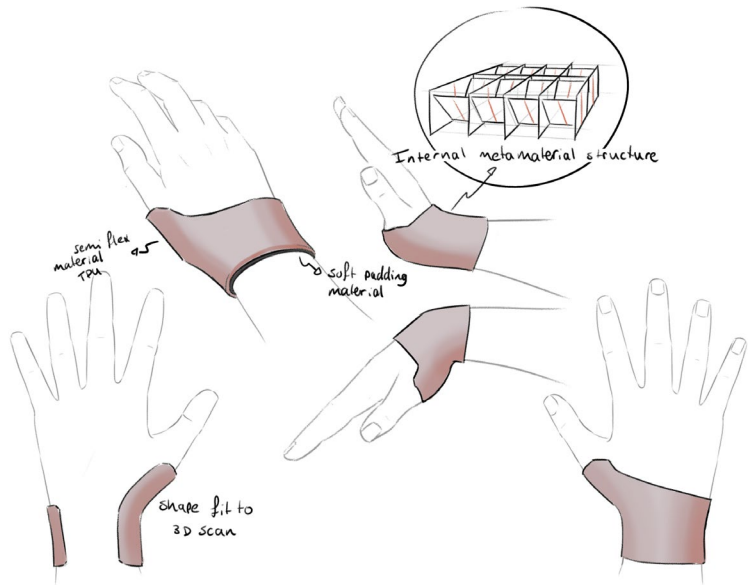


Image 56: Concept direction 6

Direction

The ideas created during ideation have been developed based on the requirements mentioned in chapter "Requirements". This means that these requirements have been fulfilled by all concept directions. In order to find the most promising concept direction, the list of wishes mentioned in chapter "List of wishes" can be consulted. Each concept direction can comply differently with each wish. This can be used to rank the concept directions and therewith find the most promising concept.

Using a weighted objectives method, see Image 57 and Image 58, the concepts were evaluated. In this method each wish is given a specific weight that corresponds with their importance for the final concept. This weight was determined by the designer, based on the expertise gathered throughout the research phase. The two most important wishes are: the wrist protector does not need any adjustments during use and it should stop the movement of the wrist in a progressive, dampened, way. Each concept was ranked by the designer on a scale from 1 - 10 based on how much they fulfilled the respective wish. By multiplying the ranking with the weight of the wish and adding all results together, a final score for each concept direction is created. The concept direction with the highest score has the most potential to be turned into a suitable final design.

	Weight
The wrist protector needs minimal adjustment during the game	20
The movement of the wrist is brought to a stop in a progressive way	20
The wrist protector is as easy as possible to put on and take off	15
The wrist protector fits as comfortably around the hand as possible	15
The wrist protector leaves the palm of the hand open as much as possible	10
The wrist protector should be as thin as possible	5
The wrist protector should be as light as possible	5
The wrist protector should take up minimal space when stored	5

CONCEPT 1		CONCEPT 2		CONCEPT 3	
Score	Total	Score	Total	Score	Total
7	140	7	140	7	140
7	140	9	180	9	180
9	135	8	120	9	135
7	105	9	135	6	90
10	100	8	80	8	80
6	30	6	30	9	45
7	35	7	35	7	35
7	35	6	30	8	40
720		750		745	

Image 57: Weighted objectives concept directions 1, 2 and 3

Direction

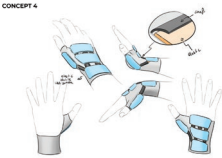
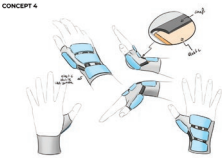
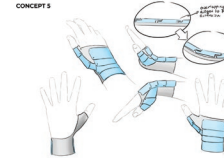
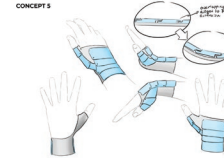
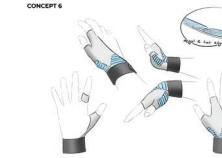
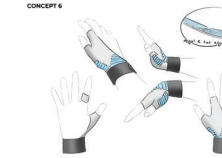
		CONCEPT 4		CONCEPT 5		CONCEPT 6	
							
	Weight	Score	Total	Score	Total	Score	Total
The wrist protector needs minimal adjustment during the game	20	8	160	8	160	7	140
The movement of the wrist is brought to a stop in a progressive way	20	9	180	8	160	7	140
The wrist protector is as easy as possible to put on and take off	15	8	120	8	120	9	135
The wrist protector fits as comfortably around the hand as possible	15	8	120	7	105	8	120
The wrist protector leaves the palm of the hand open as much as possible	10	8	80	8	80	8	80
The wrist protector should be as thin as possible	5	8	40	8	40	9	45
The wrist protector should be as light as possible	5	7	35	7	35	8	40
The wrist protector should take up minimal space when stored	5	7	35	7	35	8	40
			770		735		740

Image 58: Weighted objectives concept directions 4, 5 and 6

In the weighted objectives evaluation concept direction 4 has the highest score and would seem most promising. However, since the scores are close together, a definite conclusion can not be drawn. The weighted objectives method is a subjective way of grading. Therefore, a difference as small as in this case is purely an opinion.

Since the weighted objectives method did not give a conclusive answer, the professional goalkeeper and the hand therapist were consulted for their expertise.

The professional goalkeeper preferred concept direction 4 because of the working principle that would gradually limit extension while only slightly limiting the other directions. Concept direction 1 was a close runner up as this leaves the palm of the hand open and has an interesting working principle to limit extension.

The hand therapist preferred concept directions 4 and 5. These concept directions include the thumb, providing better injury prevention against scaphoid and thumb injuries. They also seemed to provide the most comfortable yet effective support to the rest of the wrist.

Direction

After the consult with the experts and based on the weighted objectives evaluation, the choice was made to continue with a combination of concept directions 1 and 4, see Image 59.

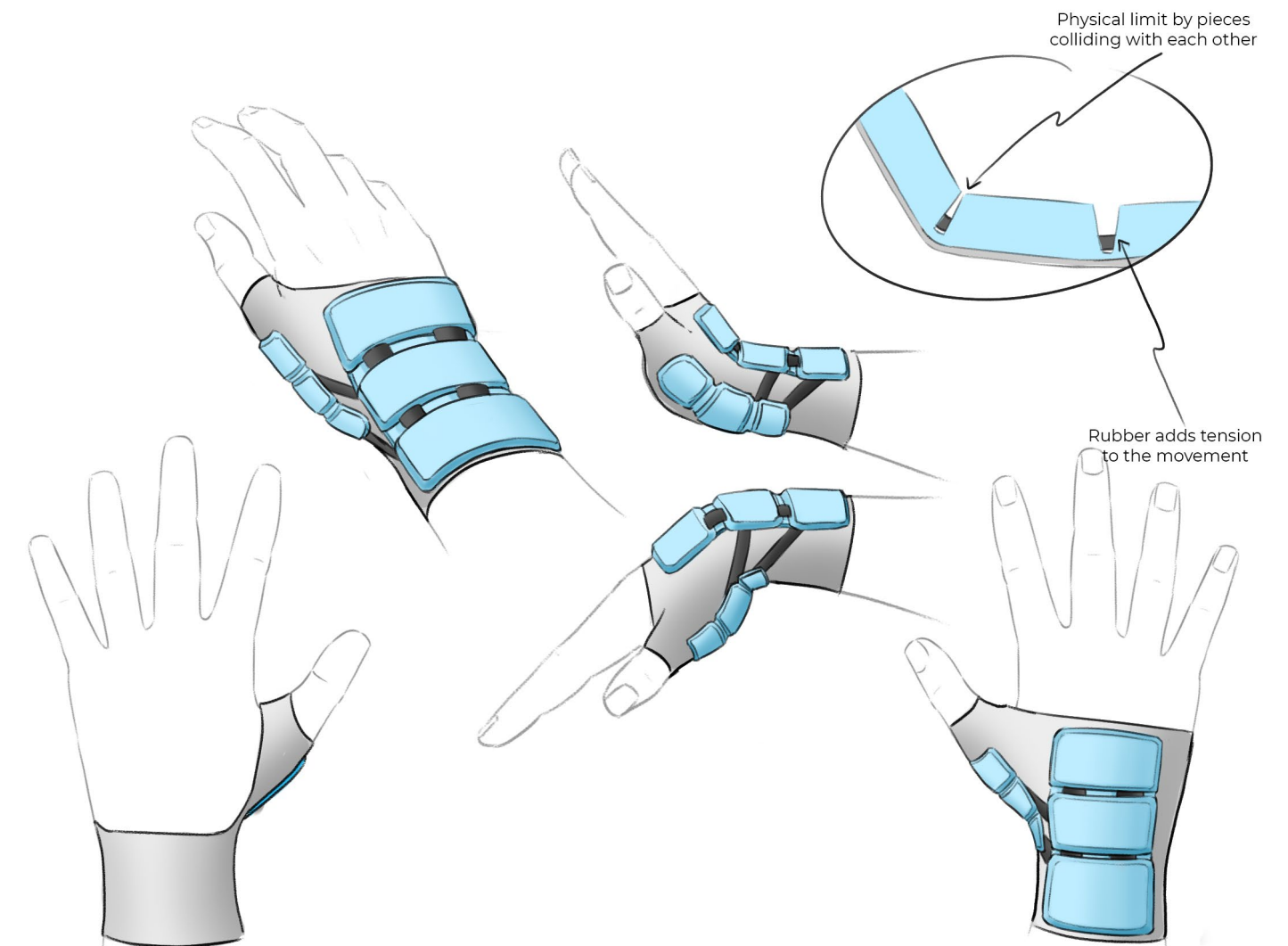


Image 59: Combined concept directions

Through this combination the best aspects of both concepts can be combined. In the weighted objectives evaluation, concept direction 1 scored low on the first two wishes. By combining it with concept direction 4 these issues can be resolved while keeping concept direction 1's working principle to support the principle of concept direction 4.

This new concept direction works as follows. The extension is limited by the plates on the back of the hand colliding. The rubbers between the plates dampen the movement, making it more gradual. By attaching the working principle to a glove it is less likely to move around during activities. Limiting extension of the thumb will also be included, such as in concept direction 4. To keep the ball feel of concept direction 1, the material of the glove at the palm of the hand is removed.

Prototyping

In the concept direction, explained in the previous chapter, the most critical part is the protection plate on the back of the hand. This plate needs to allow for a large range of motion in the flexion direction while limiting the range of motion in the extension direction. However, the extension direction cannot be fully limited or it will influence the goalkeepers performance. Furthermore, this plate needs to be rather thin in order for it to fit underneath a goalkeeping glove. Using a build - measure - learn approach the plate was developed.

