A comparison of speed skating with normal and reduced ankle eversion

Effects of skating with an ankle eversion reducing orthosis on healthy skaters with low and high skill levels

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Author
Michel Bovy

Supervisors
Ir. O. den Braver
Dr.ir. D.H. Plettenburg

Graduation Committee
Ir. O. den Braver
Dr.ir. D.H. Plettenburg
Prof.dr. F.C.T. van der Helm
Dr.ir. A.L. Schwab

Delft University of Technology
Faculty of Mechanical Engineering
Department of BioMedical Engineering
Mekelweg 2
2628CD DELFT
The Netherlands

PREFACE

Thank you! I couldn't have done it without you! I hope you will enjoy reading this master thesis. However big or small, your help was needed. I just finished writing this thesis and I still feel like I have to write short machine-gun sentences full of meaning and without ambiguity. I want to thank some people in particular and I might just do that in a very vague but very grateful way.

Special thanks go out to Otto den Braver. Hardly a week went by this year that I did not see him. He was the inspiration and mastermind behind this project. You have been a great help. Thanks for all the equipment you arranged, the critical notes and especially for the support!

I want to thank Dick Plettenburg for his go-do attitude. You never know for sure until you have tried. The orthosis was built in the workshop of our faculty by Andries Oort. He did a superb job and I was very pleased with his work. Niek Wondergem of Westland Orthopedie offered to cover the brace of the orthosis with a protective layer. This made the orthosis much more usable. Jos van Driel helped me out with measuring equipment. Maybe I went to the ice rink only to discover that stuff was not working but who cares. Everything worked really well the next day due to his help. I want to thank Frans van der Helm and Arend Schwab for their seat in my graduation committee. Special thanks to Frans van der Helm for showing me what being critical is all about.

The test skaters were all excited to join me on a trip to the ice rink. We had some fun mornings, thank you Clara Peters, Roby van Praag, Ilse Tepas, Bas Beelen, Tim Wu, Willem van Loon, Lester Houtenbos and Jelle Middendorp for your enthusiasm. Special thanks go out to two test skaters, Wytze van der Zee and Robin Philippo. They have been a great help and I couldn't have done all the measurements without them. Forget about distractions like empty laptop batteries and girls skating around the ice rink, those where but minor obstacles.

Thanks to all of you and however I might have forgotten. Thanks to the people in the Reinier de Graaf hospital were I talked to specialists and were I had my ankle fixed in a plaster cast. Finally I want to thank my parents, brother and friends for their support and for putting up with me.

CONTENTS

A comparison of speed skating with normal and reduced ankle eversion

Effects of skating with an ankle eversion reducing orthosis on healthy skaters with low and high skill levels

Michel Bovy, Faculty of Mechanical Engineering, Department of Biomedical Engineering, Delft University of Technology, Netherlands

ABSTRACT

Purpose: Executing the sideward skating push-off requires a skater's full attention and capabilities. Ankle eversion (AE) occurs during the push-off with skaters of low and high skill levels. Controlling AE requires high muscle force. AE adds unnecessary stress thus fatigue is a likely consequence. A purpose for AE in speed skating has not yet been found. Ankle eversion (AE) is considered an unwanted distraction during the execution of the push-off. The first goal is to reduce AE during speed skating. Plantar and dorsal flexion is to be left unhampered. The second goal is to prove that the skating motions can be executed with reduced AE. **Method:** An orthosis was designed to reduce AE on the right leg only. Skaters (n=10) with low and high skill levels were recorded while skating with normal and reduced AE. Video analyses resulted in relevant angles to quantify skating motions. The tested skaters filled out a questionnaire about skating with reduced AE. **Results:** On average AE was reduced by 45 to 70% from approximately 13 to 4 degrees with the tested skaters. Skating motions could be executed with reduced AE. The overall rating by the tested skaters for skating with reduced AE was neutral to positive. The orthosis functioned properly but it was considered big and clumsy. **Conclusion:** There are no negative outcomes from the angle measurements or the questionnaire on skating with reduced AE. That is a very positive situation. An estimation of the required muscle force shows that the amount is reduced significantly when skating with reduced compared to normal AE. As a result a skater saves energy and is not distracted by AE when executing the push-off. Skating with reduced AE might have a positive influence on performance. This has not been measured. A redesign of the orthosis should be stiffer and more compact.

INTRODUCTION

Speed skating is practiced by many individuals. Professionals are competing at the Olympic Games and recreational skaters enjoy themselves at the local ice rink. Understanding the biomechanics of skating is the overall desire in speed skating research. The acquired knowledge can be used to enhance skating techniques and materials. Lap time differences between professional speed skaters are small. Minor improvements can be the deciding factor between a silver and a gold medal. The klap skate is an example of such an improvement.

Skating is a unique method of propulsion. The speed skating technique is characterized by a sideward push-off [Koning 1991-a] (figure 1).

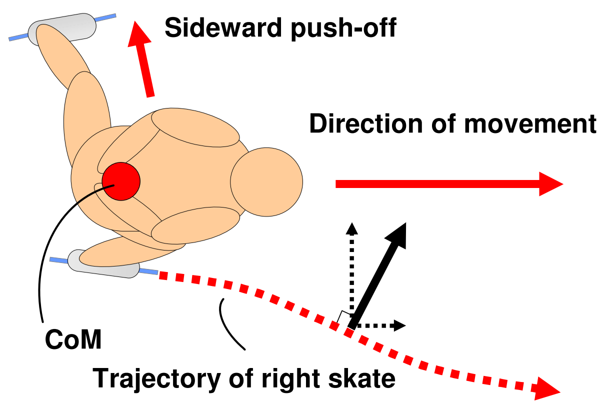

Figure 1. Top view of a skater with the direction of movement and the sideward push-off of the left leg. The right skate is directed away from the center of mass (CoM) to initiate the push-off with the right leg. The black arrow perpendicular to the trajectory of the skate blade is the component of the push-off force in the top plane. It can be divided in the forward and sideward push-off force components.

With running and cycling the propelling forces are directed opposite to the direction of movement instead of sideward. With skating grip on the ice is only present perpendicular to the trajectory of the skate blade [Ingen Schenau 1985] (figure 1). In the longitudinal direction the blade slides over the ice with very little friction [Koning 1992]. The leg is extended explosively during the sideward push-off [Boer 1986]. The foot exhibits plantar and dorsal flexion [Koning 1991-a, Koning1991-b] and ankle eversion (AE) (figure 2).

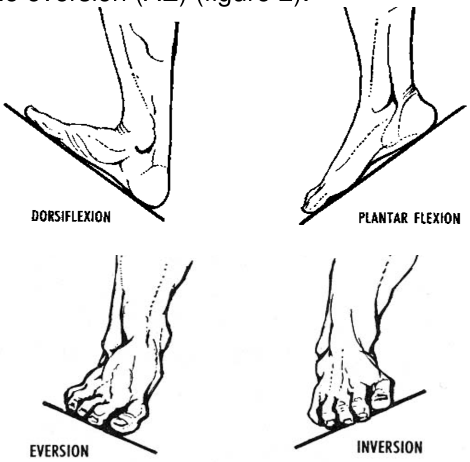

Figure 2. Top: Dorsal and plantar flexion. Bottom: Eversion and inversion.

Plantar and dorsal flexion is required for speed skating. Flexion in the ankle ensures that the skate blade stays leveled with the ice when the leg is extended explosively. No purpose has yet been found for AE. In order to push-off the skate is directed away from the center of mass (CoM) by the skater (figure 1). Professional speed skaters reach high velocities. A small difference between the direction of the skate and CoM has a large influence on the extension velocity of the leg. The extension velocity of the leg is related to the contraction velocity of the muscles in the leg. The contraction velocity of the muscles is related to the amount of power a muscle can generate (McMahon 1984). There is an optimal extension velocity of the leg that generates the highest amount of power. The orientation of the skate also defines the forward and sideward push-off force components (figure 1). A small forward component and a large sideward component will accelerate the CoM mainly sideways. A large forward component and a small sideward component will accelerate the CoM mainly forward. The extension velocity of the leg and the direction of the push-off force are important when directing the skate over the ice. It is likely that there is an optimal trajectory for the skate. Directing the skate is a sensitive motor control task. The push-off is a combination of the explosive extension of the leg and a sensitive motor control task. This is a combination of power at subtlety.

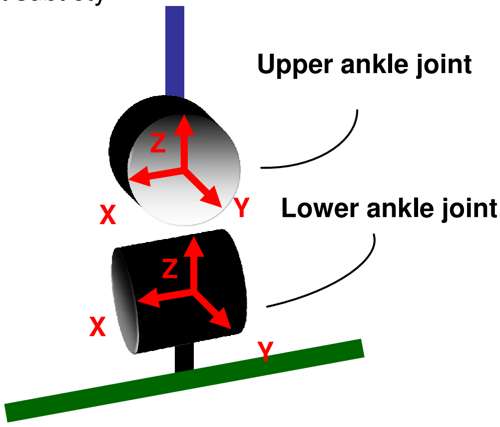

Figure 3. A model of the ankle joint and the skate blade (green line). The lower leg (blue line) is connected to the skate blade (green line) by the upper and lower ankle joint. A local coordinate system is depicted in the upper and lower ankle joint.

For future references the motions of interest are defined. The ankle is modeled as a combination of two joints (figure 3). AE and ankle inversion is defined as the rotation of the skate blade around the x-axis of the local coordinate system in the lower ankle joint. AE is the outward rotation in reference to the CoM and ankle inversion is the inward rotation. Plantar and dorsal flexion is defined as the rotation of the skate blade around the y-axis of the local coordinate system in the upper ankle joint. Plantar flexion is the downward rotation in reference to the CoM and dorsal flexion is the upward rotation. This is a simplification of the actual ankle joint.

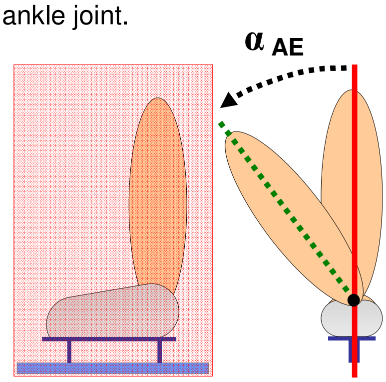

Figure 4. A side and front view of the leg with a skate. Left: The red plane is the plane of the skate blade fixed parallel to the side plane of the skate blade. Right: The ankle eversion angle (α_{AE}) is the angle between the lower leg and the plane of the skate blade depicted as a red line in the front view.

The ankle eversion angle (α_{AE}) is defined as the angle between the plane of the skate blade and the lower leg due to rotation in the lower ankle joint around the x-axis (figure 4).

AE occurs with inexperienced skaters (figure 5) and with professionals (figure 6). However, according to Houdijk (2000) no excessive inversion or eversion of the foot occurs during skating. The push-off force is defined from the CoM perpendicular to the contact line between the ice and the skate blade [Ingen Schenau 1985, Boer 1986]. Houdijk (2000) assumed that the push-off force closely follows the line through the CoM, hip, knee, ankle and skate blade (figure 7). Only Houdijk (2000) mentions AE and declared it insignificant in the context of push-off mechanics. The force perpendicular to the plane of the skate blade has never been measured.

Figure 5. An inexperienced skater with ankle eversion.

Figure 6. A professional skater (Sven Kramer) with ankle eversion. The shoe almost touches the ice.

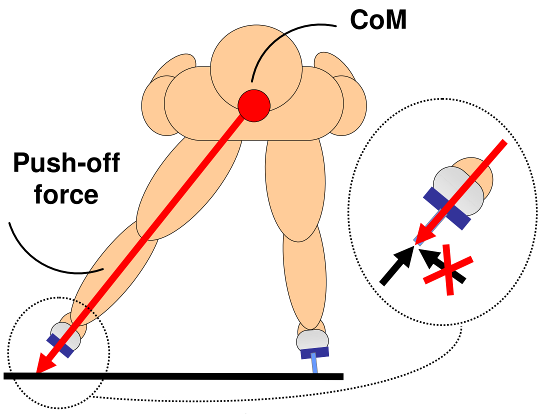

Figure 7. Front view of a skater with enlarged view of the reaction force components on the skate blade (black arrows). The push-off force follows the line from the center of mass (CoM) along the joints towards the blade as Houdijk (2000) assumed. In this situation there is no reaction force perpendicular to the plane of the skate blade.

The loading situation on the ankle joint is more complex than Houdijk (2000) assumed. The loading situation constantly changes when skating. The center of pressure (CoP) underneath the foot is not always located in the plane of the skate blade [Braver 2007] (figure 8). Once the CoP is located outside the plane of the skate blade a moment arm is present resulting in an eversion torque around the lower ankle joint (T_{ev}). The moment arm and thus T_{ev} become bigger as α_{AE} increases. This is an instable situation. AE needs to be compensated.

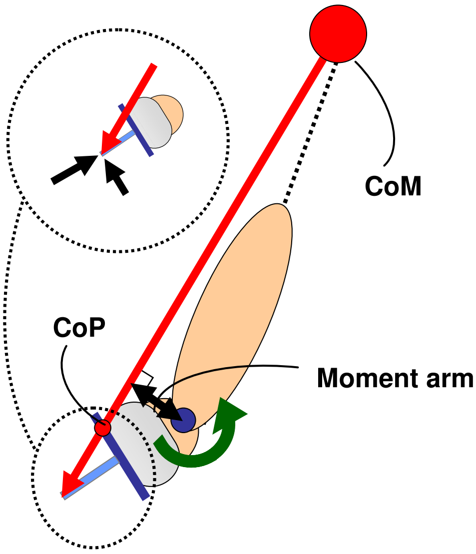

Figure 8. Front view of the lower leg with ankle eversion (AE) and an enlarged view of the reaction forces components (black arrows) on the skate blade. The push-off force (red arrow) passes through the center of pressure (CoP). A moment arm is present perpendicular to the push-off force resulting in an eversion torque around the lower ankle joint (green arrow). With AE there is a reaction force perpendicular to the plane of the skate blade.

AE can be compensated by the skater. Ligaments and muscles respectively limit and control the motions of the foot. Ligaments allow an α_{AE} of approximately 30 degrees [Dreyfuss 2002]. The muscles are needed to minimize AE. In appendix 2 T_{ev} is estimated for an average professional skater with a maximum push-off force of 140% bodyweight [Koning 1992] (table 1).

Table 1. Ankle eversion angle (α_{AE}) with eversion torque (T_{ev}) for an average professional speed skater with push-off force of 140% bodyweight. Required anthropometric data for calculations was collected by Ingen Schenau (1981).

α_{AE} (degrees)	T_{ev}(Nm)
10	24.7
20	50.4
30	75.1

The ankle can generate an inversion muscle torque (T_{mus}). The average amount of T_{mus} is 2.7% (standard deviation 0.8%) of bodyweight (N) times height (m) [Ottoviani 2001]. An average person with the same body size as an average professional speed skater can generate a T_{mus} of 37 Nm. Adding the standard deviation twice yields a T_{mus} of 59 Nm. This is the T_{mus} that an extremely fit person (97,7th percentile) with the same body size as an average profesional speed skaters can generate. The T_{ev} for an α_{AE} of 20 degrees closely resembles the maximal T_{mus} an extremely fit person can generate. Compensating AE requires high muscle force. The combination of a high load, chancing CoP position and the need for high muscle force to compensate AE are the theoretical causes of AE. Skate shoes are also able to compensate AE (figure 9). There are shoes available that reach till over the ankle joint providing stability. These shoes also inhibit plantar and dorsal flexion. Plantar and dorsal flexion is needed for skating.

Figure 9. Skate shoe with high level of support for the ankle. The shoe also inhibits plantar and dorsal flexion which is necessary to for the push-off.