Proof of principle & Grasshopper prototype 1

With three small 3D prints the proof of principle of the wrist protector was evaluated. The prototypes showed that making the parts collide was a suitable way to limit the extension. It was concluded that the distance and angle between the parts determine the amount of extension that is allowed. Weaving rubber through the parts increased the required force to move the parts into their outer position, making the limitation less abrupt.

After several tests the PLA in between the parts broke due to fatigue. From this was learned that PLA was not suitable in the long term as a material for the wrist protector. Additionally it showed that when connecting the parts only with a stretchable material, in this case the rubber, the extension is no longer limited.

A grasshopper script was created with which the plates could be shaped to a 3D scan of the goalkeeper's wrist. The previous 3D prints and the grasshopper prototype were evaluated together with another industrial designer with a background in mechanical engineering. Through a brainstorm it was concluded that the plate on the back of the hand should be split into three parts to allow for the curvature of the wrist. This split matches with the three columns of the carpal bones, as described in chapter "Kinematics of the wrist".

Grasshopper prototype 2

Through an iteration on the grasshopper prototype and small 3D prints the extra splits in the plate were evaluated. These prototypes showed that even though the plates are less wide, they would still limit the extension. The issue concerning fatigue of the PLA was not yet resolved. Several tests were performed to find the best bottom layer thickness that would connect the plates. However, due to changes in material choice this thickness is later disregarded.

During these tests the location of the protection pieces on the hand was also evaluated. This showed that when the horizontal slit in the protection pieces is right on top of the wrist joint, the extension is not limited. This means that at least one of the parts of the protection pieces should cover the wrist joint.

Full glove 1

The newly created protection pieces were tested as a full protection glove. The protection glove consisted of an elastic under-glove made out of a compression sleeve, a layer of EPDM rubber and the three protection piece columns. The prototype showed that the protection pieces were able to limit the extension. However, they had to be held to the hand tightly as they wanted to detach from the under-glove.

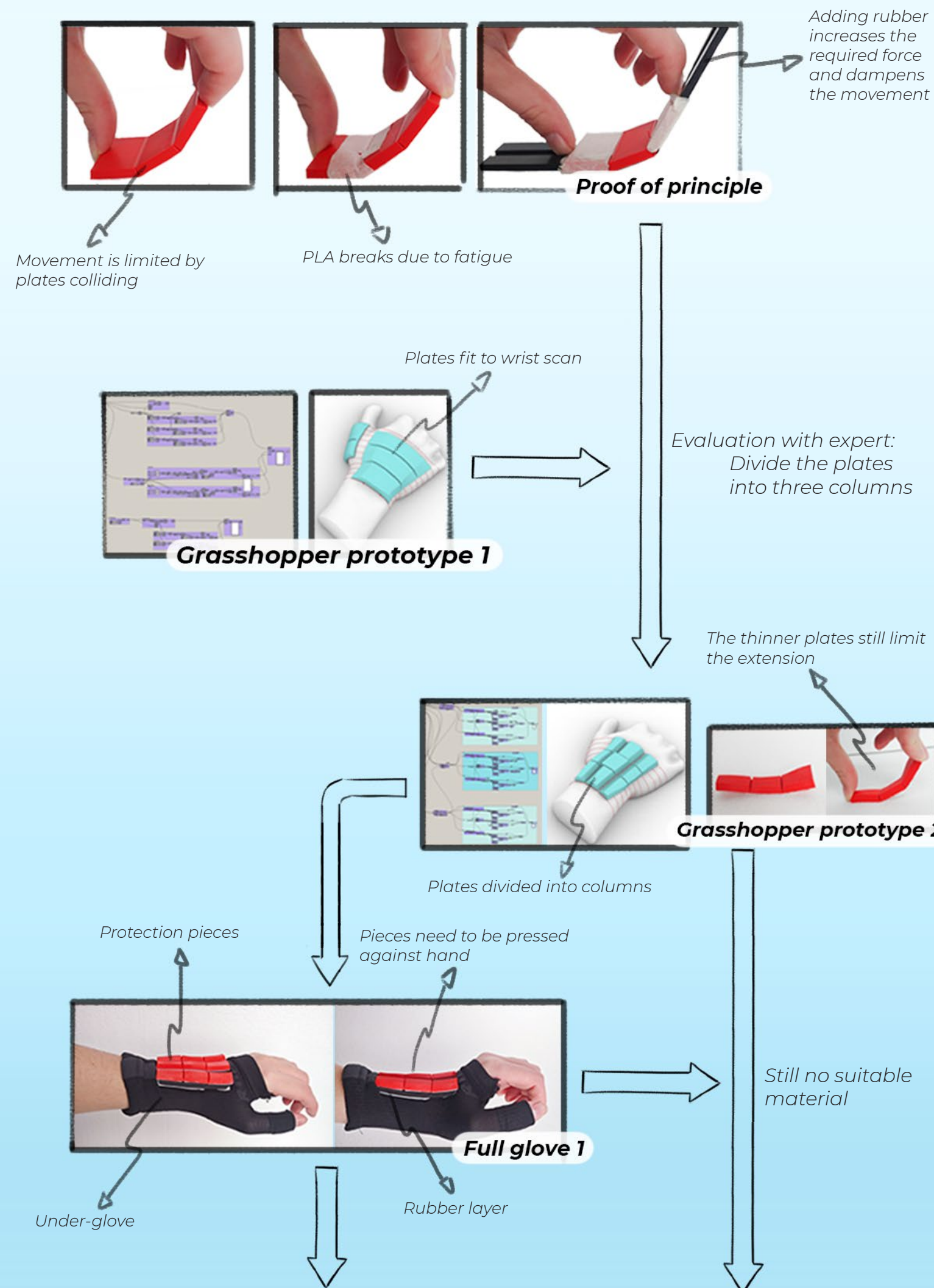
The protection glove was also slightly uncomfortable since the edges of the protection pieces would dig into the skin. Elongating the pieces to cover more area on the back of the hand as well as on the arm could decrease this effect. Adding more divisions to the pieces horizontally could also decrease this effect as it will create a smoother arc when the protection pieces are in maximum extension.

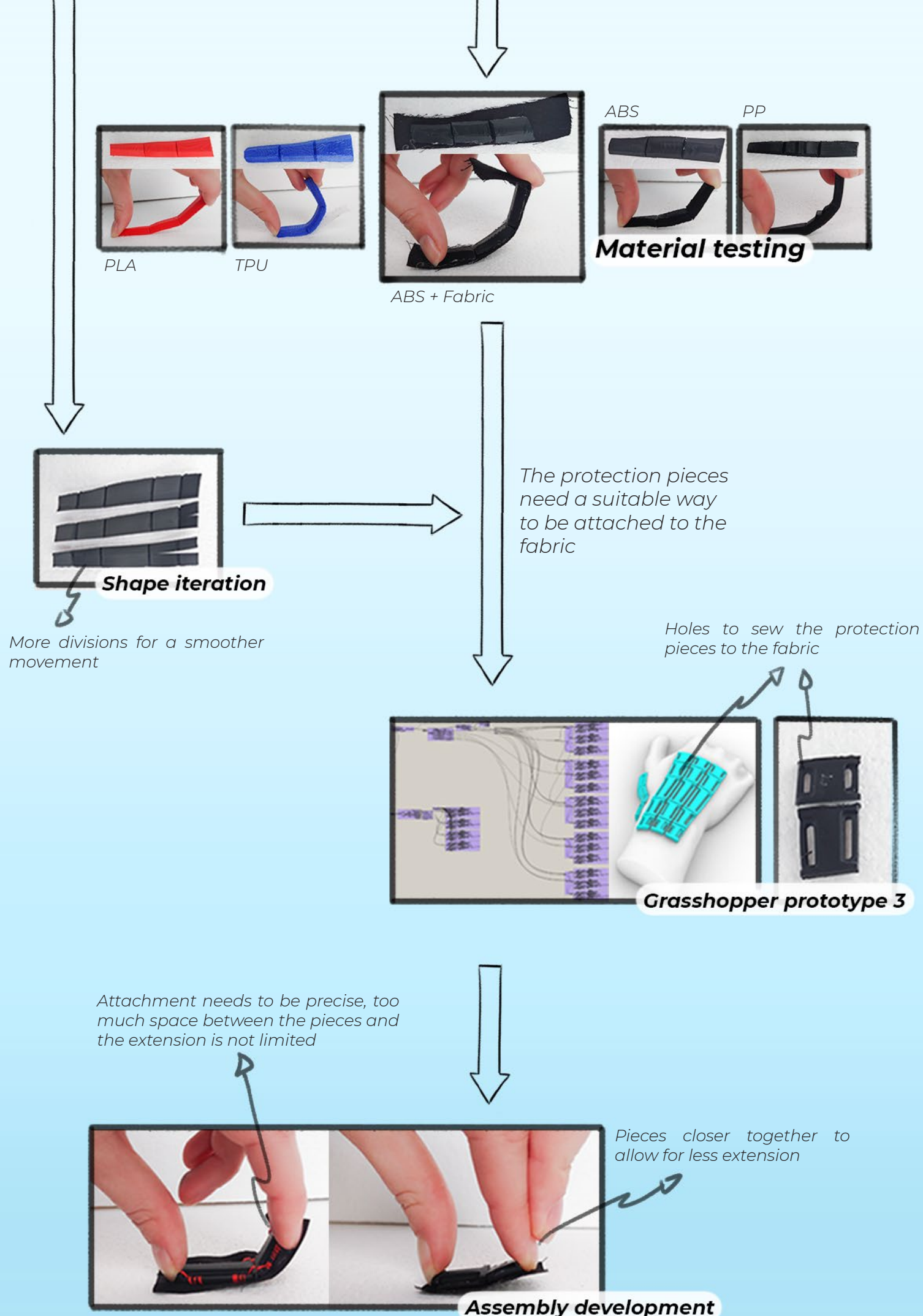
The full glove prototype was also evaluated with a goalkeeping glove. This showed that the wrist protector would fit however, it was an uncomfortably tight fit. The goalkeeper would not have been able to put on their second goalkeeping glove as the fine motor skills of the fingers were needed to put it on. To solve this, the protection pieces can be made slightly thinner and a thinner rubber could be used.

Material testing

Several different materials were tested to find the most suitable solution. The tested materials were, PLA, TPU, ABS with a non-stretch fabric bottom layer, full ABS and PP. The TPU and PP were both flexible materials. Due to their flexibility they were not able limit the extension, as was also seen in the proof of principle prototypes. The full ABS print showed the same fatigue issues as the PLA print.

The ABS print connected to a fabric bottom layer performed the best. It was able to adequately limit the extension while not showing any signs of tear or other types of damage. It had the additional benefit that the movement into flexion was left completely unobstructed.





Prototyping

Shape iteration

Based on the full glove prototype a new shape iteration was made. In this iteration the protection pieces were elongated and were given more divisions. The divisions had different sizes, with the middle divisions being the biggest and the outer divisions being the smallest. The middle division has to be the biggest in order to fully cover the wrist joint and limit the extension, as was concluded from the grasshopper prototype 2 tests. The new shape provided a more fluent arc and cuts less into the skin.