The sideward push-off is a combination of power and subtlety. Executing the push-off requires a skater's full attention and capabilities. Controlling AE requires high muscle force. AE adds unnecessary stress thus fatigue is another likely consequence. A purpose for AE in speed skating has not yet been found. AE is considered an unwanted distraction. Coaches teach skaters to minimize AE. Skate shoes for high skilled skaters are partly designed to minimize AE. Still AE occurs.

A distinction has to be made between high skilled skaters and other skaters. The preceding analysis applies to high skilled skaters. First time skaters are often unable to stand still on their skates without AE. AE causes fatigue and discomfort for recreational skaters.

The first goal is to reduce AE during speed skating. Plantar and dorsal flexion is to be left unhampered. The second goal is to prove that the skating motions can be executed with reduced AE.

METHOD

Subjects

A group of 5 low skilled and 5 high skilled skaters was used (table 2). The low skilled skaters were able to skate around the track while standing up straight. They were not able to use the crossover technique in the corners. The two high skilled skaters (High 1 and 2) competed in regional and national contest. The other high skilled skaters have had extensive training. All high skilled skaters mastered the crossover technique.

Table 2. Skating skill, sex, height, weight and age of subjects.

	Sex	**Height(cm)**	**Weight(kg)**	**Age**
Low 1	female	180	69	25
Low 2	male	180	72	26
Low 3	female	182	74	25
Low 4	male	191	82	26
Low 5	female	183	75	22
High 1	male	175	63	22
High 2	male	193	73	22
High 3	male	188	82	46
High 4	male	180	70	22
High 5	male	175	70	22

Materials

A device to reduce AE was needed. After an analysis (appendix 1 and 2) an orthosis was designed for short track skates (appendix 3 and 4, figure 10). The orthosis had one rotational degree of freedom. The orthosis allowed unhampered plantar and dorsal flexion. AE and ankle inversion was not allowed. Motion in these directions was depended on the stiffness of the orthosis. The orthosis could be adapted to the size of a skater. The location of the rotation axis of the orthosis could be adjusted. Translation in all three dimensions of the local coordinate system of the skate was possible. The rotation axis of the orthosis was always oriented in the local y-direction of the skate. Translation was also possible between the brace around the lower leg and the metal rod.

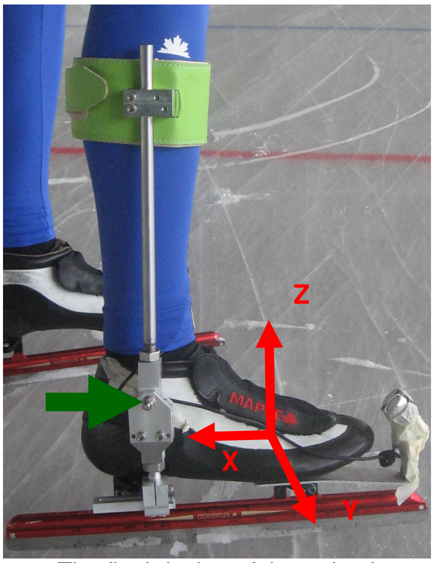

Figure 10. The final design of the orthosis worn by a skater on short track skates. A local coordinate system is depicted in the skate. The green arrow points out the bolt that is the rotation axis.

One pair of short track skate frames was used. Two pairs of short track shoes could be mounted on the frames. One pair of European size 40 and one pair of European size 44 (figure 10). The shoes were made of hard materials and reached till slightly above the ankle joint. The orthosis was bolted to the skate frame underneath the shoe. In the local y-direction of the skate the orthosis was placed as close to the skate as possible. The brace of the orthosis was loosely fastened around the thickest part of the lower leg. To position the rotation axis of the orthosis in the local z- and x-direction of the skate the skater was instructed to plantar and dorsal flex. Meanwhile the orthosis was fixed in a position comfortable for the skater. Finally the connection between the metal rod and the brace around the lower leg was fastened. The orthosis was used on the right leg only. Nothing was used on the left leg.

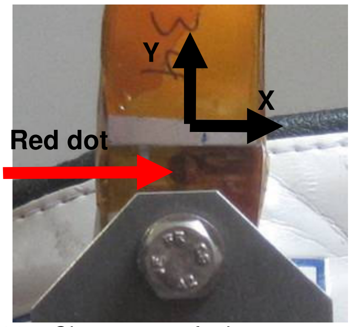

Figure 11. Close up of the area around the rotational axis of the orthosis. The strain gauges are placed on the red dot slightly above the rotation axis. Two strain gauges are placed on each side of the beam. One is directed in the local x-direction and one in the local y-direction.

The orthosis was equipped with four strain gauges (Tokyo Sokki Kenkyujo Co., Ltd., FCA-1-11, 120+/-0.5 ohms) to measure the eversion torque in the orthosis (figure 11). The four strain gauges were connected in a Wheatstone bridge. The analog signal was amplified and digitally encoded. The digital signal was collected by a laptop on the back of the skater. The system was calibrated by hanging known loads at the endpoint of the orthosis (figure 12). The angle between the horizontal and the line from the base to the endpoint of the loaded orthosis (γ_{ort}) was measured for different loads by use of photos.

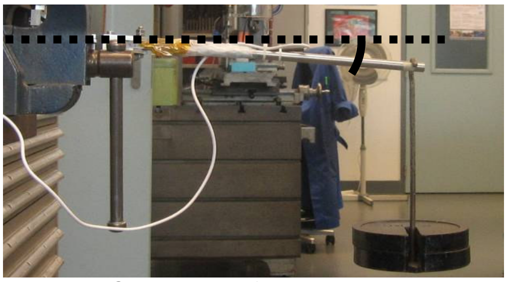
Figure 12. Calibration of the strain gauges. The base of the orthosis is fixed in a bench. Unloaded the orthosis is oriented horizontally. The endpoint is loaded. The angle (γ_{ort}) between the horizontal and the line from the base to the endpoint of the loaded orthosis is visible.

A camera (Philips Webcam SPC 2050NC, 30 frames per second) was rigidly fixed at the front of the skate (figure 13). The camera was fixed such that the vertical plane of the recording was oriented parallel to the plane of the skate blade. The camera recorded the motion that was defined as AE.

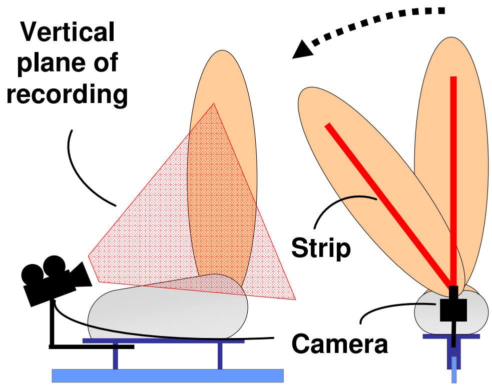

Figure 13. A side and front view of the lower leg and skate. The vertical plane of the recording is oriented parallel to the plane of the skate blade. In the front view the plane is visible as a vertical line. The camera will record the movements defined as AE.

The test skater was instructed to stand up straight on speed skates while minimizing AE. In that situation a strip was applied along the tibia. The strip was placed while looking at the image the camera produced. The strip was fixed parallel to the vertical axis of the produced image and thus parallel to the plane of the skate blade. Data from the camera was collected by a laptop on the back of the skater. A high-speed camera (Casio EX-FH20, 220 frames per second) was located at a fixed position besides the ice rink. It recorded the frontal view of the skater along a straight part of the ice rink.

Experiments

The experiments were conducted on a 400m ice rink. All exercises were conducted with normal and reduced AE. Skaters tried to skate at the same speed when skating with normal and reduced AE. The strip on the lower leg was not moved until all exercises were completed. The low skilled skaters were instructed to execute three exercises.

1. Skating straight at a personally preferred speed.
2. Sliding on the right skate for as long as possible.
3. Accelerating from slow to maximum speed.

The motions of the low skilled skaters were recorded with the camera on the skate. The high skilled skaters executed six exercises.

1. Skating straight below average speed.
2. Skating the corners below average speed.
3. Skating straight above average speed.
4. Skating the corners above average speed.
5. Sliding on the right skate for as long as possible while keeping the body close to the ice.
6. Accelerating from slow to maximum speed.

The motions of the high skilled skaters were recorded with the camera on the skate and the camera besides the track. After the experiments the low and high skilled skaters filled out a questionnaire (appendix 5). For the questionnaire the visual analog scale (VAS) was used [Grant 1999]. Two high skilled skaters (High 1 and 2) executed the first four exercises while the torque in the orthosis was measured with strain gauges.

Data analyses

The maximum ankle eversion angle during a push-off (MAX α_{AE}) was measured for the right leg only. For high skilled skaters a distinction was made between straight and corner strokes. The α_{AE} was measured as the angle between the vertical line of the recording and the strip applied along the tibia (figure 14).

Figure 14. Image from the camera on the skate. The ankle eversion angle (α_{AE}) is the angle between the vertical line of the recording (dotted line) and the yellow strip along the tibia.

Skating motions were defined as:

1. Push-off angle (β_{PO}) (figure 15)
2. Glide angle (β_{GL}) (figure 15)

The recordings of the frontal view of the high skilled skater were used to measure these angles for the right leg only.

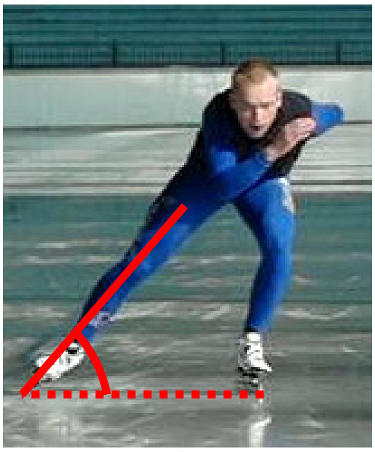

Figure 15. Front view of a skater. The angle β is measured between the horizontal and the line from the tip of the skate blade through the middle of the upper leg.

The β_{PO} is measured just before the skate is taken of the ice at the end of the push-off. The glide angle (β_{GL}) is measured when the skate is placed on the ice to initiate the gliding phase. α_{AE}, β_{PO} and β_{GL} were measured manually from the recordings with an on-screen angle measurement software tool (Screen Protractor by Iconico) Corresponding angles were averaged and the standard deviation was calculated. A two tailed Student's T-test was used to determine if the difference between selected averages was significant. A paired or unpaired test was used depending on the depended or independent relationship of the averages. The level of significance (P-value) was set at 5%.

The measured torque in the orthosis is present at the location of the strain gauges. The torque of interest is present at the rotation axis of the lower ankle joint. The rotation axis of the orthosis is aligned closely with the rotation axis of the lower ankle joint. The rotation point of the system was defined and the moment arm to the strain gauges (A1) and the moment arm to the rotation axis (A2) of the orthosis were measured (figure 16).

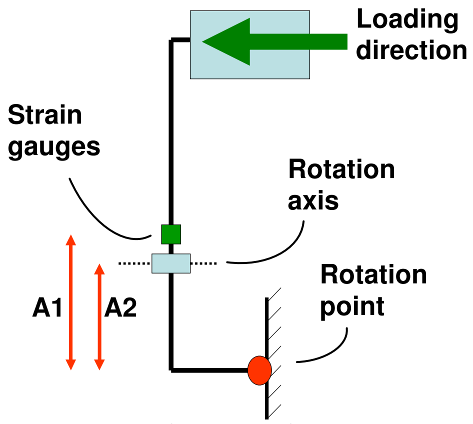

Figure 16. Front view of a model of the orthosis. The red circle is the connection point to the skate and the rotation point of the system. A1 is the moment arm to the strain gauges. A2 is the moment arm to the rotation axis of the orthosis.

The eversion torque at the location of the strain gauges and the moment arms A1 and A2 were used to calculate the torque at the rotation axis (T_{ort}). T_{ev} is compensated by T_{ort} and T_{mus} :

$$T_{ev} = T_{mus} + T_{ort}$$

The scores on the VAS questionnaires were translated into 0–10 scores.

RESULTS

Ankle eversion angle

The average MAX α_{AE} for low skilled skaters was reduced by 65 to 75% (table 3). The average MAX α_{AE} during straight and corner strokes for high skilled skaters was reduced by 45 to 70% (table 3 and 4). High skilled skaters exhibited a higher MAX α_{AE} compared to low skilled skaters (table 5). High skilled skaters had a larger MAX α_{AE} in corner strokes compared to straight strokes (table 6). In figure 17 a skater is depicted when skating with normal and reduced AE. All P-values were below 5% thus differences were significant. Box plots of the results are presented in appendix 6.

Table 3. Average maximum ankle eversion angle (MAX α_{AE}) and standard deviation over 30 straight strokes for low and high skilled skaters comparing normal with reduced ankle eversion. P-values are below 5% thus differences are significant.

	Normal	Reduced	P
Low 1	8.6 (1.7)	2.3 (0.6)	<0.001
Low 2	14.3 (3.3)	3.7 (1.0)	<0.001
Low 3	12.6 (1.8)	4.1 (0.9)	<0.001
Low 4	13.1 (2.2	3.7 (0.9)	<0.001
Low 5	8.6 (1.4)	2.5 (0.6)	<0.001
High 1	9.2 (1.0)	5.0 (0.6)	<0.001
High 2	12.9 (2.1)	4.3 (0.7)	<0.001
High 3	11.9 (0.7)	5.5 (0.8)	<0.001
High 4	17.3 (2.3)	5.1 (1.2)	<0.001
High 5	13.2 (1.4)	5.2 (0.6)	<0.001

Table 4. Average maximum ankle eversion angle (MAX α_{AE}) and standard deviation for high skilled skaters over 30 corner strokes comparing normal with reduced ankle eversion. P-values are below 5% thus differences are significant.

	Normal	Reduced	P
High 1	11.8 (1.5)	5.6 (0.6)	<0.001
High 2	15.3 (2.1)	4.9 (0.6)	<0.001
High 3	13.0 (1.0)	6.6 (0.7)	<0.001
High 4	18.2 (2.4)	6.3 (1.0)	<0.001
High 5	14.1 (1.2)	6.2 (0.6)	<0.001

Table 5. Average maximum ankle eversion angle (MAX α_{AE}) and standard deviation over 30 straight strokes with normal and reduced ankle eversion comparing the average low with the average high skilled skater. P-values are below 5% thus differences are significant.

	Low	High	P
Normal	11.4 (3.2)	12.9 (3.1)	<0.001
Reduced	3.3 (1.1)	5.0 (0.9)	<0.001

Table 6. Average maximum ankle eversion angle (MAX α_{AE}) and standard deviation for the average high skilled skater over 30 straight and 30 corner strokes with normal and reduced ankle eversion comparing straight with corner strokes. P-values are below 5% thus differences are significant.

	Straight	Corner	P
Normal	12.9 (3.1)	14.5 (2.8)	<0.001
Reduced	5.0 (0.9)	5.9 (0.9)	<0.001

Figure 17. Images from the camera on the skate. Both depict the maximum ankle eversion angle (MAX α_{AE}) during a stroke. The α_{AE} is the angle between the full line and the dotted line. In the left image with normal ankle eversion the α_{AE} is 17 degrees. In the right with reduced ankle eversion image the α_{AE} is 4 degrees.

Skating motions

In table 7 and 8 the angles β_{PO} and β_{GL} are shown for every high skilled skater with normal and reduced AE. Differences were insignificant except for β_{PO} for High 1, β_{GL} for High 2 and β_{GL} for High 5.

Table 7. Average push-off angle (β_{PO}) and standard deviation for high skilled skaters over 11 to 14 straight strokes comparing normal with reduced ankle eversion. P-values indicate significance. Significance level set at 5%.

	Normal	Reduced	P
High 1	53.8 (1.1)	52.8 (1.0)	0.020
High 2	54.5 (2.7)	53.3 (2.6)	0.244
High 3	60.6 (1.7)	60.5 (1.8)	0.916
High 4	56.3 (1.3)	55.5 (1.2)	0.108
High 5	53.6 (1.3)	53.2 (1.2)	0.316

Table 8. Average glide angle (β_{GL}) and standard deviation for high skilled skaters over 11 to 14 straight strokes comparing normal with reduced ankle eversion. P-values indicate significance. Significance level set at 5%.

	Normal	Reduced	P
High 1	107.3 (1.9)	107.2 (2.3)	0.933
High 2	110.1 (2.3)	108.2 (2.0)	0.015
High 3	99.8 (1.9)	99.0 (1.5)	0.262
High 4	99.7 (1.4)	99.7 (0.8)	1.000
High 5	102.9 (1.6)	101.1 (1.0)	0.006

Torque

The average T_{ort} for skaters High 1 and High 2 was 1.8 Nm. This was equivalent to a 6 kg eversion load at 300mm from the rotation axis. In that situation γ_{ort} was 6 degrees. In figure 18 T_{ort} is plotted. During straight strokes there was also a torque in the inversion direction with an average amount of -0.5 Nm.

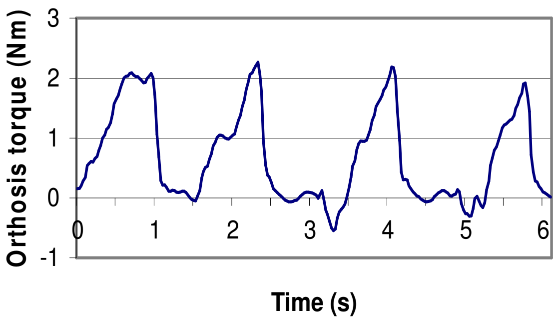

Figure 18. Torque in the orthosis. The two peaks on the left are corner strokes. The two peaks on the right are straight strokes. Positive y-values indicate eversion and negative y-values indicate inversion.

Questionnaire

The results of the VAS questionnaire are shown in table 9. The overall rating for the functioning of the orthosis was neutral for high skilled skaters and positive for low skilled skaters. Low skilled skaters felt more stable with reduced AE while high skilled skaters felt more stable with normal AE. Skaters did not feel that the AE is a really necessary motion. The orthosis was not perceived as an irritating device that hampers speed skating. The orthosis functions properly but was considered big and clumsy. The orthosis could not be used on the left leg because it will hit the ice in corner strokes.

Table 9. Questionnaire results. Average grade with standard deviation for low and high skilled skaters (AE is ankle eversion).

	Low	High
Overall skating with reduced AE	7.4 (0.9)	5.8 (0.8)
I prefer skating with reduced AE	5.4 (1.8)	4.8 (1.3)
I feel stable with normal AE	5.2 (1.3)	8.4 (1.3)
I feel stable with reduced AE	7.2 (1.1)	7.4 (0.9)
AE is a necessary motion	2.2 (2.2)	5.4 (1.5)
The orthosis is irritating	1.4 (0.9)	2.4 (2.8)

Additional comments by the test skaters were written in the remarks section.

Low skilled skaters:
1. Skating on one leg was not made easier with reduced AE.
2. Reduced AE was a pleasant help to execute the push-off.
3. The orthosis is considered big and clumsy.

High skilled skaters:
1. There was a learning curve to adapt to skating with reduced AE.
2. There is potential for reduced AE in speed skating.
3. The hand of the skater hits the lower leg brace during the arm swing.

Two high skilled skaters (High 1 and High 2) used the orthosis on multiple occasions. After multiple tests they adapted. They did not notice the orthosis anymore and had to look down to check if they were wearing it. When skating with normal AE after multiple sessions with reduced AE they had to remember to stabilize their ankle by themselves again. One lap was needed to readapt.

The rotation axis of the orthosis did not have to be aligned with the ankle joint very precisely. Skaters were easily satisfied with the ability to plantar and dorsal flex. There were no complaints about friction between the skin and the brace around the lower leg.

DISCUSSION

Goal and results

The first goal is to reduce AE during speed skating. Dorsal and plantar flexion is to be left unhampered. The second goal is to prove that the skating motions can be executed with reduced AE. According to the results the α_{AE} is reduced significantly. The average α_{AE} for straight strokes of high skilled skaters is reduced from approximately 13 to 5 degrees. This would results in a reduced T_{ev} from approximately 32.5 to 12.5 Nm for professional skaters (table 1). 1.8 Nm of the 12.5 Nm is compensated by the orthosis resulting in a T_{mus} of 10.7 Nm. T_{mus} would be reduced from 32.5 Nm to 10.7 Nm at the end of the push-off. This is a reduction of 70% for T_{mus}. The 70% reduction is calculated with rough estimates of the T_{ev} for an average profesional speed skater and with measured values of the tested high skilled skaters. This is a rough indication of the possible reduction in T_{mus}. It is a promising result. Plantar and dorsal flexion is left unhampered. According to the results β_{PO} and β_{GL} do not vary significantly when skating with normal and reduced AE. The skating motions can be executed with reduced AE. The results from the questionnaire showed that skaters were not negative about skating with reduced AE. There were very positive comments from skaters that used the orthosis often enough to adapt.

Measurement accuracy

It is assumed that the MAX α_{AE} occurs simultaneously with maximum push-off force. T_{ev} will also be at its maximum. Maximum push-off force occurs near the end of the push-off [Koning 1992]. At that instant the angle between the skate blade and the lower leg in the flexion direction will be approximately 90 degrees [Houdijk 2000]. The existence of projection errors due to plantar and dorsal flexion is unlikely. The manually applied strip along the tibia and the manual on-screen angle measurements will result in errors. The errors due to the strip are exactly the same for the normal and reduced AE measurements because the strip is not moved. The error due to the applied strip will not affect differences in skating between normal and reduced AE. The errors due to manual on-screen measurements will. However, the reductions in MAX α_{AE} are still considered big enough to be significant. The torque measured in the orthosis proves that the AE is reduced.

Skating motions were only measured for high skilled skaters. High skilled skaters are familiar with detailed technical aspects of the sport and strive to execute the motions similarly each time. Low skilled skaters are not performance driven in the same way as high skilled skaters. Skating motions were defined as β_{PO} and β_{GL}. This is a major simplification of the skating motions. β_{PO} and β_{GL} are relatively easy to measure compared to other skating motion characteristics. β_{PO} was defined by Ingen Schenau (1985) and Boer (1986) as the angle between the horizontal and the push-off force at the end of push-off. β_{PO} is directed more horizontal with better skaters [Ingen Schenau (1985), Boer (1986)]. Due to the link with performance β_{PO} is more important than β_{GL}. In this paper β_{PO} was defined as the angle between the horizontal and the line from the tip of the skate blade through the middle of the upper leg. This is an approximation of the actual definition. Measuring β_{PO} from the frontal camera will result in projection errors when the push-off force is not oriented parallel to the frontal plane (figure 19, table 10). At the end of push-off the amount of rotation to the frontal plane is estimated at 0 to 20 degrees resulting in an error of 0 to +1.7 degrees.

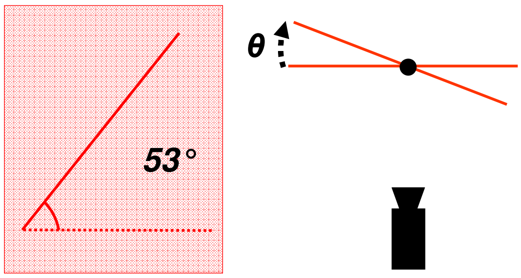

Figure 19. Left: Front view of β_{PO} with a common value of 53 degrees. Right: Top view of β_{PO}. The camera records β_{PO} with an angle θ to the plane of the force vector.

Table 10. Measured β_{PO} for given force vector rotation (θ) according to figure 19. The true β_{PO} is 53 degrees.

θ (degrees)	**Measured β_{PO} (degrees)**
0.0	53.0
10.0	53.4
20.0	54.7

β_{PO} and β_{GL} are measured manually on-screen. Errors due to projection and manual measuring are considered significant for the results. Measurement accuracy is not high enough to ensure the correctness of the results. The results of the questionnaire show that skaters were not hampered while executing the skating motions. This level of additional verification is considered sufficient to prove that the skating motions are possible with reduced AE. Small differences might exist.

Relevance

The results prove that the tested skaters were less bothered by AE when skating with the orthosis. The body does not have to supply the same amount of energy to stabilize the ankle compared to skating with AE. This might have positive consequences on the endurance of a skater. The force pattern between the ice and the skate blade is probably different when comparing skating with normal and reduced AE. It is possible that more energy is used for propulsion. This might have a positive effect on the efficiency of the push-off. There are no negative outcomes considering skating with reduced AE. That is a very positive situation. Reducing AE might have a positive influence on performance.

Orthosis

The designed orthosis is the device used to reduce AE. Other options have been addressed. Skate shoes that support the ankle also restrict dorsal and plantar flexion. These motions are needed to skate. The option to design a totally new skate shoe is dismissed. Designing an add-on to an existing skate is a better idea. A skater can wear the same skate when skating with normal and reduced AE. The skate will not have an influence on the measurements. Skaters will not give up the traditional skate shoe easily. An add-on will be less of a shock. Taping and sports braces are other options. Thacker (1999) reviewed 113 papers that discussed ankle sprain in sports. Sports braces are preferred over tape. Sports braces are mainly made of soft materials and they are not rigidly connected to the skate. The metal skate frame does provide an ideal attachment point to connect an orthosis rigidly. Hereby motion between the skate and the orthosis can be minimized increasing the chances of reducing AE. The foot and the sports brace will have to fit in the skate shoe. There is no extra space for a sports brace. Designing an orthosis for the experiments is considered the best option to reduce AE. There might be other ways to the reduce AE. The orthosis is evaluated to give an overview of the positive and negative aspects of the used AE reduction method.

Skaters did not notice slight differences in the location of the rotation axis of the orthosis. One rotation axis in the orthosis is sufficient to guarantee comfort for all the tested skaters. The exact location of this axis is less crucial then expected. The orthosis functions properly but was considered big and clumsy. It can not be used on the left leg because it will hit the ice in corner strokes. Skaters stated that their hand hits the calf brace during their arm swing. A T_{ort} of 1.8 Nm corresponds with a 6 degree γ_{ort}. A stiffer construction to reduce AE is preferred. The orthosis was designed for short track speed skates. The short track frames under the skate shoe are standardized. This is not the case with long track speed skates. Designing for standardized frames ensures that the orthosis can be used with different skate shoe and thus different skaters. The distance between the ice and the shoe is larger with short track frames. This increases the eversion torque providing a more challenging situation for the orthosis.

CONCLUSIONS

1. The average MAX α_{AE} is reduced from approximately 12 to 4 degrees for all tested skaters.
2. The skating motions can be executed with reduced AE. Small differences might exist.
3. The overall rating by the tested skaters for skating with reduced AE is neutral to positive.
4. There are no negative outcomes from the angle measurements or the questionnaire on skating with reduced AE. That is a very positive situation.
5. An estimation of the required muscle force shows that the amount is reduced significantly when skating with reduced compared to normal AE.
6. A skater saves energy when skating with reduced AE and is not distracted by AE when executing the push-off. Skating with reduced AE might have a positive influence on performance.
7. A redesign of the orthosis should be stiffer and more compact.

RECOMMENDATIONS

More research is required to investigate the effects of skating with reduced AE on performance. Controlled experiments with physiological and force measurements should be conducted while AE is reduced on each leg. It will be hard to measure differences accurately.

The orthosis can be optimized according to the points mentioned in the discussion. Currently there are no skate add-ons on the market that can reduce AE. Considering the positive outcomes it might be worth to develop the idea into a commercially available product.

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Appendix 1: The ankle and speed skating

Ankle physiology

The presented information is adapted from Gray (1918). The lower leg and the foot are connected at the ankle joint (figure 1). The ankle and the foot consist of many bones and joints. The foot is also taken into account because of its close relationship to the function of the ankle. The plantar surface provides a platform to support the weight of the body. Balance and stability is provided by numerous bones, joints, muscles and ligaments. The system can adapt to perturbations and uneven surfaces. The foot and ankle also play a role in locomotion. Strong muscles in the lower leg can plantar flex the foot propelling the CoM forward.

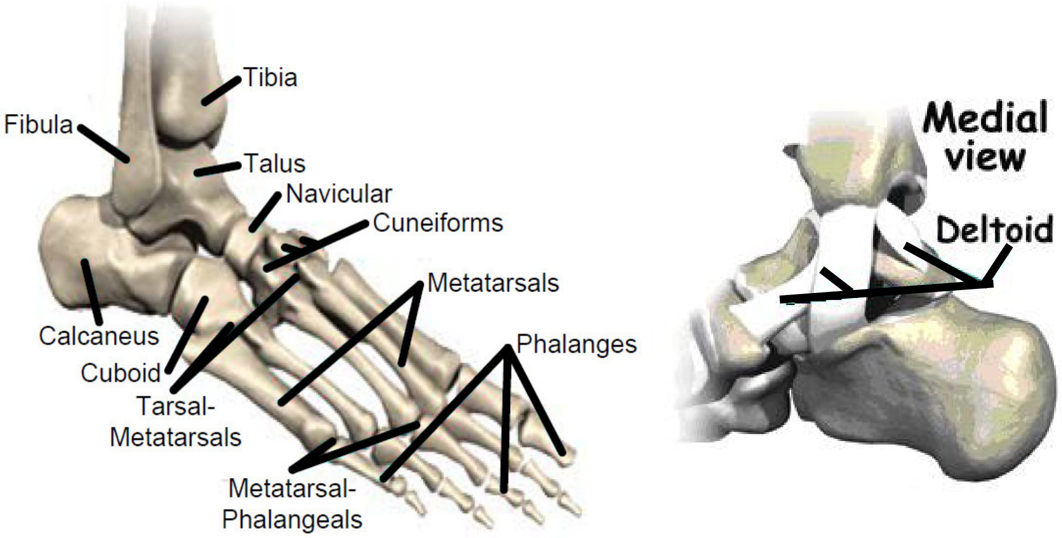

Figure 1. Left: The bones in the lower leg are the tibia and the fibula. The relevant bones in the foot are the talus and calcaneus. Right: Medial view of the ankle with the deltoid ligament. Adapted from http://www.eorthopod.com.

The lower leg consists of the tibia and fibula. These are located on the inside and the outside of the lower leg respectively. The talus and the calcaneus interface with the lower leg. The ankle is actually made up out of two joints. The talocrural joint is the interface between the two bones in the lower leg (fibula end tibia) and the talus. It is a hinge joint that mainly facilitates dorsal and planter flexion. The subtalar joint is the plane joint between the talus and the calcaneus. It allows for inversion and eversion of the foot. The deltoid ligament stops ankle eversion (AE) after a certain limit. The deltoid ligament is a strong, flat, triangular band. It is attached to the malleolus, the lower part of the tibia and several other bones. The deltoid ligament can not prevent AE, it sets a limit. Muscle force is needed to compensate AE. AE can be counteracted by several muscles. The tibialis anterior (figure 2) can invert the foot. This muscle crosses the ankle joint and a large part of the mid-foot. The tibialis posterior can also invert the foot. It is connected to the fibula and the middle part of the foot (figure 2). The location of the axis of rotation of the talocrural joint and the subtaler joint are depicted in figure 3 and figure 4 respectively. The range of motion for the ankle joint is presented in table 1.

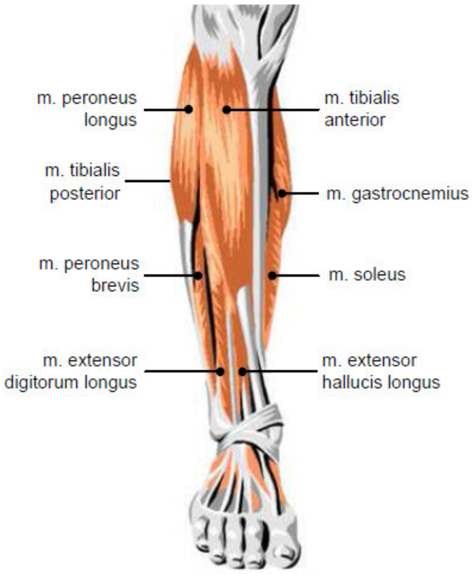

Figure 2. Front view of the lower leg and its muscles. the muscles that can invert the foot to resists ankle eversion are the tibialis anterior and the tibialis posterior. Adapted from http:// http:// www.eorthopod.com.