The new shape was printed in ABS and clearly showed one of the main issues in printing with this material, delamination. Because of the difference in temperature between the extruded filament and the last printed layer, the layers would not melt together. The shorter the time between the different layers, the less likely delamination becomes. This principle was used in the next prototypes.

Grasshopper prototype 3

Applying all the previously found insights a new grasshopper prototype was created. In this prototype the protection columns are made up out of five separate pieces which will have to be sewn onto a piece of fabric with the appropriate distance between them to limit extension. Holes were made in the protection pieces to be able to hand sew them onto this piece of fabric. The pieces were printed on their shortest side to prevent delamination.

Assembly development

The assembly was tested by attaching two of the protection pieces to a small piece of fabric. This showed that the distance between the pieces had to be fairly exact. When the pieces were slightly to far apart they were able to move on top of each other, making them able to create up to a 90 degree angle instead of limiting the movement. By making the pieces slightly higher this margin for error was decreased. In the assembly development close attention was payed to making the distance between the protection pieces as small as possible. When sewing the pieces onto the fabric it was also necessary to sew around all edges of the piece to avoid the piece from moving separately from the fabric.



Image 60: Full glove 2

Full glove 2

A second full glove prototype, see Image 60, was created that could fit goalkeeper Norbert Alblas. The protection pieces were printed in ABS with the shortest side attached to the build plate. This decreased the time between the layers, decreasing the chance of delamination. An under-glove, made out of the same compression sleeve material as the first full glove, was made to fit the goalkeeper's hand. The protection pieces were hand sewn onto a non-stretch piece of fabric which in its turn was attached to the under-glove using a sewing machine. The rubber layer was excluded from this prototype.

The full glove prototype was evaluated with Norbert Alblas. The prototype showed a few flaws when worn. The protection pieces were not fully in line with the hand, the under-glove made the protection pieces bulge up due to the stretch in the fabric and some pieces still broke due to delamination of the layers.

The under-glove was not tight enough, allowing the protection pieces to come free from the hand. This was also due to the stretch in the fabric. However, when the protection pieces were held onto the hand, The goalkeeper mentioned that the extension limit could be felt. He also did not expect any problems with fitting it underneath his goalkeeping glove.

Based on the prototyping the following insights should be incorporated into the final design: There should be 3 columns of protection pieces made up out of 5 rows of protection pieces. These pieces should be attached to a non-stretch fabric layer to get the desired limiting effect. The under-glove, to which the protection pieces and fabric layer are attached, should also have no stretch. A solution for getting into the glove needs to be explored. Layer delamination will continue to be a problem, a suitable production method should be explored.

Conclusion

Through sketching and prototyping several ideas were generated. The ideas were based on specific working principles such as skeleton structures or advancements in material technology. The ideas that did not comply to the list of requirements were filtered out. Based on the expertise gathered in the previous parts, the most promising ideas were chosen and developed into concept directions. Six concept directions were created.

The concept directions were evaluated with a list of wishes, derived from the program of requirements, and the experts' feedback. A combination of two of the concepts seemed to be the best solution. With this combination the best aspects of concept direction 1 and 4 were combined. This resulted in a concept direction where the extension direction is limited by collision of three plates on the back of the hand. By adding a rubber layer in between the plates, the limitation is dampened to make it more comfortable. The pieces are attached to an under-glove that can be easily put on and leaves the palm of the hand free.

To develop this concept direction into a final concept, several prototypes were made. Each prototype gave a new insight into how the wrist protector would be able to work. For example, through prototyping it was found that the plates on the back should be split into three columns to allow for the curvature of the wrist.

The main insights from prototyping were as follows. The plates on the back of the hand should be divided into three columns and divided into five rows. This will allow for a smoother movement into the limited extension position. The plates should not be made with a production technique that influences the structural integrity of the pieces, such as FDM printing. Lastly, the under-glove should be made out of a non-stretch material to keep the protection pieces in place even during vicious movements.

By incorporating all the insights, a final concept was created. This final concept will be explained in part 5 "Final concept."

Final concept

The final concept, see Image 61, is a personalized wrist protector that limits extension of the wrist and thumb but does not limit movement in the other directions. With the wrist protector, goalkeepers can catch high speed balls without feeling obstructed in their movement.

Using a 3D scan of the goalkeepers hand and wrist and a grasshopper script, the wrist protector can be fit to the goalkeepers wrist. By using 3D printing, the parts can be made quickly and with low costs. 3D printing also allows for easy personalization in material and color. With this the goalkeeper can get a fully custom wrist protector in fit and appearance.

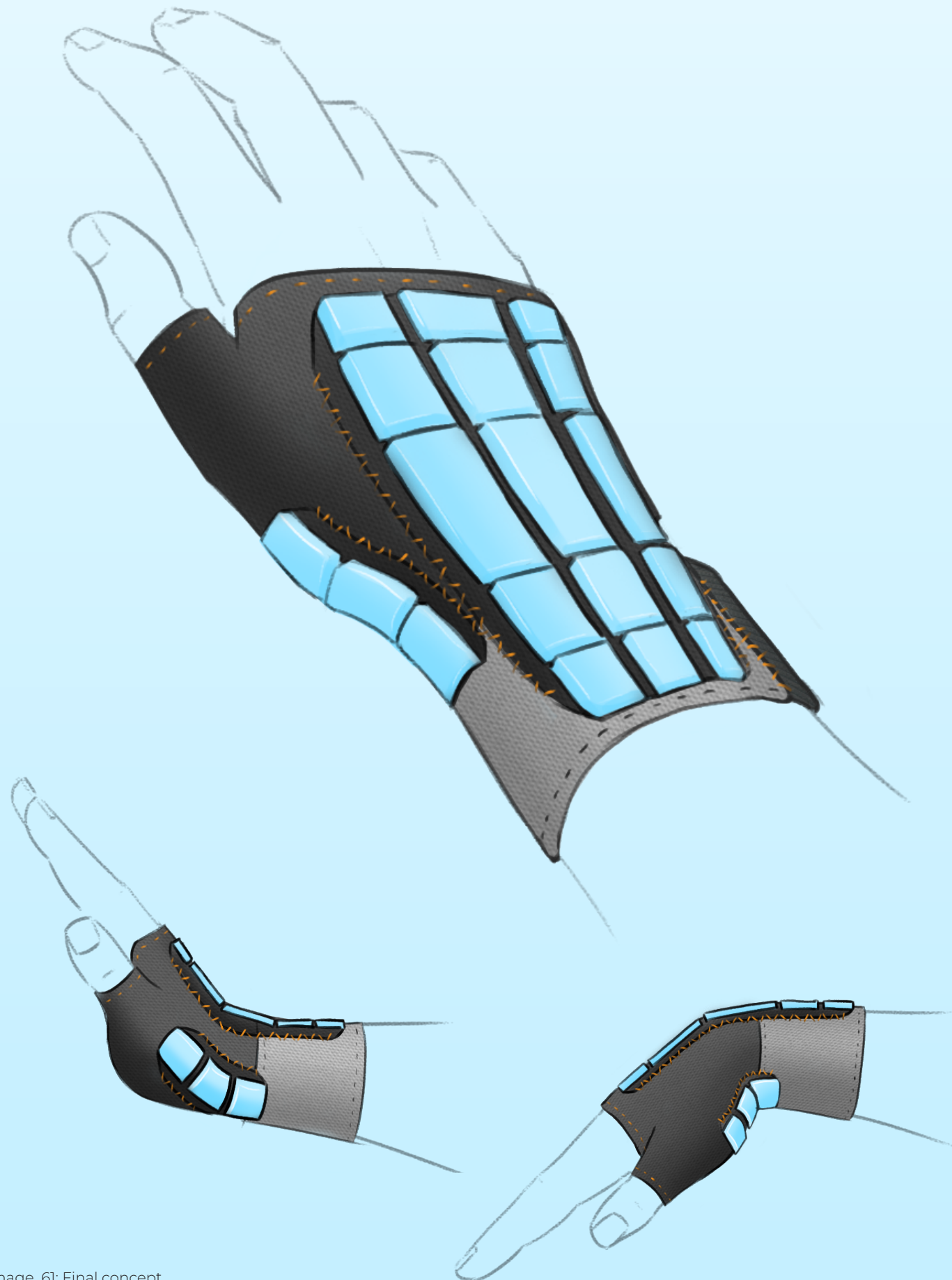


Image 61: Final concept

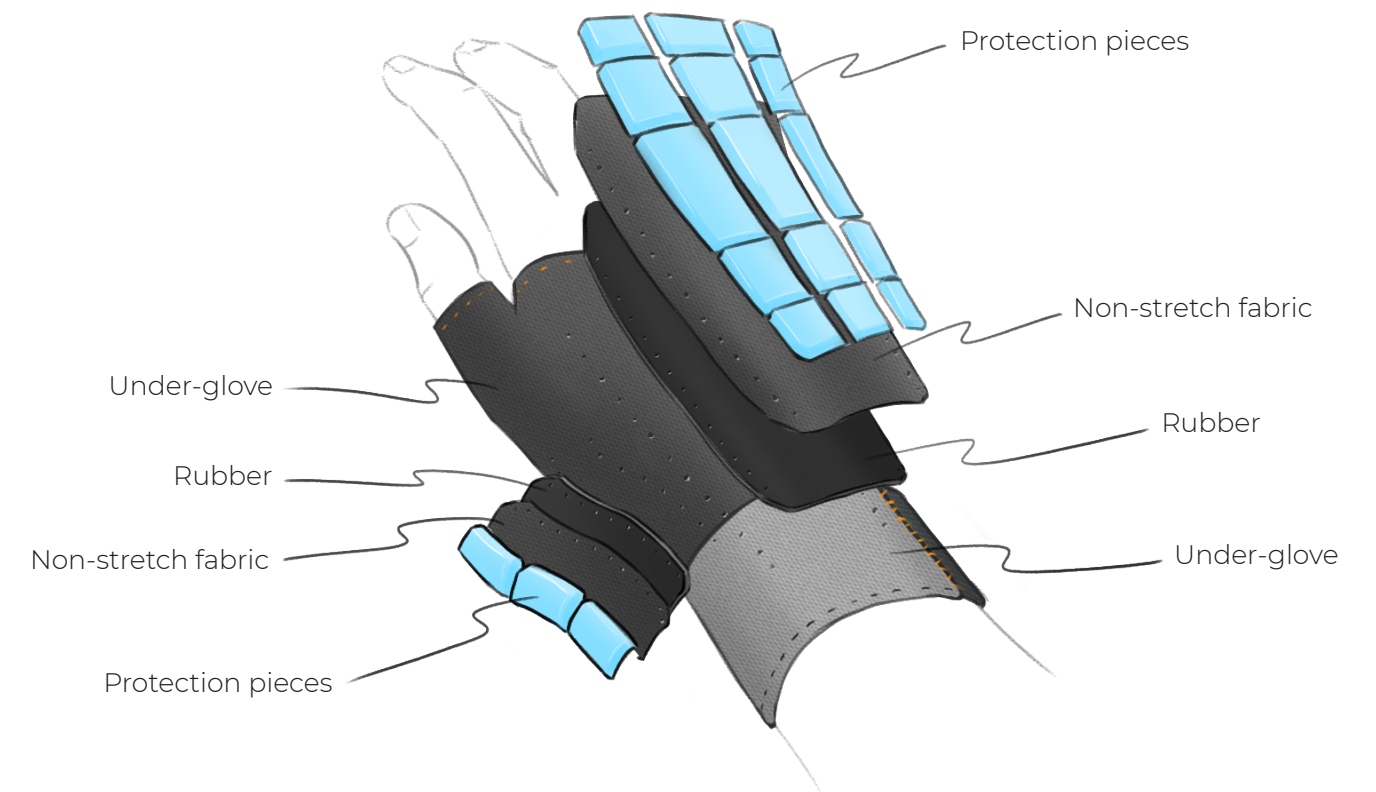


Image 62: Exploded view final concept

The wrist protector consists of four layers, see Image 62, which together give the wrist protector its functionality. Each layer has a specific functionality. The first layer, closest to the skin of the goalkeeper, is the under-glove. This under-glove keeps the wrist protector on the hand and protects the goalkeepers' skin from hard parts. The second layer is a patch of rubber that dampens the movements of flexion and extension. The third layer is a fabric patch that serves as the living hinge of the last layer, the protection pieces. The protection pieces create the actual limitation of the movement into extension. The different layers will be explained in detail the upcoming chapter.

Final concept

Protection pieces

The protection pieces are a set of rigid plates located on the back of the hand, see Image 63. These plates collide with each other when the wrist is extended, limiting the movement. By varying the distance between the plates the amount of allowed extension can be controlled.

The plates are divided into three columns, to allow for the curvature of the wrist, and five rows, to create a smooth arc when the protector is in its maximum extension. The size of the rows vary, with the largest row covering the wrist joint. The shape of the plates is based on a 3D scan of the goalkeeper. Using a grasshopper script, see appendix “8. Grasshopper”, the size and shape of the plates can be fully customized to fit the goalkeeper. The protection plates are sewn to the non-stretch fabric by hand.

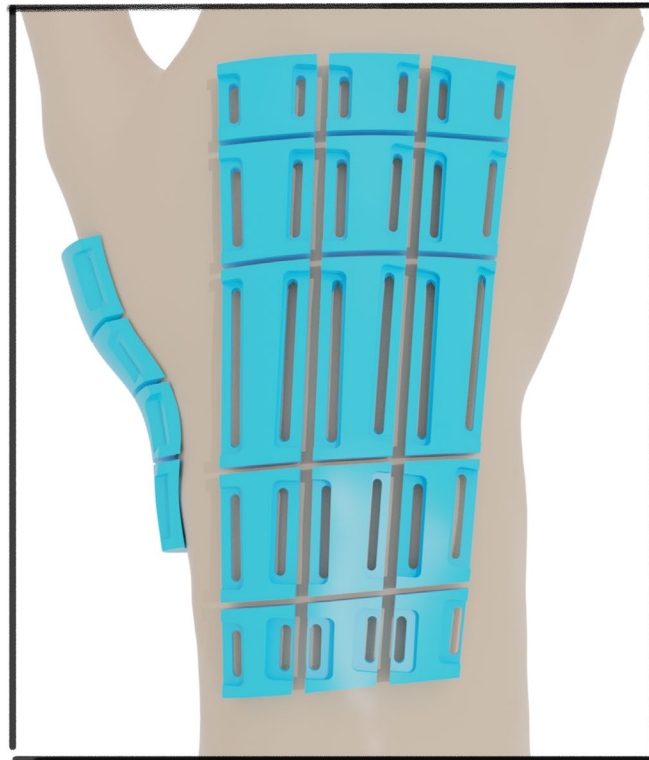


Image 63: All protection pieces on back of hand

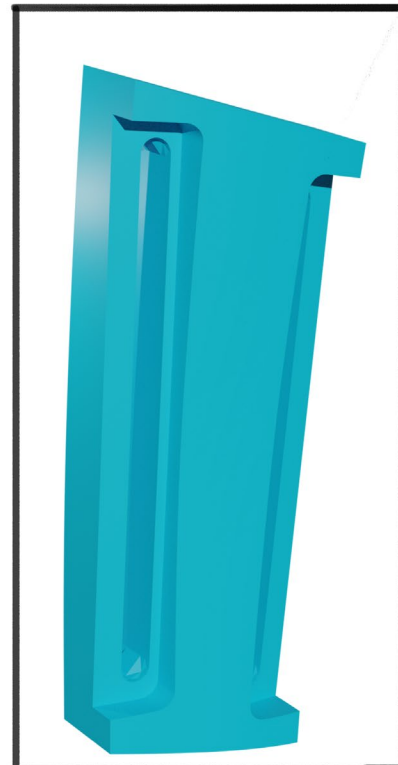


Image 64: Single protection piece

Production

Since the protection pieces are personalized for each goalkeeper, the way they are produced needs to fit this one of a kind product. This means that production methods like injection molding and casting are not suitable, since they require large production volumes in order to pay for the initial investments.

Advanced manufacturing methods such as 3D printing and CNC milling are more suitable for a one of a kind application. Because the protection pieces have no flat sides, see Image 64, CNC milling becomes extremely intricate and therefore expensive.

3D printing does allow for the complicated shape of the protection pieces. The most suitable 3D printing method for this application would be selective laser sintering (SLS). SLS printing produces products with mechanical properties that rival those of injection molded parts. It also allows for small components with intricate details. (Materialise, n.d.)

Material

SLS printing is possible with several types of plastics and metals. The most common SLS printable plastic is Nylon or PA. Nylon has excellent mechanical properties. SLS printed Nylon can even be used as a substitute for injection molded parts. (3D Hubs, n.d.) For this application, nylon would be the most suitable material. Using a metal, such as aluminum, for this application is not advisable. The strength that aluminum would give the protection pieces is not necessary for this application. On top of that using aluminum would increase the price of one protection piece almost 15 times compared to using nylon, see appendix “9. Cost estimation”.

Final concept

Non stretch fabric

The non-stretch fabric connects the protection plates to each other. The fabric ensures that the plates will collide during extension but can move unobstructed into flexion, see Image 65. The goalkeeper can move into flexion without obstruction since the fabric will fold with the wrist. During extension the fabric between the protection plates is pulled taut, prohibiting the plates from moving on top of each other and only allowing them to collide with each other.

Material

As discussed in chapter “Prototyping” this fabric layer should have no stretch in it. Next to that, it needs to be strong enough to last, without damage due to wear and tear, for at least two years (Requirement 3.1). A high performance fabric that is able to withstand moisture would be most suitable. For this application Polartec Delta would be a suitable fabric. Since the fabric for the under-glove needs similar functional properties, using the same fabric for both layers would be beneficial for the overall costs. The chosen fabric will be explained in further detail in the material explanation of the under-glove.

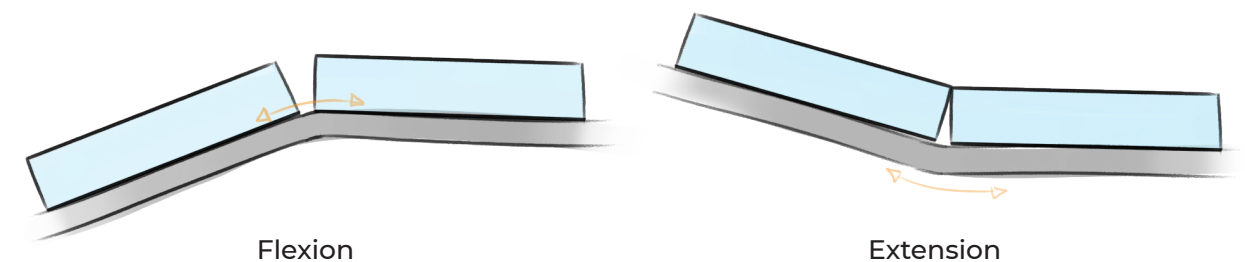


Image 65: Non-stretch fabric and protection pieces interaction during flexion and extension

Rubber

Attached to the fabric layer is a thin layer of rubber. The rubber functions as a dampening mechanism for the movements, ensuring that the movement is not stopped abruptly but more gradually. This makes the wrist protector more comfortable. As the wrist moves into extension, the rubber will be subjected to tension. The rubber will at first elongate, giving little resistance, but the further it is stretched the less it will be able to elongate and the more resistance it will give. The rubber will also give slight resistance when moving into flexion, providing light protection for that direction as well.

Material

The rubber used in this layer should have a low maximum elongation. This will result in an increasingly high resistance when moving the wrist into extension. Increasing the resistance can also be done by making the layer thicker. This way a rubber with more stretch can be used. However, since the whole wrist guard should be able to fit underneath the goalkeeping glove (requirement 6.1), it is advisable to keep this layer as thin as possible. Therefore, using a thin rubber with less stretch is more suitable.

FKM or Viton rubber is the best option for this as it only has maximum elongation of 300% compared to other rubbers which start at an elongation of 400%. Next to that, viton rubber also has good tear resistance and water resistance. (Piersol et al., 2009, p. 33.1)

Viton rubber can be bought in strips with standard sizes. For this application, a strip with 0.5 mm thickness and a width of 1200 mm would suffice. This can be bought in rolls of 5 - 9 meters from rubbermagazijn.nl for €69,-. (Rubbermagazijn, n.d.)

Final concept



Image 66: Final concept dorsal view (left) and palmar view (right)

Under-glove

All previous layers are, as a whole, attached to the under-glove. The under-glove keeps the wrist protector in place, see Image 66. It is made out of a non-stretch, breathable fabric. The wristband of the under-glove has an elastic piece on the ulnar side. This allows the goalkeeper to easily put the wrist protector on and take it off. The glove only includes the thumb while leaving the other fingers unobstructed. The palm of the hand is also kept free of material as to not interfere with the hand-ball contact of the goalkeeper.

Material

During testing with the prototypes it was discovered that the under-glove should be made out of a non-stretch fabric as stretch in the fabric would give too much freedom of movement, not keeping the protection pieces snug to the hand. Since the wrist protector will be used during sports it is also necessary for this fabric to allow the skin to breath and wick sweat. On top of that it should be able to be easily cleaned with water (requirement 2.1 and 7.1). Lastly it should be a high performance fabric that will be able to last for at least two years in use (requirement 3.1).