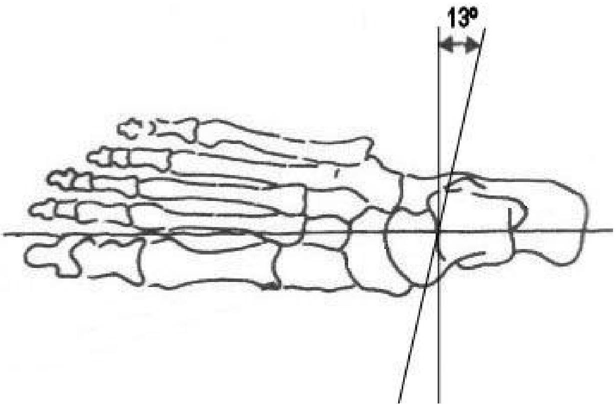

Figure 3. A top view of the foot with the talocrural joint with its rotation under a slight angle. Figure from Snijders, C.J., Nordin, M., Frankel, V.H., Biomechanica van het spierskeletstelsel.

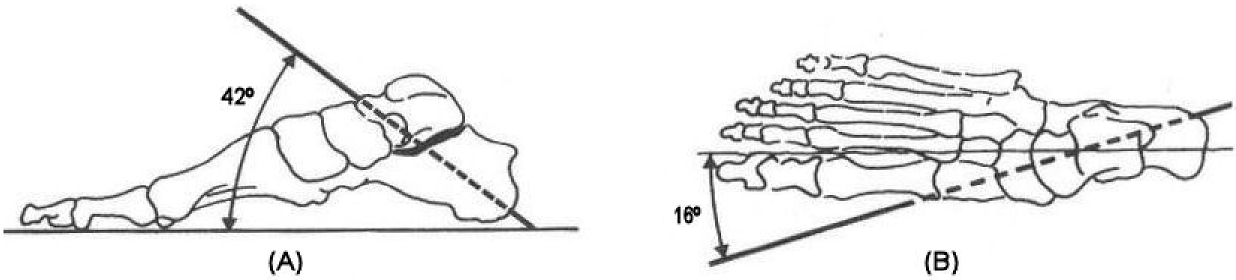

Figure 4. Side and top view of the axis of the subtalar joint. Figure from Snijders, C.J., Nordin, M., Frankel, V.H., Biomechanica van het spierskeletstelsel.

Table 1. The range of motion for the movements of the ankle joint [Dreyfuss 2002].

Motion	**5th percentile**	**90th percentile**
Plantar flexion	25	51
Dorsi flexion	15	43
Inversion	14	36
Eversion	11	33

Ottoviani (2001) measured the eversion and inversion strengths in the weight bearing ankle of healthy young men and woman. After normalizing for length and bodyweight the maximum eversion and inversion torques were defined at 1.6% of bodyweight (N) times height (m) and 2.7% N*m respectively.

Ankle use in speed skating

The amount of plantar flexion used during speed skating on skates without a klap hinge has been measured by Houdijk (2000).

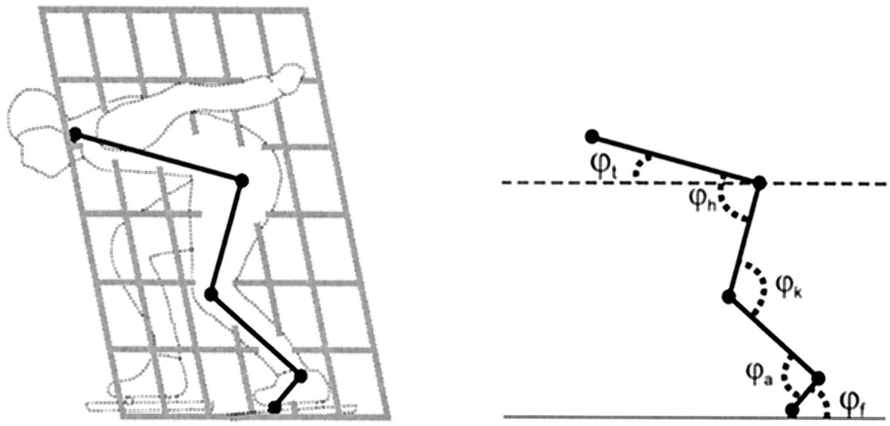

Figure 5. Model of the leg. The angle of interest is φ_a. Adapted from Houdijk (2002).

According to Houdijk (2000) the ankle angle is approximately 90 degrees at the start of push-off. The foot is flexed by 125 degrees after the push-off (figure 6). Data on the orientation of the ankle joint other then flexion during the push-off is not available.

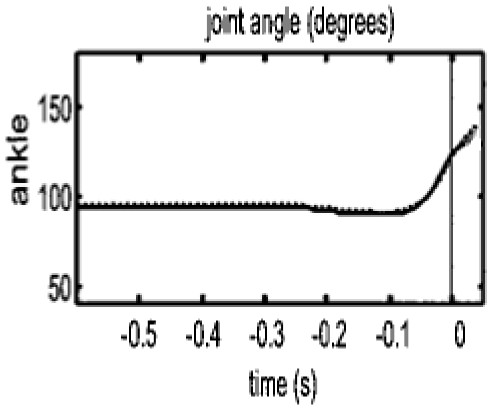

Figure 6. Joint angle of the ankle during the push-off with conventional skates. The end of the push-off is marked by the vertical line. Adapted from Houdijk (2000).

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Appendix 2: Force analysis

The goal is to find the maximum loading situation in the ankle when speed skating. It is assumed that the load on the ankle is higher when skating through a turn (figure 1). This is attributed to the centrifugal forces. The following figures depict the analysis.

Figure 1. An impression of a skater in a turn. The 5th image displays the skater approximately at the end of the push-off. Figure adapted from Koning (1991).

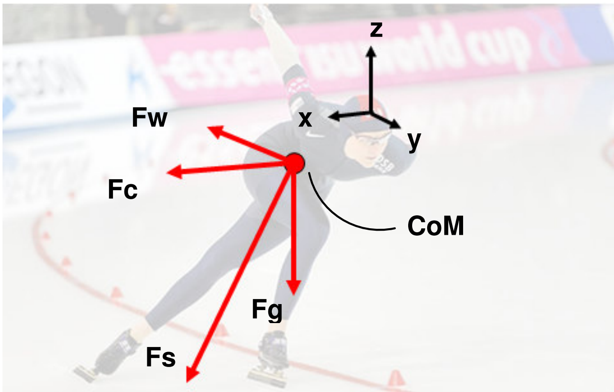

Figure 2. Center of mass (CoM) of a skater in a turn in a local coordinate system. Forces acting on the CoM:
1. *Gravitational force (Fg in z-direction)*
2. *Frictional forces due to ice and air (Fw in y-direction)*
3. *Centrifugal forces due to skating in a curved trajectory (Fc in x-direction)*
4. *Push-off force due to pushing off with a leg and partly supporting the body with the other leg (Fs has a component in all directions)*

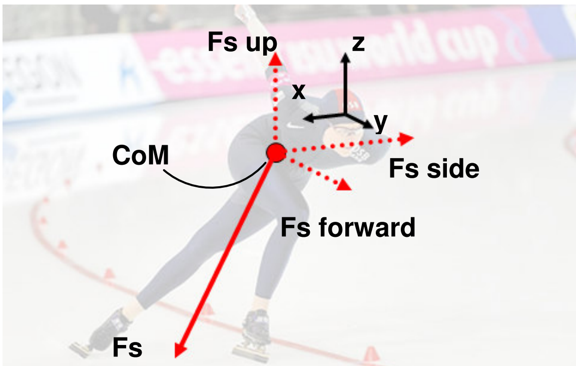

Figure 3. Center of mass (CoM) of a skater in a turn in a local coordinate system. Push-off force components:
1. *Fs upward to compensate the gravitational force. (z-direction).*
2. *Fs sideward to compensate the centrifugal force. (x-direction)*
3. *Fs forward. This force will probably be small or inexistent when skating through a turn.(y-direction)*

Depicting all the relevant forces in a 2D plane makes calculations easier (figure 4). Placing all the forces in a 2D plane required redirecting the push-off force so it loses its forward component. This does not change the loading situation on the ankle. Frictional forces are unimportant when focusing is on the loads in the ankle.

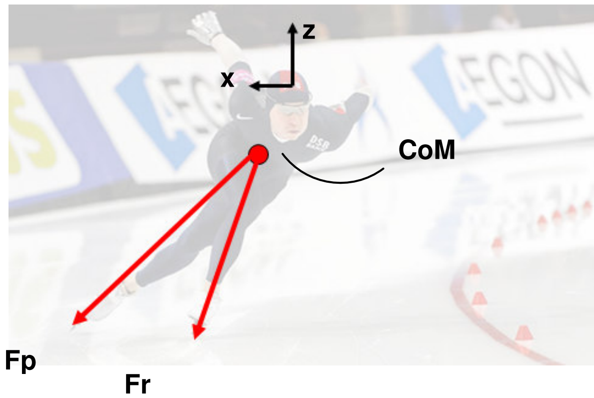

Figure 4. Centre of mass (CoM) of a skater in a turn in a local coordinate system. The push-off force is divide over both legs.

At the end of the push-off a skater is supported by both legs. One is mainly pushing off (Fp) and the other one is mainly supporting the skaters mass (Fr) (figure 4). Fp loads the ankle joint of the push-off leg. The highest push-off force occurs at the end of the push-off phase in a corner stroke [Braver 2007]. For further analyses the focus is directed to the leg (figure 5).

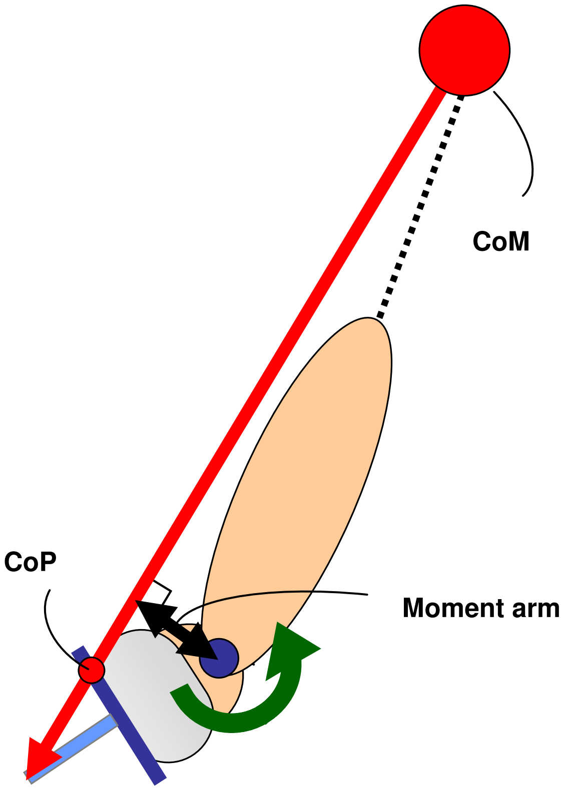

Figure 5. Front view of the lower leg and skate during the push-off leg with ankle eversion. The push-off force (red line) passes through the center of pressure (CoP). A moment arm is present perpendicular to the force line towards the ankle joint resulting in a torque (green arrow).

A model of the leg is made to analyse the torques and forces (figure 6).

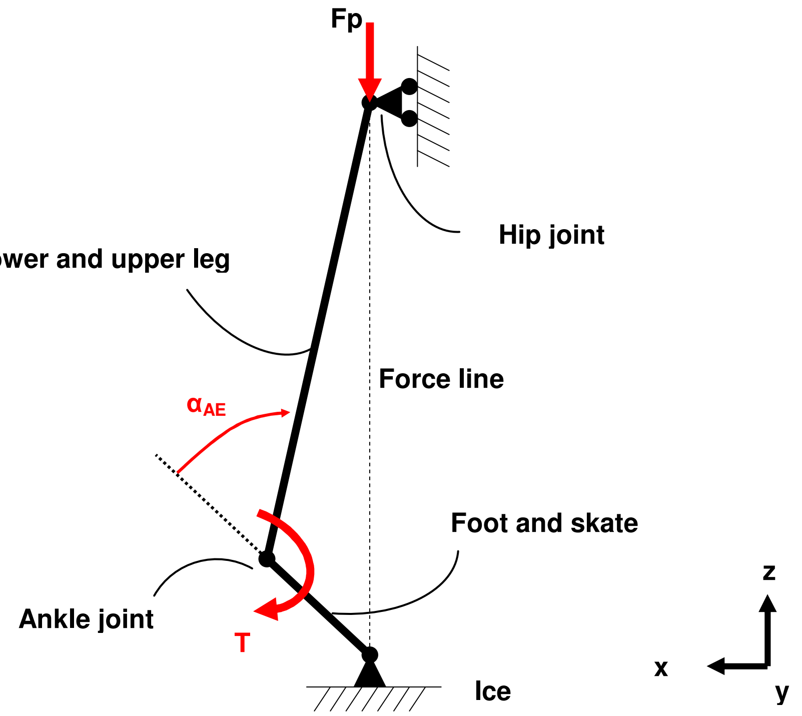

Figure 6. The leg and foot of a skater modelled in the x-z plane. The skate blade is connected to the ice with a 1 degree of freedom (DoF) joint rotation around the y-axis. The hip and ankle joint are modelled with a rotation around the y-axis. The hip joint is fixed to a roller. The ankle eversion angle (α_{AE}) is depicted by a red arrow. The lower leg and upper leg are modelled as one member The roller is loaded with the push-off force Fp. A torque T around the ankle joint is needed to compensate ankle eversion.

Table 1. Anthropometric data of elite speed skaters is collected by Ingen Schenau (1981)

		Body weight [kg]	Body length [m]	Upper leg length [m]	Lower leg length [m]	Shoulder width [m]	Circumference of the upper leg at 25% of upper leg length [m]	Fat (%)
Elite skaters	$\overline{x}$	73.6	1.81	0.437	0.451	0.412	0.424	9.45
	Sd	7.4	0.03	0.021	0.014	0.014	0.040	2.16

The push-off force and anthropometric data of a skater are required to approximate the torque needed to compensate ankle eversion (AE). Koning (1992), using a measurement skate by Jobse (1990), found a maximum push-off force of 140% bodyweight. Anthropometric data is presented in table 1. The length of the foot and skate (figure 6) is estimated at 180mm. The ankle can be everted up to approximately 30 degrees [Dreyfuss 2002]. The required torque to inhibit AE will be calculated for the average elite skater for an AEA of 10, 20 and 30 degrees.

Table 2. Ankle eversion angle with corresponding torque.

AEA (degrees)	**M (Nm)**
10	24.7
20	50.4
30	75.1

Muscle strength to resist AE
To resist AE the muscles that can rotate the ankle inwards need to be activated. Ottoviani (2001) defined the average maximum inversion torque at 2.7% of bodyweight (N) times height (m) for both men and woman. The standard deviation (SD) is 0.8% of N*m. The average person can resist a torque of 2.7% * 74 * 9.81 * 1.81 = 37 Nm. Adding the SD twice yields the 97,7th percentile with a torque of 59 Nm. This can be compared with the torques calculated previously. An eversion torque of 50Nm with an AEA of 20 degrees is slightly less than the torque that can be generated by an extremely fit person. This means that compensating AE with muscle force is a demanding task. It has to be stressed that these calculations and conclusions are estimates and that no direct research has been executed.

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Appendix 3: List of demands

GOAL**:** Design an orthosis to reduce the ankle eversion in speed skating.