A suitable material for this would be the delta cooling fabric from Polartec. Polartec Delta is a knit fabric that is developed to be a fast drying and highly breathable fabric. It uses a combination of hydrophobic and hydrophilic yarns to disperse the moisture. (Polartec, n.d.) Polartec works together with their clients to optimize the fabric. Since Polartec Delta is a knit fabric it will always have some stretch, at least in one direction. The way the fabric is knit influences the amount of stretch. The stable knit has the lowest stretch factor, only 15 % - 20%. (Reyes-Chouinard, 2016)

Final concept

To allow the goalkeeper to get into the wrist protector there is an elastic band sewn into the wrist band of the under-glove. The elastic band should stretch enough to let the goalkeeper put on the wrist protector. However, once the wrist protector is in place, the elastic should be tight enough to keep the whole protector in place. For this a simple woven elastic, used in for example waistbands in clothing, such as the 50 mm wide elastic tape from Pry should suffice. (Prym, n.d.)

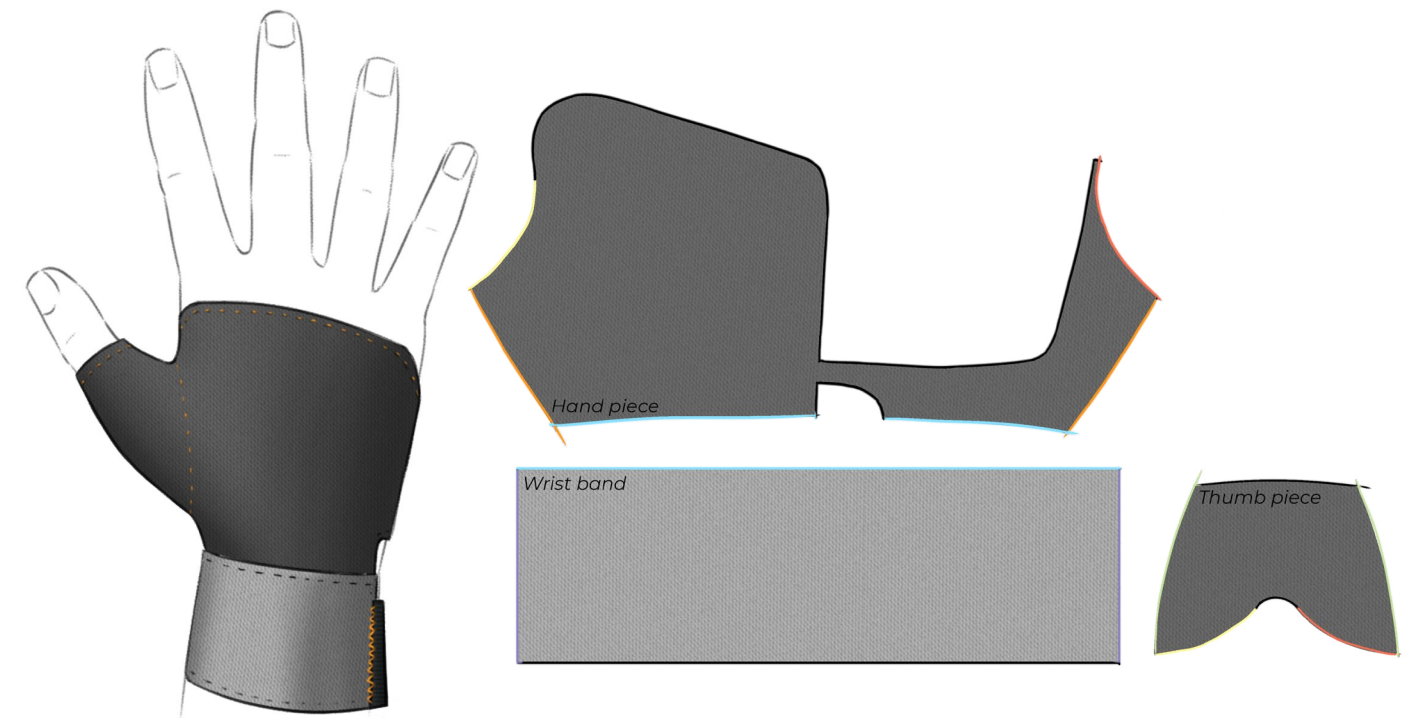


Image 68: Under-glove dorsal view

Image 67: Under-glove rough pattern

Production

The under-glove will be sewn together to create one piece, see Image 68. By altering a conventional glove pattern a rough pattern for the under-glove was created. The conventional pattern has been altered so that there is no seam in between the thumb and index finger, there is no material at the palm of the hand and so that the goalkeeper can easily put it on while the glove is still snug to the hand, even at the wrist.

The pattern of the under-glove will consist of 3 pieces, see Image 67. It is made up out of a wrist band, thumb piece and hand piece. In the image the similar colored edges will be sewn together. All black edges will be finished with a hem.

With this pattern, the under-glove will have one large seam on the radial side and a seam to attach the thumb to the rest of the glove. The elastic will be sewn in between the wrist band edges on the ulnar side of the hand.

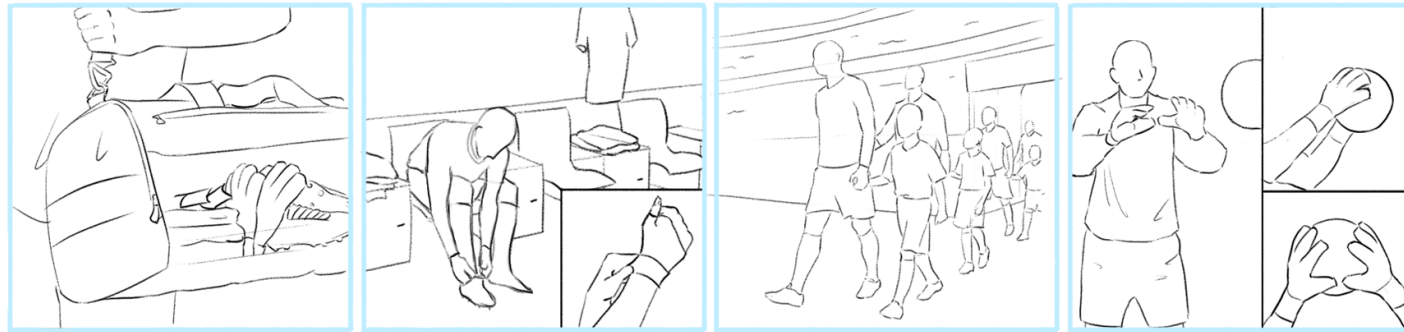
Based on the 3D scan of the goalkeeper, the pattern for the under-glove can be personalized to create a close to perfect fit. This ensures that the under-glove will be snug to the hand and keep the wrist protector in place during activities. Making the pattern personalized will increase the cost of the product since it involves more manual labor than using a sizing system. Since the under-glove consists of separate pieces, an accent color can be given to, for example, the wrist band. More personalization can be added by using a contrasting stitch color.

Product assembly

The separate layers are sewn together to create the wrist protector. The assembly starts by sewing the under-glove together with a sewing machine. Next, the protection pieces are sewn onto the non-stretch fabric by hand. Once all protection pieces are attached this subassembly is laid on top of the under-glove with the rubber sandwiched in between. The under-glove, fabric layer with protection pieces and rubber layer are attached to each other by sewing through them with an industrial sewing machine. This finishes the construction of the wrist protector.

Use scenario

The final concept is easy to use as it only takes one step to put it on and take it off. During a match or practice, the goalkeepers' wrists are protected from injury yet they are still able to perform all their tasks without obstruction from the wrist protector. Since the wrist protector is worn underneath the goalkeepers' gloves, they will not be able to hurt themselves or other players with it. Afterwards, the wrist protectors are easily taken off and can be cleaned with some water. The full use scenario can be seen in Image 69.

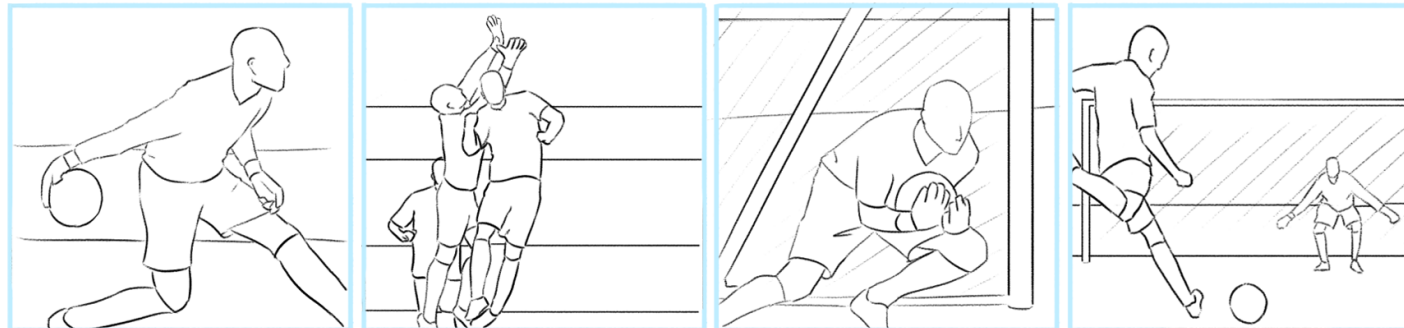


The goalkeeper takes their soccer gear, including his wrist protection, with them in a sports bag. The wrist protector easily fits in his bag.

The goalkeeper puts on their soccer gear and wrist protection. The wrist protection fits tightly and secure around his wrist. The wrist protection fits within his goalkeeping gloves.

The players walk onto the field for the match or training.

The goalkeeper has to make a save against a hard shot ball. The wrist protector keeps their wrists from overextending, preventing injury.

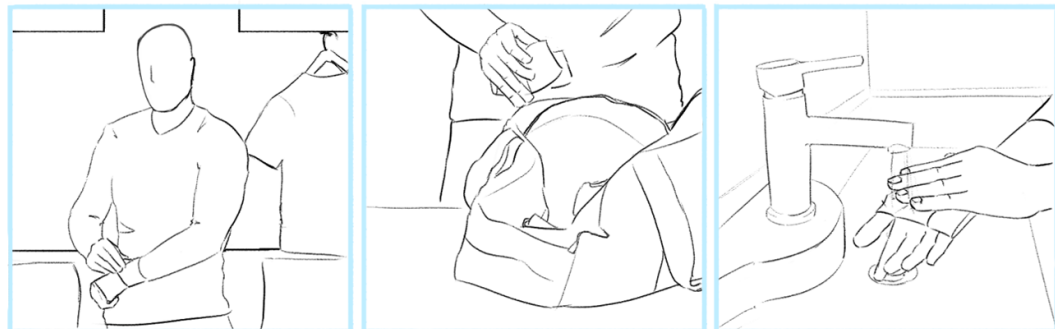


The goalkeeper distributes the ball back onto the playing field. The wrist protector allows him to move freely in the flexion direction.