General

- The device has to be an add-on which can be connected and disconnected to the skater and/or the skate.

Motion

- Fix the ankle eversion angle to 0 degrees.
- Compensate an ankle eversion torque of 50Nm (appendix 2).
- Unhampered dorsi flexion up to 40 degrees and unhampered plantar flexion up to 50 degrees.
    - Movements within the given boundaries have to be frictionless.

User

- Adjustability for different skaters
    - Lower leg length
    - Ankle joint location.
- Prevent motion between skin and designated connecting point of device.
    - Minimize shear forces on skin. Only normal forces are allowed.

Skate type

- Characteristics of a skate the device will be designed for:
    - Skate used for the purpose of speed skating.
    - No clap hinge.
    - Short track skate frame.

Design space

- Device should not touch body parts other than then designated connecting points.
- All necessary skating motions besides ankle eversion should not be hampered by the device.

Miscellaneous

- Maximum mass is 500 grams
- Modularity, build the device out of as few parts as possible which should be easily detachable from each other.
- Corrosion resistant

Appendix 4: Design of an orthosis

In order to ensure reproducibility of the research project an overview of the design process is presented. A design process is a vague and abstract undertaking. Only the important directions that were investigated and decisions that were made are documented here.

Solutions to similar problems

The goal is to design an ankle orthosis to reduce ankle eversion (AE) in speed skating. An overview of solutions to similar problems was made for inspirational purposes.

UTX

The UTX is a knee-ankle-foot orthosis [Leerdam 1993] (figure 1). It is an exoskeleton that provides support for patients with an instable knee. The ankle section allows for dorsal flexion and plantar flexion and it inhibits inversion and eversion of the foot. For extra stability a cable can be added on the medial side of the leg. This is often done with patients that suffer from valgus deformity, a condition were the lower leg is angulated outwards in reference to the upper leg. The UTX is custom fitted to the user.

Figure 1. The UTX knee-ankle-foot orthosis. Adapted from http://www.ambroise.nl/.

Ankle braces

Ankle sports braces are often used in sports to prevent injuries (figure 2). The average ankle sports brace is predominantly made out of soft materials. Hard materials can be added to provide for extra stiffness. Velcro or laces are often used to fasten the sports braces. Some models are equipped with a hinge.

Figure 2. Two ankle sports braces. The brace on the left has a hinge. Adapted from http://.bio-shop.co.uk/.

Taping
The tape is wrapped around the ankle (figure 3). Stiffness is added to the inversion and eversion motion of the foot while dorsal flexion and plantar flexion is still possible. Tape is a soft material. It can only accommodate tensile forces.

Figure 3. An ankle with tape applied. Adapted from http://www.rehab.com/.

Self-aligning exoskeleton axis
Human joints are seldom simple hinges. The location and orientation axis of human joints are often dynamic variables. The self-aligning joint is a solution that addresses this problem [Stienen 2009] (figure 4). The self-aligning joint adapts to the location of human joint axis. This ensures that shear forces are not present on the skin.

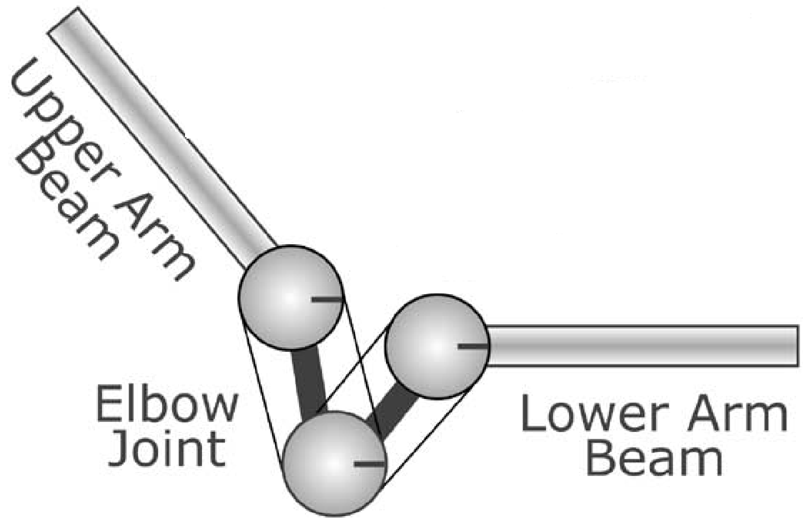

Figure 4. Self-aligning joint for the elbow. Adapted from Steinen (2009)

Evaluation of solutions to similar problems
Jerosch (1997) and Shapiro (1994) conducted experiments to determine the stabilizing effects of sports braces and tape. Jerosch (1997) addressed mechanical and proprioceptive effects. Shapiro (1994) only addressed mechanical effects. Both concluded that there are sports braces available that perform better then tape. Thacker (1997) reviewed 113 papers that discussed ankle sprain in sports. Most studies indicated that appropriately applied sports braces, tape, or orthosis do not adversely affect performance. Sports braces are preferred over tape. This leaves both sports braces and exoskeletons as possible directions. Sports braces are still mainly made of soft materials and they are not rigidly connected to the skate. The metal skate frame does provide an ideal attachment point to connect an exoskeleton rigidly. Hereby motion between the skate and the orthosis can be minimized. Sports braces are worn around the foot and the lower leg. The foot and the sports brace will have to fit in the skate shoe. Skate shoes are designed to fit the foot of a skater tightly. There is no extra space for a sports brace. To prevent the need to design a completely new skate shoe it was decided to design an add-on to the current skate. The add-on can be connected to the skate frame rigidly and will be made out of hard and stiff materials.

Concepts

The problem was divided in sub problems.

1. Connection to the skate
2. Connection to the skater
3. Construction providing stiffness for AE and motion freedom for flexion

For every sub problem multiple solutions were generated. Sketches are added to clarify the ideas.

Connection to the skate

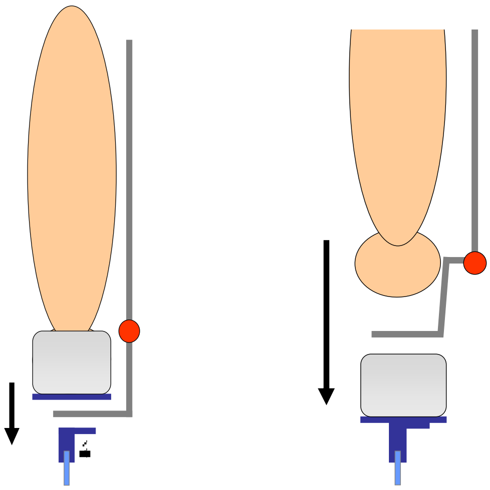

Figure 5. Left: A frontal view of the lower leg and the skate. The orthosis (grey and red) is rigidly fixed between the skate frame and the shoe. Right: A frontal view of the lower leg and the skate. The orthosis (grey and red) is connected to the skate by means of an inlay in the shoe. The orthosis can be connected to the inlay.

Connect to the skater

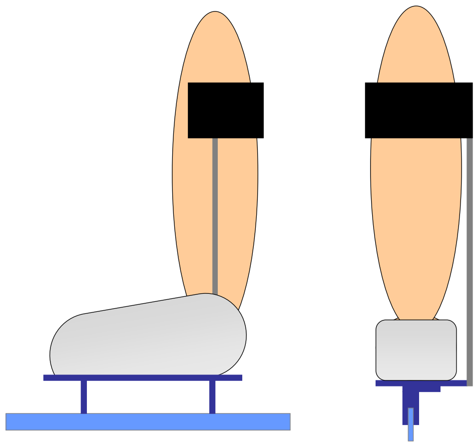

Figure 6. A side and frontal view of the lower leg and the skate. The orthosis (grey and black) is connected to the skater with a brace that is padded with soft materials.

Construction providing stiffness for AE and motion freedom for flexion

Self-aligning joints:

1. A self-aligning joint set up with 3 hinges allows for dorsal and plantar flexion. The hinges will adapt to the situation. Movements will be smooth and no additional stress due to misalignment will be present.
2. A self-aligning joint set up with 2 hinges. Since it is possible to position the hinges close to the rotation axis of the ankle 2 hinges may be enough.
3. A combination of one hinge joint and a linear bearing. The linear bearing provides an extra degree of freedom to adjust to misalignment.

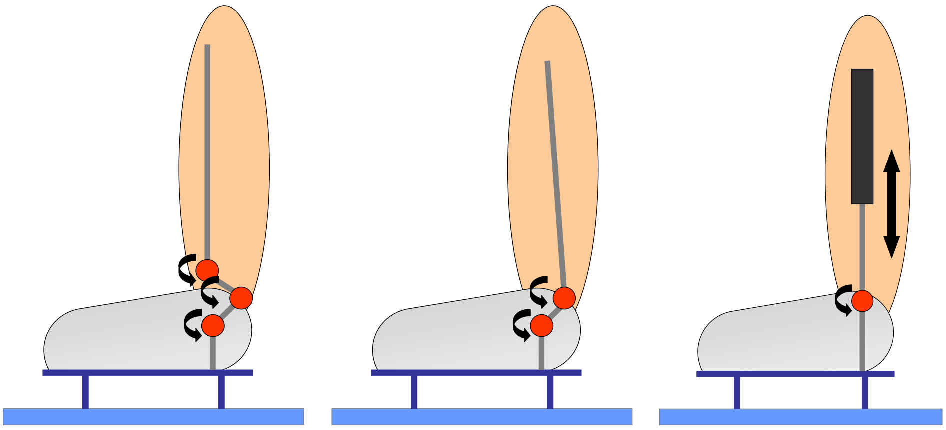

Figure 7. Side view of the lower leg and the skate. A grey bar is a rigid part of the orthosis and red circle is a rotation point. The black square on the right is a linear motion bearing.

Single adjustable joint:

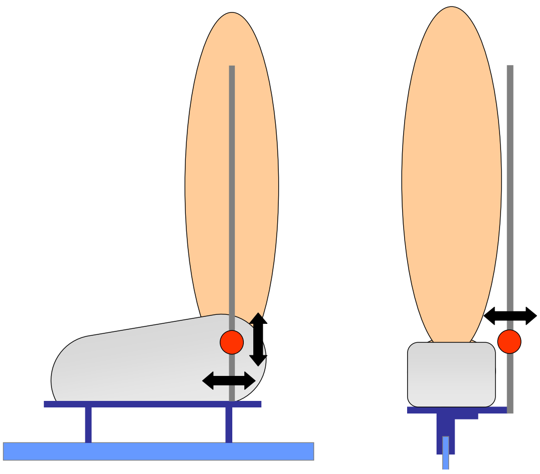

Figure 8. Side view of the lower leg and the skate. The red circle is a rotation point. This point can be adjusted in all three dimensions. Misalignment will not be compensated. It is crucial to fix the hinge in the right position.

Compliance or posterior of the leg:

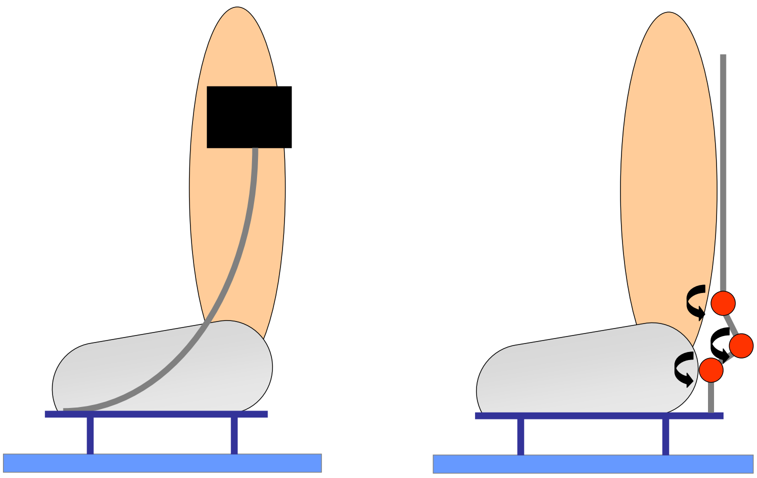

Figure 9. Side view of the lower leg and the skate. Left: The grey bar is a compliant connection between the skate and a brace on the skater. It is compliant for dorsal flexion and plantar flexion. Stiffness in the other direction will prevent ankle eversion. Right: The orthosis could also be placed behind the leg. Self-aligning joints will be necessary because the rotation axis of the ankle is located at a distance from the rotation axis of the joints. The red circles are rotation points.

Bilateral exoskeleton or cables:

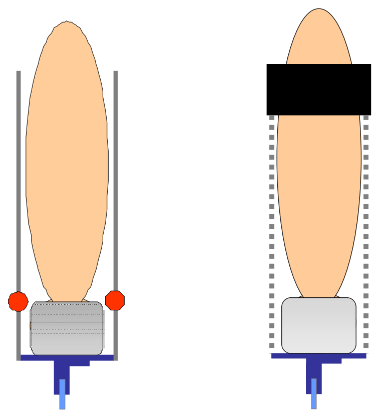

Figure 10. Rear view of the lower leg and the skate. Left: The red circles are rotation points. A bilateral orthosis supports the ankle on both sides. An orthosis on both sides of the leg will make for a very stiff construction. Aligning both hinges will be a challenge. Right: The black brace is connected to the skate with cables. A cable on both sides of the leg will prevent inversion and eversion. Only tensile forces will be compensated by the cables.

Evaluation of ideas

Connection to the skate
According to the list of demands (appendix 3) ankle eversion should be inhibited till 0 degrees. To fix the skate and foot a rigid connection has advantages over the inlay option. There is no movement between the orthosis and the skate if the connection is rigid. The orthosis will be connected rigidly.

Connection to the skater
This connection should be as rigid as possible. Ideally one would want to connect the orthosis to the bones in the lower leg. A rigid brace that can be fastened to the lower leg is the best option. This technique is used with the UTX and with other orthosis.

Construction providing stiffness for AE and motion freedom for flexion
The self-aligning joints provide a solution for misalignment. According to Houdijk (2002) the range of dorsal flexion and plantar flexion during speed skating on skates without a klap hinge is 50 degrees. How the location of the rotation axis of the ankle joint changes within this range is hard to determine. The UTX and other ankle orthosis have one hinge to accommodate the motion. According to an orthopedic specialist (Westland Orthopedie, Delft) using a single joint which is aligned correctly should suffice. Self-aligning joints will make the orthosis a lot more complex. Models were made to address the misalignment problem (figure 11). The conclusion was that one rotation axis on the orthosis aligned with the ankle joint axis will be enough.

Figure 11. Simple models to test the alignment issue.

A compliant orthosis is another alternative. Dorsal flexion and plantar flexion will not be frictionless which is a demand (appendix 3). Most orthosis work with hinges. Attempting to design a compliant orthosis will be a challenge in itself. This will only complicate matters and the outcome is hard to predict. The option is dismissed. Placing the orthosis posterior to the leg does not provide any advantageous compared to placing it at the side. The orthosis will not be an obstacle when it is placed either lateral or posterior to the leg. It will be more complicated to align the joints when it is located in the posterior position. When it is placed medial to the leg it will be an obstacle. The orthosis might hit the other leg while skating. The bilateral alternative is also dismissed. Locating it on the lateral side is the best option. The only alternative left is the option with two cables. The brace around the lower leg will be loaded in the axial direction of the lower leg. This will result in shear forces on the skin. These should be minimized. This leaves the single joint with an adjustable location as the best option. An orthosis with a single hinge that can be aligned with the ankle joint will be designed. The orthosis will be connected to the skate rigidly. A brace will be connected to the skater around the lower leg.

Final design

Figure 12. Total view of the orthosis. The height of the green brace along the bar can be adjusted as can the location of the rotation axis

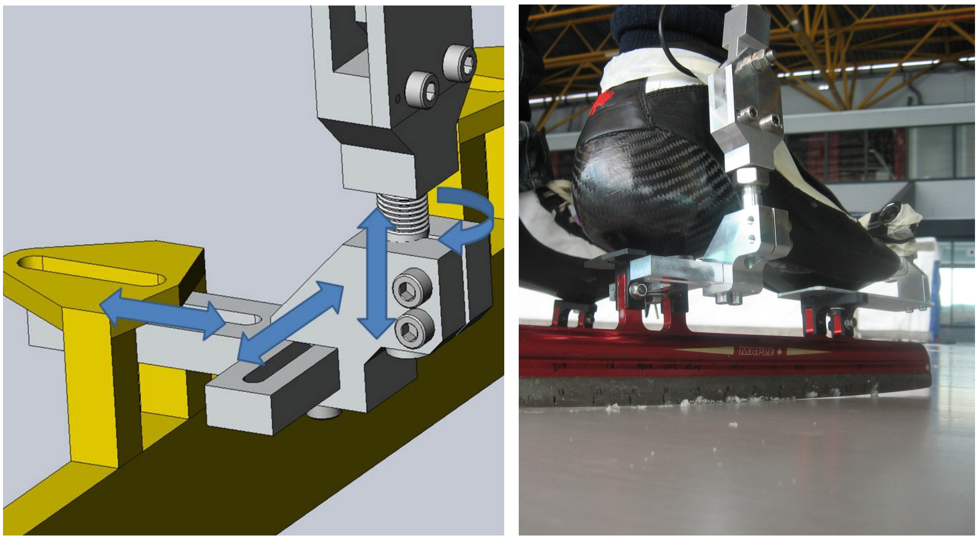

Figure 13. View of the lower part of the orthosis in Solidworks and in a materialized version. The arrows in the left image indicate the adjustable dimensions to adjust the location of the hinge. This makes it possible to align the orthosis and the joint precisely. One rotational degree of freedom might be useful to position the orthosis even more precise. The orthosis is rigidly connected with the same bolt that connects the frame to the skate shoe. This part is designed to precisely fit in the connectors between frame and skate. The orthosis will not be able to rotate around the bolt when it is assembled.

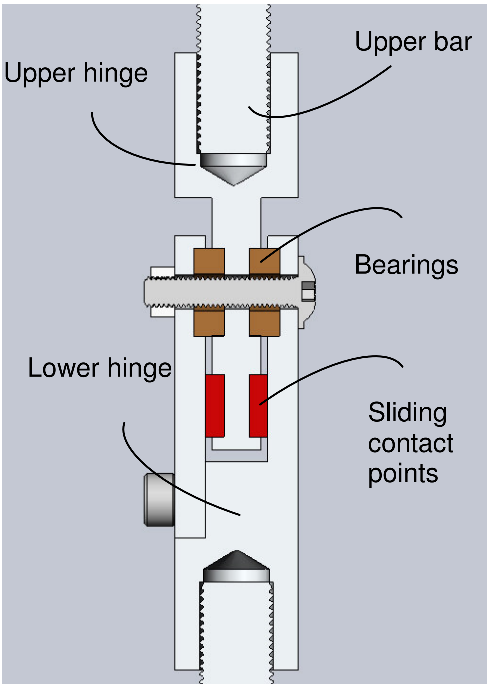

Figure 14. Section cut of the hinge. The upper bar is bolted into the upper hinge part. The brown colored bearings provide the rotational freedom between the two hinge parts. The red parts are sliding contact points between the upper and lower hinge parts. They help carry the torque load on this hinge.

A sideward torque load is one of the most challenging loads for a hinge. The torque load is divided over a surface located at a distance from the hinge (figure 14). These contact points will be made out of a material with a low friction coefficient. Two thrust bearings (SKF BA6) are used to provide the rotational freedom. Thrust bearings were chosen over radial bearings because the forces in the hinge will mainly be directed axial to the rotation axis. Calculations and simulations with finite element software were made to determine the required thickness of the parts and thus guarantee the structural integrity. The orthosis will be made from aluminum 7075 T6 which is a high grade alloy that is extremely stiff. The long member from the hinge to the lower leg brace will be made from RVS316. An exploded view is shown in figure 15. Technical drawings can be found in appendix 7.

Exploded view

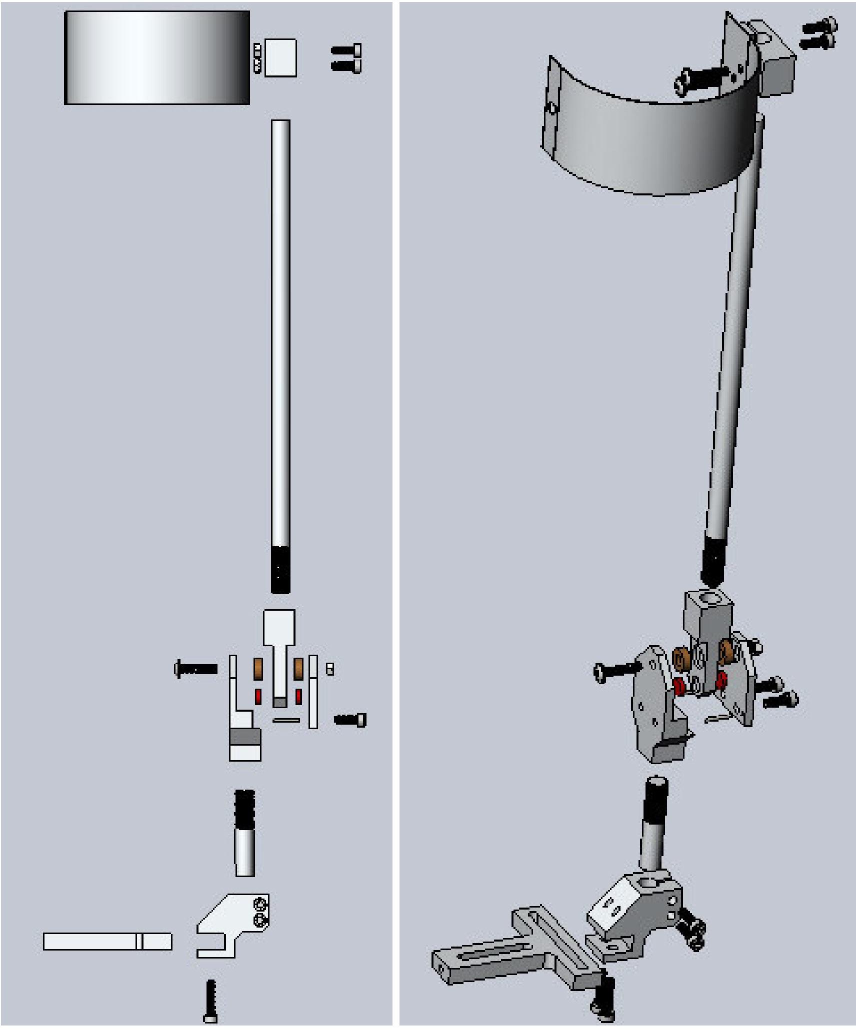

Figure 15. Front and 3D view of the exploded view of the orthosis. The brown parts are the bearings. The bearings indicate the location of the rotation axis. The red parts are the sliding contact points.

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Appendix 5: VAS questionnaire

Research: Skating with reduced ankle eversion (with orthosis)

Personal data

Name:................................. Sex: ……………………. Height:……………………Weight:……………

Skating skill level: low skilled skater high skilled skater

Questions

Answer by placing a mark on the line.

1. What do you think of skating with reduced ankle eversion (with orthosis)? Give a grade from 1 to 10.

   ....

2. I'd rather skate with reduced ankle eversion (with orthosis)?

   Disagree ***Agree***

3. *Stability: The amount by which you lose balance trough vibrations and external forces.*
   How stable do you feel while skating? With normal and reduced ankle eversion (AE)

   Normal AE
   (without orthosis)

   Unstable ***Stable***

   Reduced AE
   (with orthosis)

   Unstable ***Stable***

4. Ankle eversion is a motion I need to skate.

   Disagree ***Agree***

5. The orthosis is irritating.

   Disagree ***Agree***

Remarks:

Appendix 6: Box plots of results

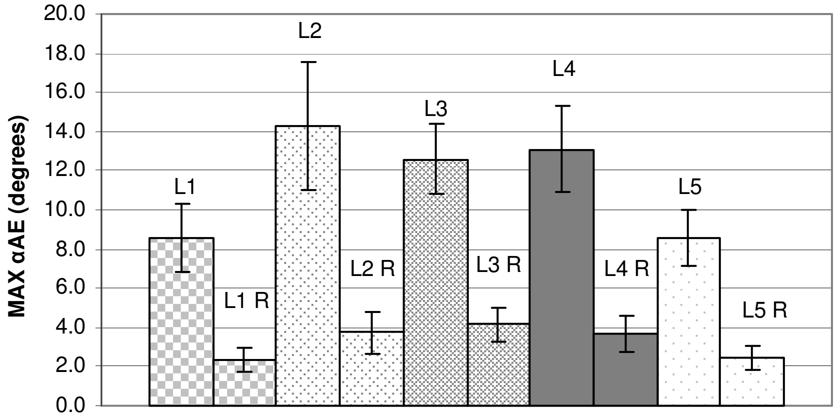

Figure 1. Average maximum ankle eversion angle (MAX α_{AE}) and standard deviation over 30 straight strokes for low skilled skaters (L) comparing normal with reduced (R) ankle eversion.

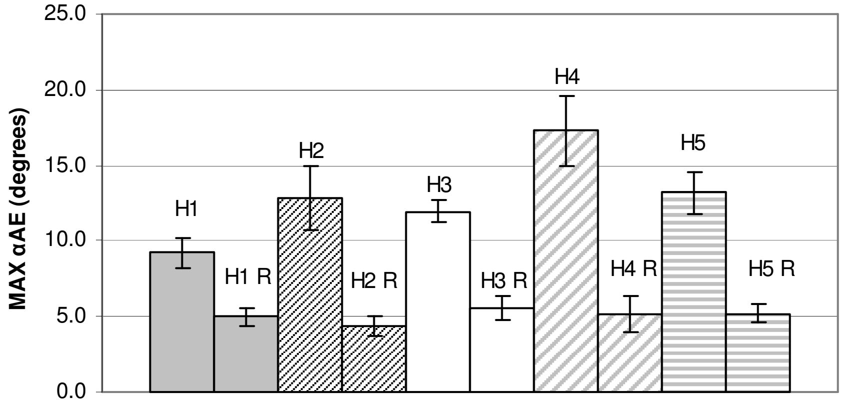

Figure 2. Average maximum ankle eversion angle (MAX α_{AE}) and standard deviation over 30 straight strokes for high skilled skaters (H) comparing normal with reduced (R) ankle eversion.

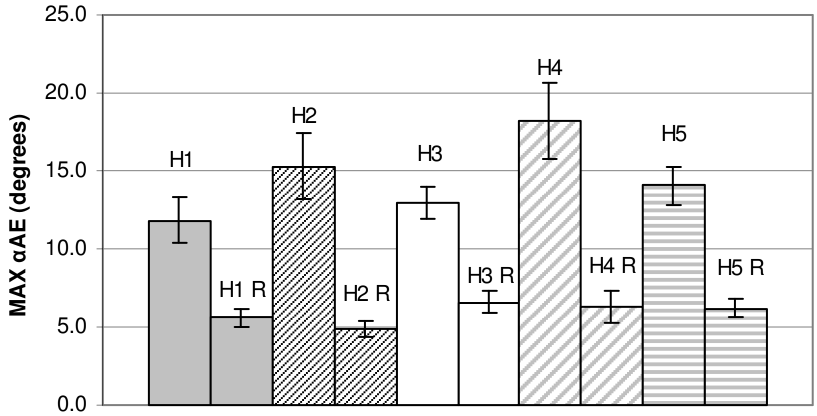

Figure 3. Average maximum ankle eversion angle (MAX α_{AE}) and standard deviation for high skilled skaters (H) over 30 corner strokes comparing normal with reduced (R) ankle eversion.

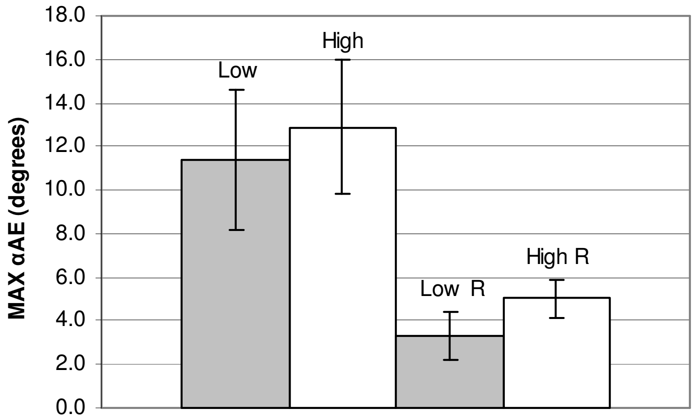

Figure 4. Average maximum ankle eversion angle (MAX α_{AE}) and standard deviation over 30 straight strokes with normal and reduced (R) ankle eversion comparing all low with all high skilled skaters.

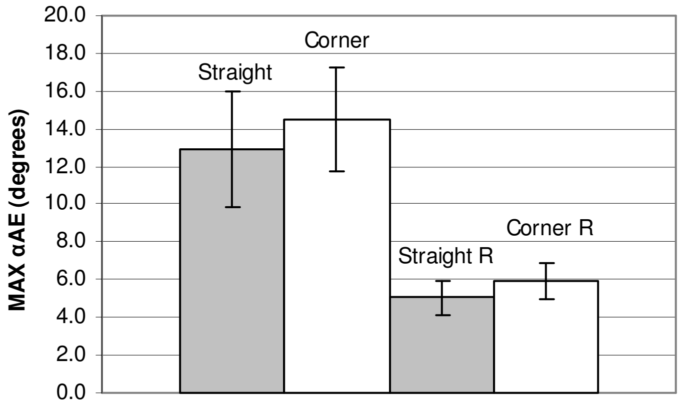

Figure 5. Average maximum ankle eversion angle (MAX α_{AE}) and standard deviation for high skilled skaters over 30 straight and 30 corner strokes with normal and reduced (R) ankle eversion comparing straight with corner strokes.

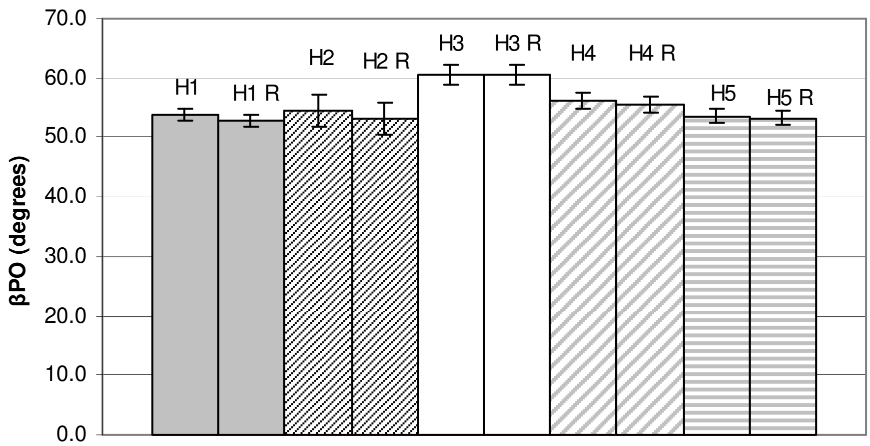

Figure 6. Average push-off angle (β_{PO}) and standard deviation for high skilled skaters over 11 to 14 straight strokes comparing normal with reduced (R) ankle eversion.