Due to the intensity of the game the goalkeeper collides with an opponent when trying to save a ball. The wrist protector does not harm the other players.

During another save the goalkeeper catches the ball and locks it between his arms and upper body. The wrist protector does not obstruct this movement.

The opponents have gotten a penalty in their favour. The goalkeeper feels confident in their own ability and that of the wrist protection.



Afterwards, the goalkeeper takes off their wrist protection and soccer gear. The wrist protector is easily doffed.

The wrist protection is put away into his sports bag.

The goalkeeper cleans and washes the wrist protector in the sink with some water.

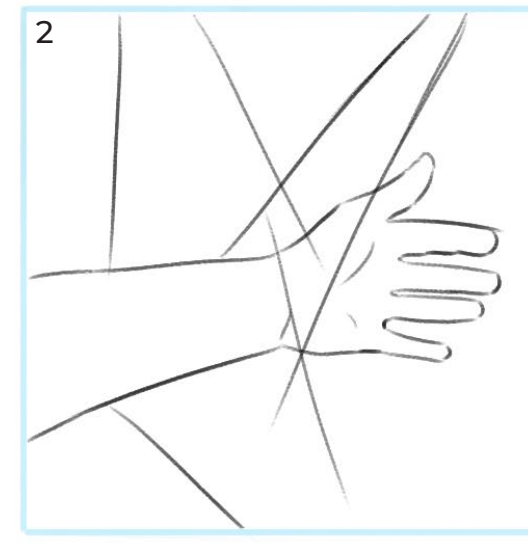
Image 69: Use scenario final concept

Service scenario

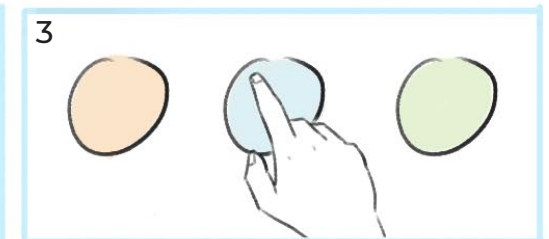
Next to the wrist protector, there should be a service in which the goalkeepers can get their hand scanned and choose their personalized color palette, see Image 70. Color of the under-glove, accent color of the stitches and color of the protection pieces are all parts that can be personalized.



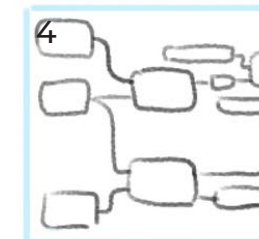
The goalkeeper goes to the flagship store to get a custom wrist protector



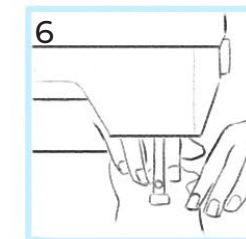
A 3D hand and wrist scan is made



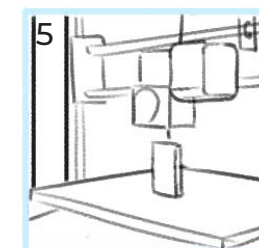
The goalkeeper selects preferences such as colour of the glove, colour of the protection pieces and the accent colour.



3D scan is processed



Wrist protector gets assembled



The protection pieces are printed

Image 70: Service scenario final concept



Goalkeeper comes back to pick up the wrist protector and do a final fitting

Cost estimation

To verify the viability of the wrist protector, a rough cost estimation has been done. This cost estimation is based on quotes and expert consultations. The cost estimation can be divided into two parts, the material costs and the assembly costs.

Material costs

The four layers of the wrist protector are each made out of different materials and different production techniques. To get an estimation for each part several approaches have been used. For the SLS printed protection pieces a quote was requested from a company that produces these prints, 3D Hubs. Since each protection piece for both the right an left hand is a one of a kind, the price for producing the protection pieces becomes relatively high. The price for one protection piece can be lowered by almost half its price when it is printed in a quantity of two, see appendix “9. Cost estimation”. Working towards a sizing system for the protection pieces to up the production quantity could therefore significantly reduce the protection piece costs.

For the Polartec fabric an expert was consulted since Polartec does not show their prices. The price for the rubber layer was calculated based on its retail price. The full cost estimation for each material can be found in appendix “9. Cost estimation”. The material costs can be seen in table 1.

Part	Material	Price
Protection pieces	<div><div>Nylon (PA12) SLS printed</div><div></div><div>(3D Hubs, n.d.)</div></div>	€ 207.96 (Including production)
Fabric layer	<div><div>Polartec Delta</div><div></div><div>(Polartec, n.d.)</div></div>	€ 0.23
Rubber	<div><div>Viton rubber</div><div></div><div>(Rubbermagazijn, n.d.)</div></div>	€ 0.40
Under-glove	<div><div>Polartec Delta</div><div></div><div>(Polartec, n.d.)</div></div>	€ 10.-
Total material costs		+ - € 219,-

Table 1: Material costs

Cost estimation

Assembly costs

The four layers have to be attached together by means of sewing. All assembly steps can be done with a sewing machine except for the attachment of the protection pieces. This should be done by hand. The average pay of a seamstress in the Netherlands is €1762 a month including taxes. (Nationale Beroepengids, n.d.) When hiring a freelance seamstress this translates to roughly €30 an hour. (Mijn ZZP, n.d.) An estimation was made for each assembly step based on experience from the prototyping phase. The assumption is that the seamstress will be able to perform the tasks faster than was done during prototyping. However, to allow for a margin of error the actual time spent during prototyping on each part was used. This results in the assembly costs shown in table 2.

Production step	Description	Assembly time	Assembly costs
Under-glove pattern making	Create the personalised pattern based on the 3D scan	60 min	€ 30.-
Pattern cutting	Cut out the under-glove pattern and fabric layer out of the Polartec Delta fabric	15 min	€ 7.50
Under-glove assembly	Machine stitch under-glove together	20 min	€ 10.-
Protection piece attachment	Hand stitch the pieces to the fabric layer	60 min	€ 30.-
Full wrist protection assembly	Machine stitch fabric layer with protection pieces and rubber layer to the under-glove.	5 min	€ 2.50
Total assembly costs			€ 80.-

Table 2: Assembly costs

Total costs wrist protector

After adding the material and assembly costs together the estimated production costs of one wrist protector come to a total of approximately €300.- In this cost estimation, the costs of 3D scanning and processing of the scan has not been taken into account. There are also some assumptions that were made that could influence the final costs. Therefore, the price should be estimated between €250.- And €350.-

A profit margin of 30% for this type of product is considered a healthy margin. This brings the sales price of one wrist protector to between €325.- and €455.-. Considering the assumptions made during this cost analysis, the price is more likely to be on the higher end of the scale. This means that a set of wrist protectors, at the highest price, €810.-, would be able to compete with the price of taping over a period of 2 years, €1539,-(Requirement 5.1). There are several actions that could be taken to potentially reduce the costs. These actions will be explained in the chapter “Recommendations”.

The cost estimation is made up out of two parts, the material costs and the assembly costs. The material costs of the total wrist protector come up to a total of +- € 219,-. The majority of these costs are the material and production costs of the protection pieces. The assembly costs of the total wrist protector come up to a total of €80.-. After taking into account that some costs have been roughly estimated the total costs of one wrist protector will be in the range of € 250 - € 350. With this production cost, the retail price of a set of wrist protectors is able to compete with the costs of taping over a period of two years.

Use scenario evaluation

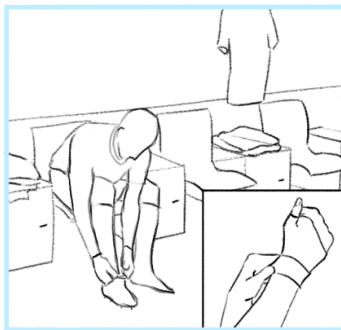
From the research at the start of the project, an ideal use scenario was created in which the wrist protection should be able to function, see chapter “Envisioned use scenario”. The final concept fits well into this use scenario. There are two scenes in the scenario in which the final concept differs, see Image 71.

The first scene is scene six. This scene does no longer apply to the wrist protector. The wrist protector does not need adjustments such as tightening. The only adjustment the goalkeeper can make is moving it back in the correct position. However, ideally this should not be needed.

The second scene that should be discussed is scene nine. The final concept has not been designed to evoke confidence in the goalkeeper. The wrist protector will influence the goalkeepers' performance and mindset. However, to what degree and in what way the wrist protector makes the goalkeeper feel more confident has not been researched.



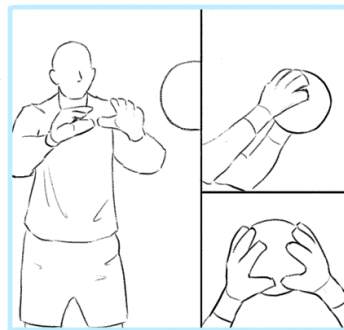
The goalkeeper takes their soccer gear, including his wrist protection, with them in a sports bag.



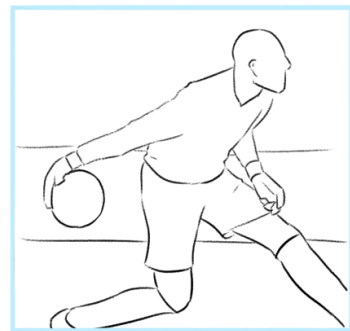
The goalkeeper puts on their soccer gear and wrist protection. The wrist protection fits tightly and secure around his wrist.
The wrist protection fits within his goalkeeping gloves



The players walk onto the field for the match or training.



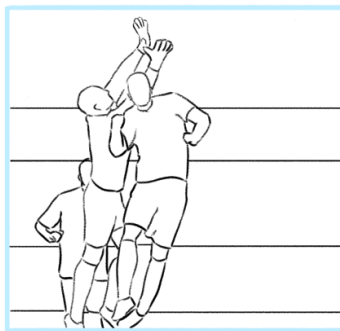
The goalkeeper has to make a save against a hard shot ball.
The wrist protector keeps their wrists from overextending, preventing injury.



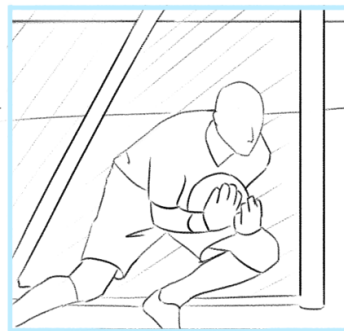
The goalkeeper distributes the ball back onto the playing field.
The wrist protector does not obstruct the movement.



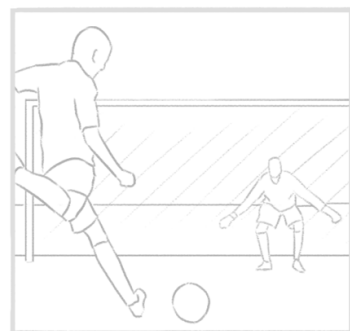
During the practice or match the goalkeeper makes some slight adjustments to the fit of the wrist protection.



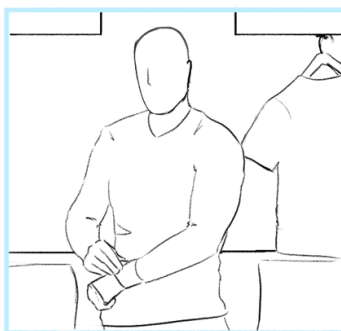
Due to the intensity of the game the goalkeeper collides with an opponent when trying to save a ball. The wrist protector does not harm the other players.



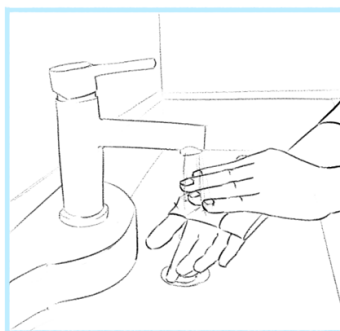
During another save the goalkeeper catches the ball and locks it between his arms and upper body.
The wrist protector does not obstruct the movement.



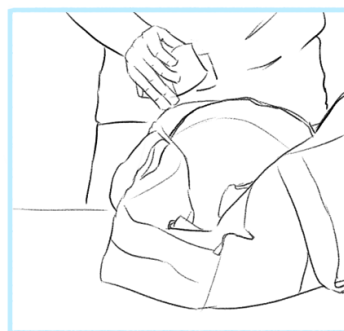
The opponents have gotten a penalty in their favour. The wrist protector makes the goalkeeper feel confident in his abilities.



Afterwards, the goalkeeper takes off their wrist protection and soccer gear.



The goalkeeper cleans and washes the wrist protection.



The wrist protection is put away into his sports bag.

Image 71: Use scenario final concept

Requirement evaluation

The final concept has been designed to fulfill all the requirements that were obtained throughout the research phase. However, there are still recommendations that can be made as to how the concept fulfills the requirements. On top of that, the final concept has not been tested for the fulfillment of all requirements. This means that in theory the final concept should fulfill the requirement but that in practice there might still be need for improvement. In this chapter, the final concept has been evaluated based on the requirements. These result in recommendations for further development of the product in chapter “Recommendations”.

The wrist protector should limit extension to a degree while not obstructing the goalkeepers' performance

Through its working principle, the wrist protector is able to effectively limit extension. The distance between the protection pieces influences the amount of possible extension. This comes down to millimeter work and can therefore be tricky to accurately replicate with the current assembly method.

The wrist protector should allow movement in the other directions

Because of the fabric layer that serves as the bottom layer of the protection pieces, the movement in flexion direction is not obstructed. The ulnar and radial deviation are not obstructed either.

The wrist protector should be able to provide protection for the left and right hand

The wrist protector can be made both for the right and left hand based on the respective 3D scan. Only using one scan and mirroring the protection pieces to the other hand could speed up the modeling process.

The wrist protector should have minimal influence on the goalkeeper's performance

Because the wrist protector only limits the extension direction, the goalkeeper is not obstructed during their goalkeeping tasks.

The wrist protector should provide a personalized fit for the goalkeeper

Since the wrist protector is based on a 3D scan of the goalkeeper, it has a fully personalized fit.

The wrist protector should not cause harm to the user or to other players

The protection pieces of the wrist protector are made of a hard material. This has the potential to harm others. However, since the wrist protector is worn underneath the goalkeeping gloves there is a protective layer on top of the protection pieces.

The wrist protector should be able to withstand moisture from sweat and cleaning

The materials used in the wrist protector have been chosen specifically for this requirement. The Polartec Delta fabric is specifically made to wick sweat away from the body.

The wrist protector should withstand an average use of 6 days a week for 4 hours a day for a duration of 90 weeks (2 years with 6 weeks of break per year)

In the material choice, the highest quality materials have been selected. By SLS printing the protection pieces in Nylon they should have comparable mechanical properties to injection molded parts. This means that in theory the wrist protector should be able to withstand 2 years of use. However, the materials have not been tested for this purpose.

The wrist protector should not need any maintenance during life in service

As explained in the previous requirement, the materials used should be able to withstand heavy use over 2 years. Therefore, the wrist protector should not need any maintenance during its life in service. However, similar to the previous requirement, this has not been tested.

The wrist protector should be washable/cleanable

The materials used have been selected to be able to withstand water. Cleaning of the wrist protector can therefore be done by rinsing it off in the sink.

The wrist protector should be able to compete with the price of 3 rolls of tape a week used over a period of 90 weeks for a total of €1539

As was explained in chapter “Cost estimation” a set of wrist protectors with a price of €810.- is able to compete with the price of taping for a period of two years.

The wrist protector should be usable with the standard goalkeeping gloves

By keeping all layers as thin as possible, the wrist protector easily fits underneath the goalkeeping gloves.

Requirement evaluation

The wrist protector should be made of lightweight materials

All materials used are thin and lightweight.

The wrist protector should be able to store away neatly

The wrist protector is designed to be as thin as possible in order to fit underneath the goalkeeping gloves. This also makes them easy to store away. Adding a storage bag could add to the experience of the product while at the same time making storing of the wrist protectors even easier.

The material used in the wrist protector should allow the goalkeepers skin to breathe

The Polartec Delta fabric has been designed for great moisture wicking abilities. Furthermore, the under-glove pattern leaves the palm of the hand open, allowing the skin to breathe. On the back of the hand, underneath all the different layers, it might get warm due to the amount of material on top. However, since the rest of the glove either has no material or the Polartec Delta fabric, it is not expected to cause any problems. The effect of this on the comfort of the wrist protector should still be tested.

The wrist protector should not cause skin irritation

The fabric of the under-glove is specifically designed for highly active situations and skin tight clothing. Therefor, it should not

cause any irritations to the skin. Since the under-glove serves as a layer between the protection pieces and the skin, irritation can also not be caused by the protection pieces.

The wrist protector should be made of soft materials

The only non soft material in the wrist protector is the material of the protection pieces. It is not possible to make these out of a soft material as this would remove the functionality. Since the goalkeeping glove goes over top of the wrist protector it does not have to be a problem. In case it does turn out to be a problem there are several solutions. Adding a soft layer will increase the overall thickness of the wrist protector which could effect the fit with the goalkeeping gloves.

The wrist protector should not cause discomfort to the user

The wrist protector has been designed to have a personalized fit to the goalkeeper's hand an wrist. This means that the fit of the wrist protector should not be able to cause discomfort. During prototyping, a great effort was made to make sure that the protection pieces do not dig into the skin. There are some improvements that can be made to the concept that would decrease the chance of discomfort even more. For example rounding the outer edges of the protection pieces.

The user should be able to apply the wrist protector with one hand

Because of the elastic that is sewn into the under-glove, the goalkeeper can easily get in and out of the wrist protector with only one hand.

The user should be able to apply the wrist protector by themselves

Similar to the previous requirement, the goalkeeper can put the wrist protector on with one hand by themselves.

When a part of the wrist protector breaks it should be replaceable to increase the protectors life in service

Since the wrist protector is 3D printed, the protection pieces can be easily recreated and replaced. The current assembly method, sewing, does make it labor intensive to do so.

Test evaluation

The wrist protector has been tested with professional goalkeeper J. Schuurman during a full training. During this test the concept was evaluated based on first impressions, comfort, usability with a goalkeeping glove and usability with the different techniques. The full evaluation can be found in appendix "10. Prototype evaluation".

Schuurman mentioned that the wrist protector reminded him of the fingersafe that is used in goalkeeping gloves to prevent finger injuries. He mentioned that he felt the extra layer of protection and the wrist protector felt nice underneath his goalkeeping glove. The wrist protector was compared to his normal taping technique during training. With both prevention methods he felt that his wrist was protected. Next to the positive feedback Schuurman also mentioned some points of improvement which will be discussed below.

Wrist protector is too short

Schuurman mentioned that the wrist protector was too short as it was shorter than his goalkeeping glove. This resulted in the fasteners of his goalkeeping glove being loose around his arm where the wrist protector ends. If the wrist protector would be longer the tightness of the goalkeeping glove would be even across the arm.

Pressure on the hand

When moving his hand back Schuurman mentioned that he felt pressure from the protection pieces on his hand. The protection pieces did not move with his hand enough. Most likely this is due to the limitations of the prototype. The prototype's fit was loose around the wrist, not keeping the protection pieces in place. On top of that the prototype was made out of a stretch fabric to fit more sizes. This also resulted in less pressure to hold the protection pieces in place.

Difficulty with donning the goalkeeping glove

Due to the separate protection pieces Schuurman found it difficult to put on his goalkeeping glove over the wrist protector. Whether this is due to the prototype or the principal behind the final concept is uncertain.

Limitations of the prototype

There are also some limitations of the prototype that have to be taken into account as they could have influenced the results of this test.

First of all, since the prototype was made only in one size it was too tight around Schuurman's thumb and too loose around his wrist. This influences the effect of the protection pieces as they are not kept tight to the hand. The thumb being too tight influenced the overall comfort however, after looking past this the prototype was still perceived as comfortable to wear.

Second of all, due to the printing technique used in the prototype some of the protection pieces broke off. This resulted in the goalkeeper having to press the protection pieced back down after catching a ball.

Expert evaluation

The final concept has been evaluated by dr. Videler. Overall dr. Videler was positive about the final concept and its functionality. She mentioned that it looked easy to don and doff, that having no material at the palm of the hand is good for the goalkeeper's grip on the ball, that the concept having free movement into flexion is positive and that all aspects that were discussed with her before were covered. She also mentioned some points of risk. These points of risk are explained below.

Pressure points on the arm

Since the protection pieces end right where the under-glove ends, a pressure point could be created when the wrist is bent. In normal braces the brace is extended up the forearm to cover up to one third of the forearm. By extending the wrist protector, like in normal braces the chance of a pressure point can be reduced. Another solution would be to add an extra thick and wide wristband to the under-glove.

Protection of the thumb

Currently the extension of the thumb is limited at the first thumb joint, at the widest part of the hand. This can cause the second thumb joint, the first knuckle of the thumb, to have to absorb all forces when a ball hits the thumb. Similar to hyper extension of the wrist, hyper extension of this second wrist joint can cause injury. A consideration can be made to extend the protection pieces of the thumb upwards to also cover the second thumb joint.

Bump of the ulna

On the ulnar side of the wrist, the ulna has a bump that can be prominently seen and felt. This bump is known to cause irritation in normal braces. Since the protection pieces run over top of this bump, this can also happen for the final concept. Since the wrist protector is custom fit to the goalkeeper, this bump can be taken into account. However, when the goalkeeper's wrist is bent it can still cause irritation.