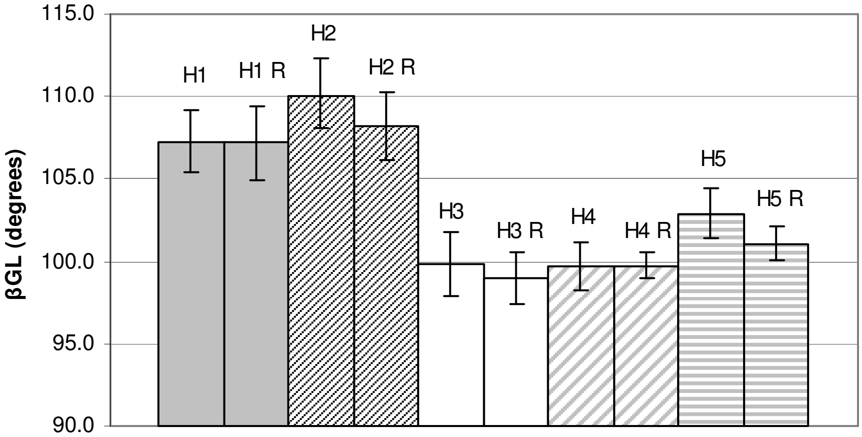

Figure 7. Average glide angle (β_{GL}) and standard deviation for high skilled skaters over 11 to 14 straight strokes comparing normal with reduced (R) ankle eversion.

Appendix 7: Technical drawings

Drawing number	Drawing name
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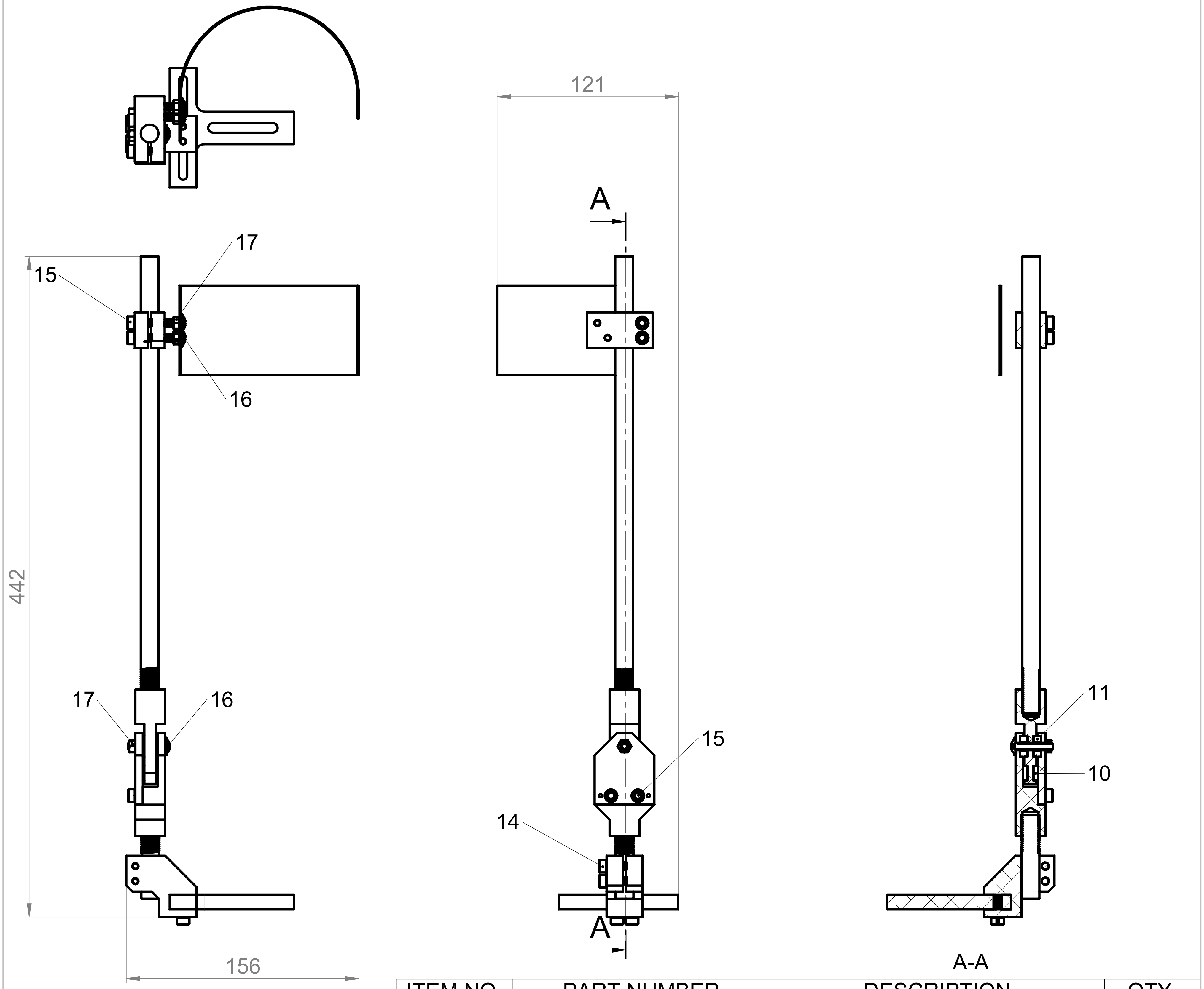
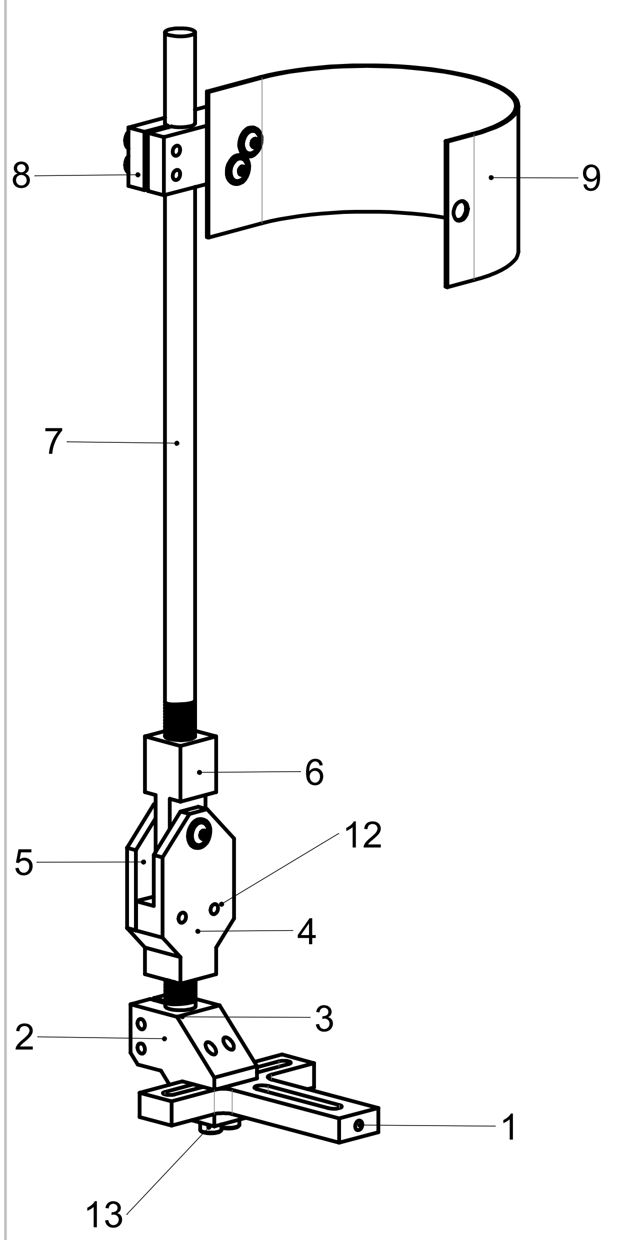
1	Part: T stuk
2	Part: Hoekklem
3	Part: Buis kort
4	Part: Scharnier onder
5	Part: Scharnier onder deksel
6	Part: Scharnier boven
7	Part: Buis lang
8	Part: Kuitklem
9	Part: Kuitkap





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4	Scharnier onder		1
5	Scharnier onder deksel		1
6	Scharnier boven		1
7	Buis lang		1
8	Kuitklem		1
9	Kuitkap		1
10	Schuif lager		2
11	SKF BA6		2
12	Pas pen		2
13	M5 22mm		2
14	M5 18mm		2
15	M5 14mm		4
16	M5 25 mm platte kop		3
17	M5 moer		3
18	Short Track onderstel		1

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maateenheid	mm	4-10-2010	
getekend	Michel Bovy		
	bovymichel@gmail.com, 06-41522796		

benaming

Orthese Finall Design

TU Delft
Industrial Design Engineering

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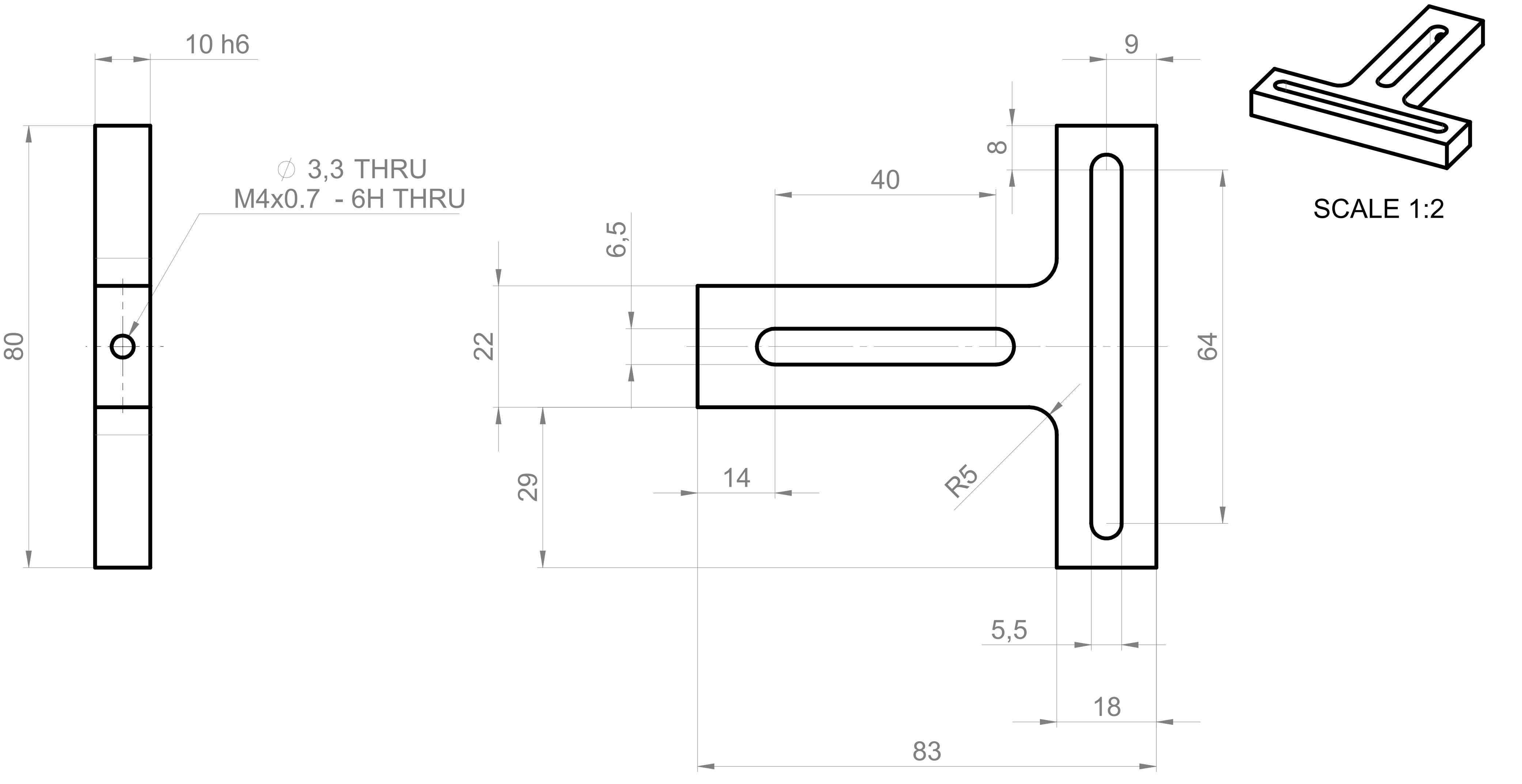
tekeningnummer: 00



TU Delft

Industrial Design Engineering

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datum 4-10-2010

maateenheid mm

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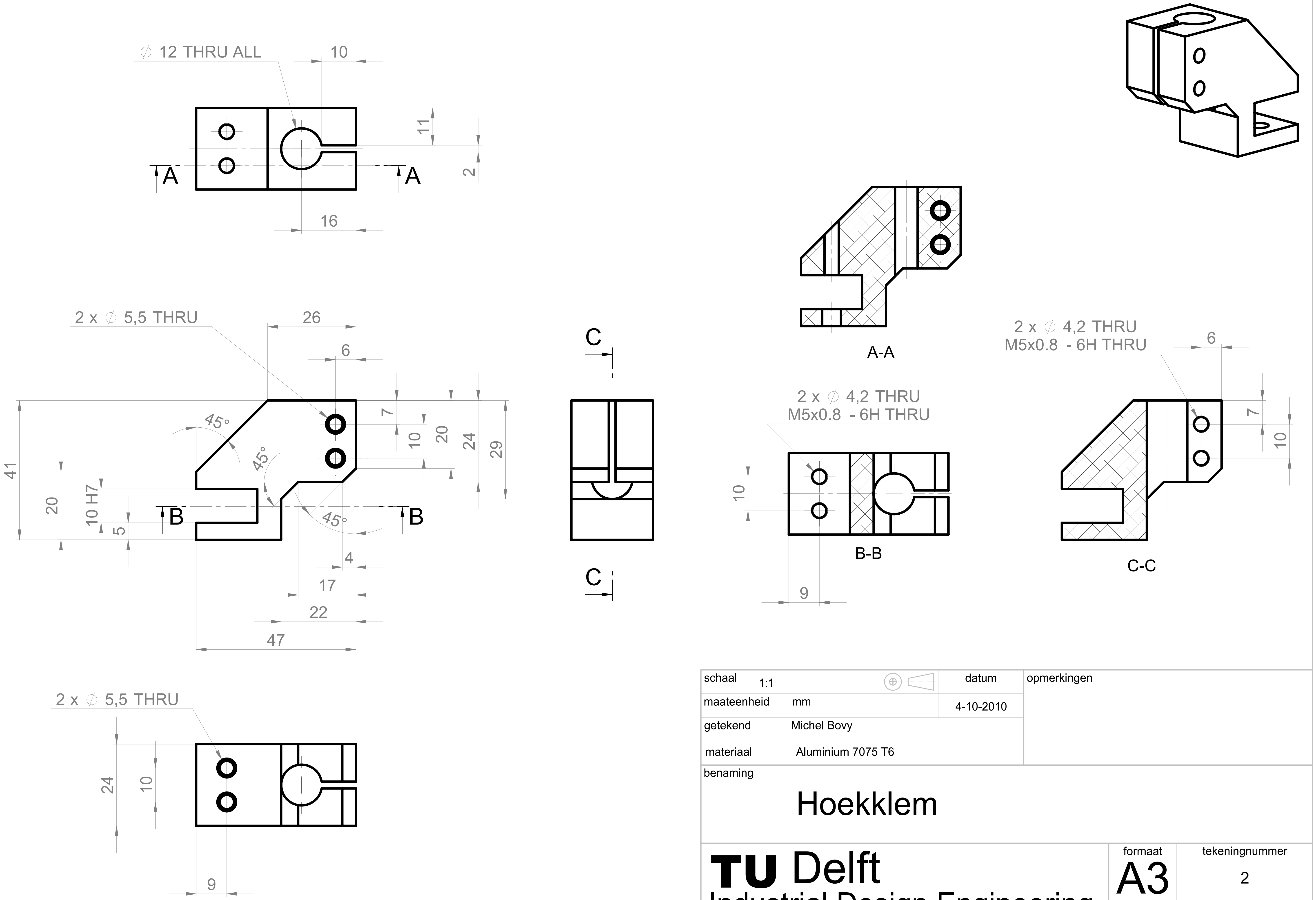
materiaal Aluminium 7075 T6