Thumb pulled into extension

Since the under-glove is made out of a non stretch material, the thumb will be pulled into extension when the goalkeeper bends their wrist. This could influence the grip of the goalkeeper as well as the functionality of the limiting effect of the wrist. Whether this obstructs the goalkeeper or is perceived as beneficial should be tested.

Necessity of the thumb protection pieces

To prevent wrist injuries, including the thumb is not necessary. Whether the goalkeeper needs this extra protection at the thumb or whether this will obstruct the goalkeeper in their tasks should be tested.

Recommendations

Based on the previous evaluation chapters, recommendations can be made for the further development of the wrist protector. The recommendations will be explained in this chapter.

Protection pieces

Extending the protection pieces of the wrist

As was mentioned by dr. Videler, the protection pieces could create an unwanted pressure point on the under arm.

Schuurman also mentioned that due to the length of the wrist protector his goalkeeping glove could not be tightened evenly.

By extending the protection pieces further along the arm, the pressure will be distributed more evenly, removing the pressure, and the goalkeeping glove can be tightened evenly. Adding a thicker and wider wrist band could also reduce the discomfort caused by the pressure point.

Evaluating the protection pieces of the thumb

dr. Videler stated that adding the limitation to the thumb is not necessary when preventing against wrist injuries. The goalkeeper can experience the thumb protection pieces as uncomfortable and restricting. A test of the wrist protector with these protection pieces should be performed in order to evaluate the necessity and potential discomfort.

Extending the protection pieces of the thumb

Currently only the first joint of the thumb is included in the protection pieces. Dr. Videler mentioned that by including the second joint, thumb injuries can be avoided.

Personalization

Sizing system for under-glove

Currently the under-glove pattern is based on the 3D scan of the wrist protector. This increases price and lead time since every under-glove needs to be made personalized. A sizing system for the under-glove should be investigated to reduce these costs.

Personalization based on previous injuries

Goalkeepers might have had a previous wrist injuries which weakened the wrist in a specific part. Adding personalization to these parts could be beneficial for the safety of the goalkeeper. This should be investigated further.

Sizing system for protection pieces

For this wrist protector, the personalization is based on creating a perfect fit for the goalkeeper. As it is labor intensive to create the 3D model and since the personalization creates high production costs of the protection pieces, a sizing system should be investigated. Another solution would be to mirror the wrist protector for one hand to the other hand. This reduces the time needed to create the personalized 3D model.

Personalization based on maximum range of motion

From the performed research it was concluded that most injuries occur during extension. However, the amount of extension required to cause injury is only described as "during hyperextension". The degree of extension that is called hyperextension can differ from goalkeeper to goalkeeper. The standardized maximum extension limit from the wrist protector does therefore not have to be the best solution for all goalkeepers. A better solution could be adding a personalized limitation to the movement based on the goalkeeper's wrist and range of motion.

Recommendations

Shape & material

Material evaluation

The materials of the goalkeeping glove have been selected for the highest performance. This means that they should be able to withstand 2 years of use without maintenance. However, this has not been tested. The materials should be tested and evaluated.

Evaluating the effect of a rubber layer on dampening the movement

During the early prototypes, the effect of adding rubber to dampen the movement was investigated. In the development stage the focus was shifted to the protection pieces. Therefore, tests to evaluate the effect of rubber have not been performed yet. These should be done in order to substantiate or disprove the addition of a rubber layer.

Testing under-glove shape

Due to time constraints the decision was made to focus less on the under-glove. During testing a few aspects were identified that should be taken into account when developing the under-glove.

One of the main requirements from the professional goalkeeper is to reduce the amount of material around the palm of the hand. However, this could influence the functionality of the wrist protector. Tests should be conducted to find out whether this material can be reduced and in what way.

Evaluating the effect of the under-glove on thumb extension during flexion

Dr. Videler mentioned that the the non stretch fabric of the under-glove will pull the thumb into extension when the wrist is bent. This can influence the goalkeeper's grip as well as the protection at the wrist. A test should be performed to evaluate the effect the under-glove has on the goalkeeper's performance and the performance of the wrist protector. To reduce this effect, a piece of elastic could be inserted on the inside of the thumb.

Comfort

Decreasing potential discomfort from sharp edges

Since the protection pieces have sharp edges, discomfort from the pieces digging into the skin can occur. However, because of the fabric and rubber layer underneath the protection pieces this is unlikely. To decrease the potential discomfort the outer edges of the protection pieces can be rounded off. The edges in between the rows should not be rounded off.

Evaluating the discomfort around the bump of the ulna

The bump of the ulna is in current braces a consistent cause of discomfort according to dr. Videler. Even though the final concept is fit around this bump, it could still cause discomfort during activity. A test to evaluate the discomfort caused around this bump should be performed. To reduce the discomfort, extra padding or rearrangement of the protection pieces to avoid the bump can be considered.

Evaluating the effect of sweating on the comfort of the wrist protector

On the back of the goalkeeper's hand the material has become thick because of the different layers stacked on top of each other. During high activity tasks, this area can get sweaty. To what extend this area gets sweaty and how this influences the comfort of the wrist protector should be investigated. The layer most likely to cause this is the rubber layer. By, for example, adding holes in the rubber the breathability of this area could be increased.

Recommendations

Usability

Evaluating donning and doffing of the goalkeeping glove

As was mentioned by Schuurman, donning the goalkeeping glove over top of the protection pieces was difficult due to all the separate protection pieces. However, it is uncertain whether this is due to the limitations of the prototype or the principle behind the final concept. Another evaluation with a new prototype should be performed.

Cleaning the wrist protector

Since the wrist protector will have to be used for at least 2 years, it is important that the wrist protector can be cleaned. In the current concept this is done by rinsing it in the sink. With such heavy use, only rinsing the wrist protector might not be enough to get it clean. A way in which the wrist protector can be more easily cleaned, for example by putting in the laundry, should be investigated. The materials and assembly method should be able to withstand this new way of cleaning.

Addition of a storage bag

Even though the wrist protectors are thin and will therefor take up little space, adding a storage bag would be beneficial to the product. With a hard case storage bag the left and right wrist protectors will always be kept together and cannot be damaged by other items in the goalkeeper's sports bag. Adding a special bag can also make the product feel more exclusive and of higher quality.

Other

Grasshopper script clean-up

The grasshopper script shows a proof of principle on how the wrist protection can be made from a simple 3D scan. There are still slight inconsistencies in the script which result in clean up work when switching between different scans. To reduce working time the grasshopper script should be optimized so that inputting a new scan instantly results in the correct protection pieces.

Evaluating the increase in the goalkeeper's confidence

In the envisioned use scenario it was mentioned that the wrist protector should make the goalkeeper feel more confident in his abilities. Since the wrist protector adds a sense of security to the goalkeeper this can be expected. However, whether this is actually the case and to what extend the goalkeeper's confidence is increased should be researched.

Decreasing the risk of injury to other players

Even though the wrist protector is worn underneath the goalkeeper's gloves, there is still a small chance that the hard protection pieces cause injury to another player when the players collide. This can happen when the protection pieces continue past the goalkeeping gloves' wrist band. This can be avoided by adding a soft layer on top of the protection pieces. Adding a soft layer will make disassembly more difficult and make the fit with the goalkeeping glove tighter since it adds thickness.

Assembly optimization

For the current prototype the protection pieces are sewn on individually. This is time and labor intensive. On top of that, the placement of the protection pieces needs to be precise. Doing this by hand has a high chance of error and is difficult to accurately replicate for all the protection pieces. Research into a new assembly method for the protection pieces should be performed. When selecting a new assembly method, easy disassembly of the product should be taken into account.

Conclusion & reflection

The goal of this project was to design a strong, comfortable and reliable wrist guard for the professional goalkeeper. The wrist protection should allow plenty of movement for the goalkeeper to accurately perform their tasks while limiting movements that would cause injury.

From the research phase, many insights were found that set the boundary conditions for the wrist protector. The most important findings were that injuries mostly occur during hyper extension of the wrist and goalkeepers need to be able to move their wrists into flexion unobstructed to perform their tasks. A concept direction based on the found research and inspired by plated structures and existing wrist protectors was created and developed into a final concept. This final concept has a personalized fit to the goalkeeper's wrist, allows movement in the flexion direction and obstructs the movement in the extension direction.

The final concept is in line with the goal of the project. With the final concept, goalkeepers can easily protect their wrists against injuries caused by a fast ball hitting their hands. Due to the working principle of the wrist protector, the goalkeeper can freely move into flexion. The wrist protector is made out of high quality materials, making it strong and reliable. The personalized fit and the fabric used in the wrist protector ensure the wrist protector fits comfortably even during high activity and sweating.

In the previous chapters the final concept has been evaluated and recommendations have been made to develop the final concept further. The evaluations show that even though the final concept has great potential there are still improvements that can be made to optimize it.

Similarly to the final concept there are also improvements that can be made to the process. It might not come as a surprise that this project was influenced by the COVID-19 pandemic and the lock-downs that were instated to tackle this. There are a few insights that I have gained throughout this project that are due to doing a project during a pandemic.

First of all, with everyone mostly working from home, getting resources for the project can be difficult as special arrangements have to be made to pick up these resources. For my project this resulted in tests being postponed and therefore crucial information being left behind in the early stages of the project.

Second of all, setting up communication with experts takes longer as everything has to go through e-mail and phone. There is no such thing as simply walking past someone's office to quickly ask a question.

Lastly, since the project is done from home, discussions with other students, friends and family about the project are minimal. This resulted in one of the biggest mistakes I made during this project, thinking that I had to do it all by myself. Quick discussions about your project can help with identifying flaws in your thought process, gaining new insights about your project and creating new ideas. I think that if I would have consulted with peers earlier in the process I would have been able to speed up the process and spend more time on the development of the final concept.

I set up this project with a large ideation phase. During this phase I chose to focus on finding innovative working principles with which the problem could be solved. With small prototypes I tried to figure out the feasibility of the different working principles. However, even with the prototypes it was difficult to understand how and in what way they would work. Together with simultaneously trying to create a personalized product the difficulty of the project increased significantly, causing me to spend a lot of time in this phase. If I would have spend more time looking into current wrist protectors at the start and based my design on this, more time could have been spent on developing the final concept.

In this project I have had the most difficulty with developing the concept. Throughout the prototyping and concept development flaws in how I thought the prototypes and principles would work kept surfacing. This gave me a personal set back in the perception of my capabilities. Through discussions with my supervisory team, friends and family I was able to regain control of the project and develop a final concept which I am proud of.

All in all, this project is something the client and I are proud of. Without setbacks during the process it would not have been a development project nor a learning experience for me. The client will continue development of the product based on the results I have shown in this report.

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