formaat A4

tekeningnummer 1

getekend Michel Bovy



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benaming	Hoekklem		

TU Delft
Industrial Design Engineering

formaat	tekeningnummer
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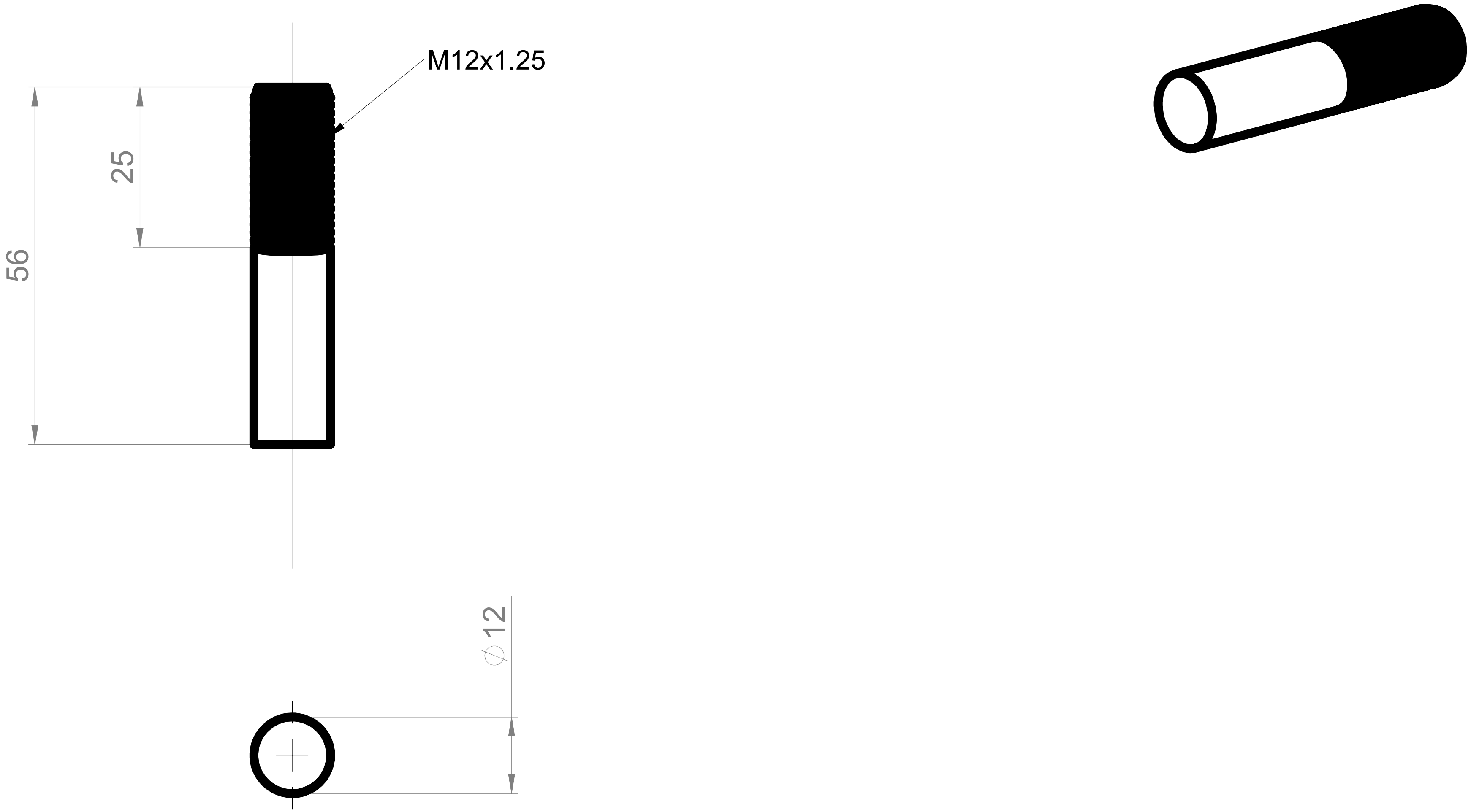

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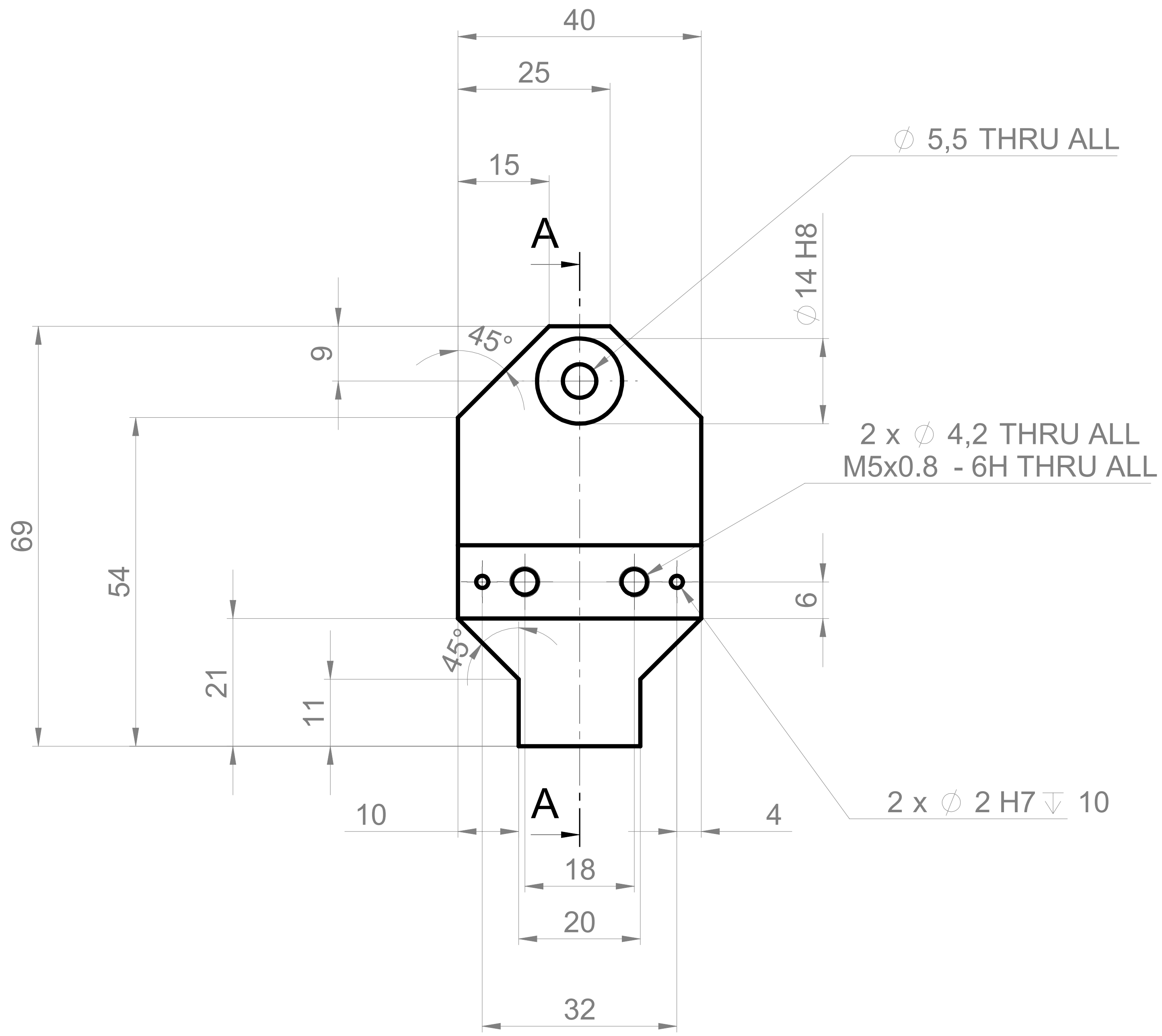

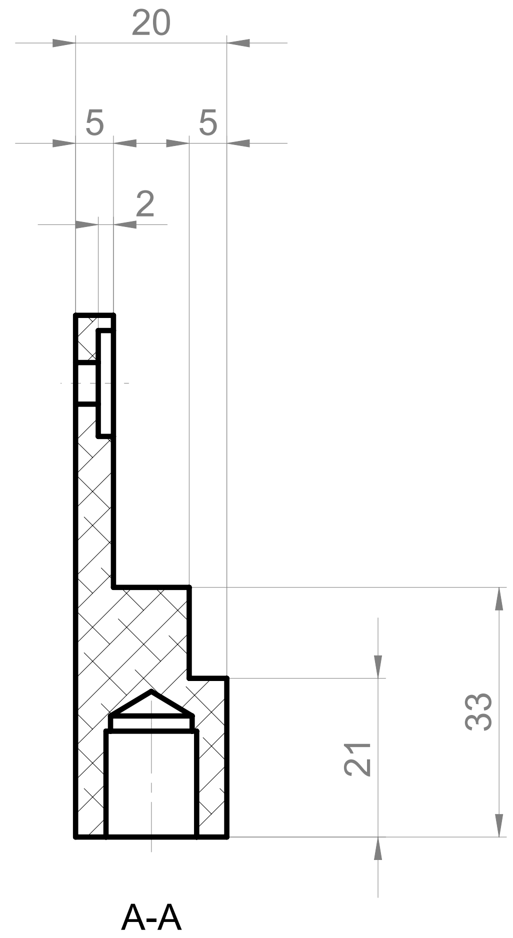

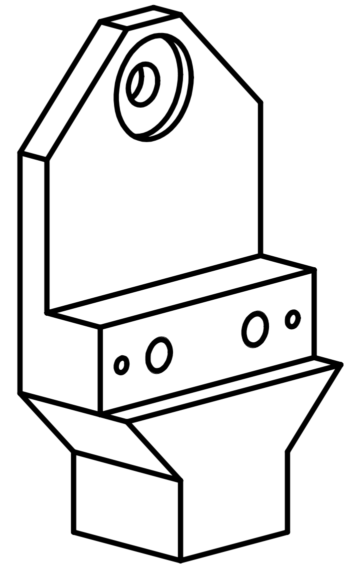

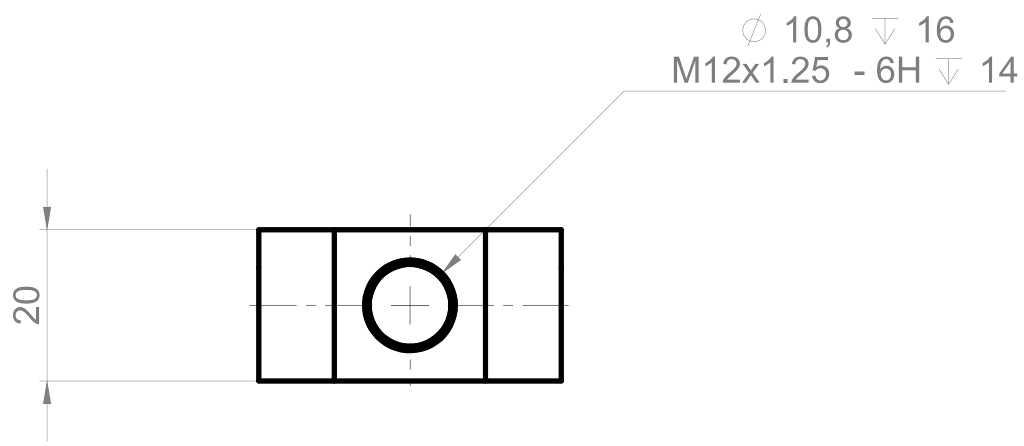

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Industrial Design Engineering

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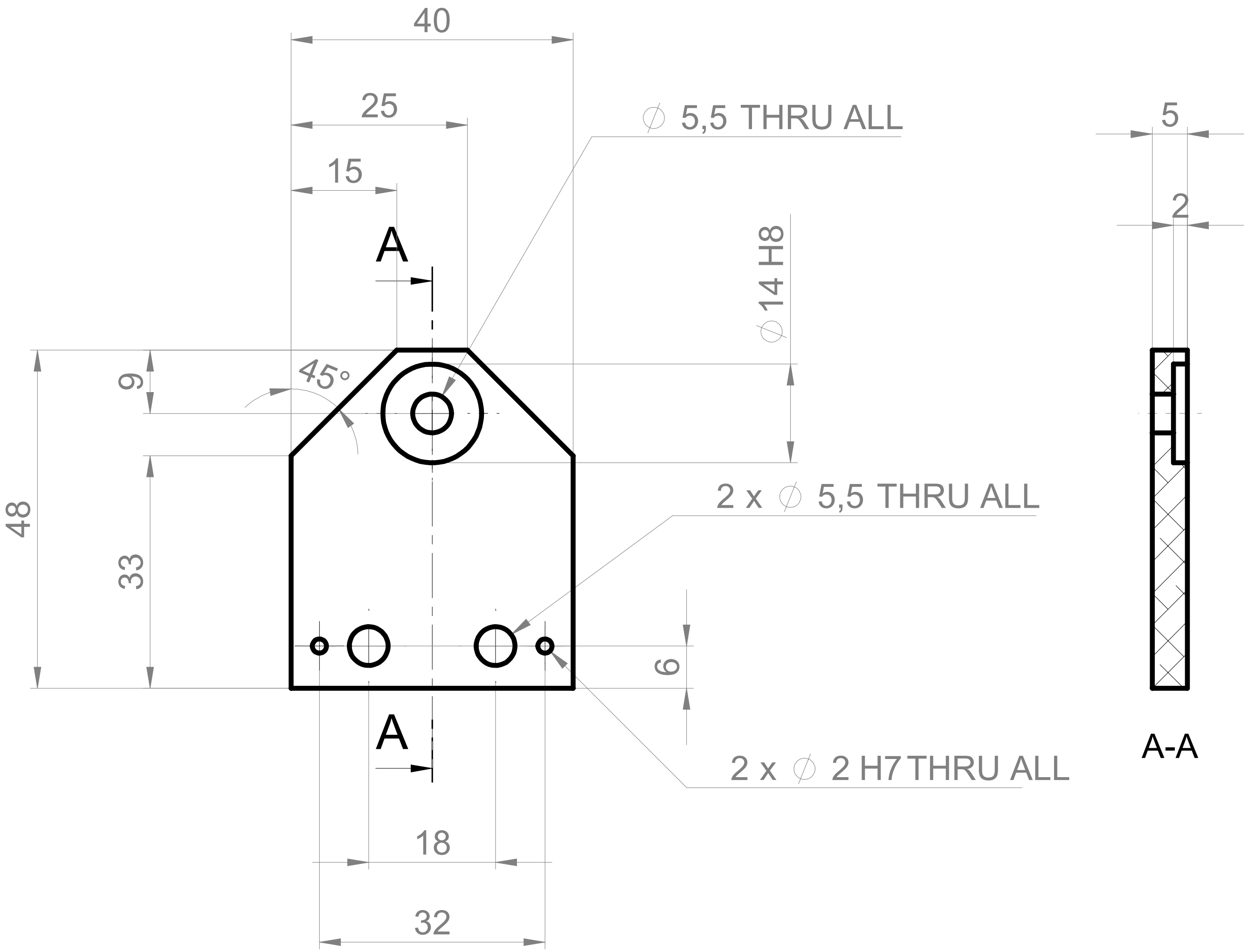

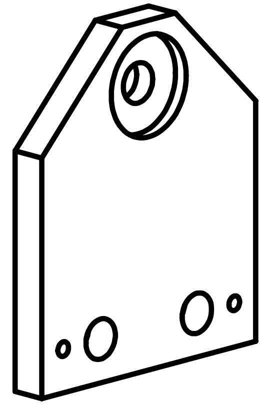

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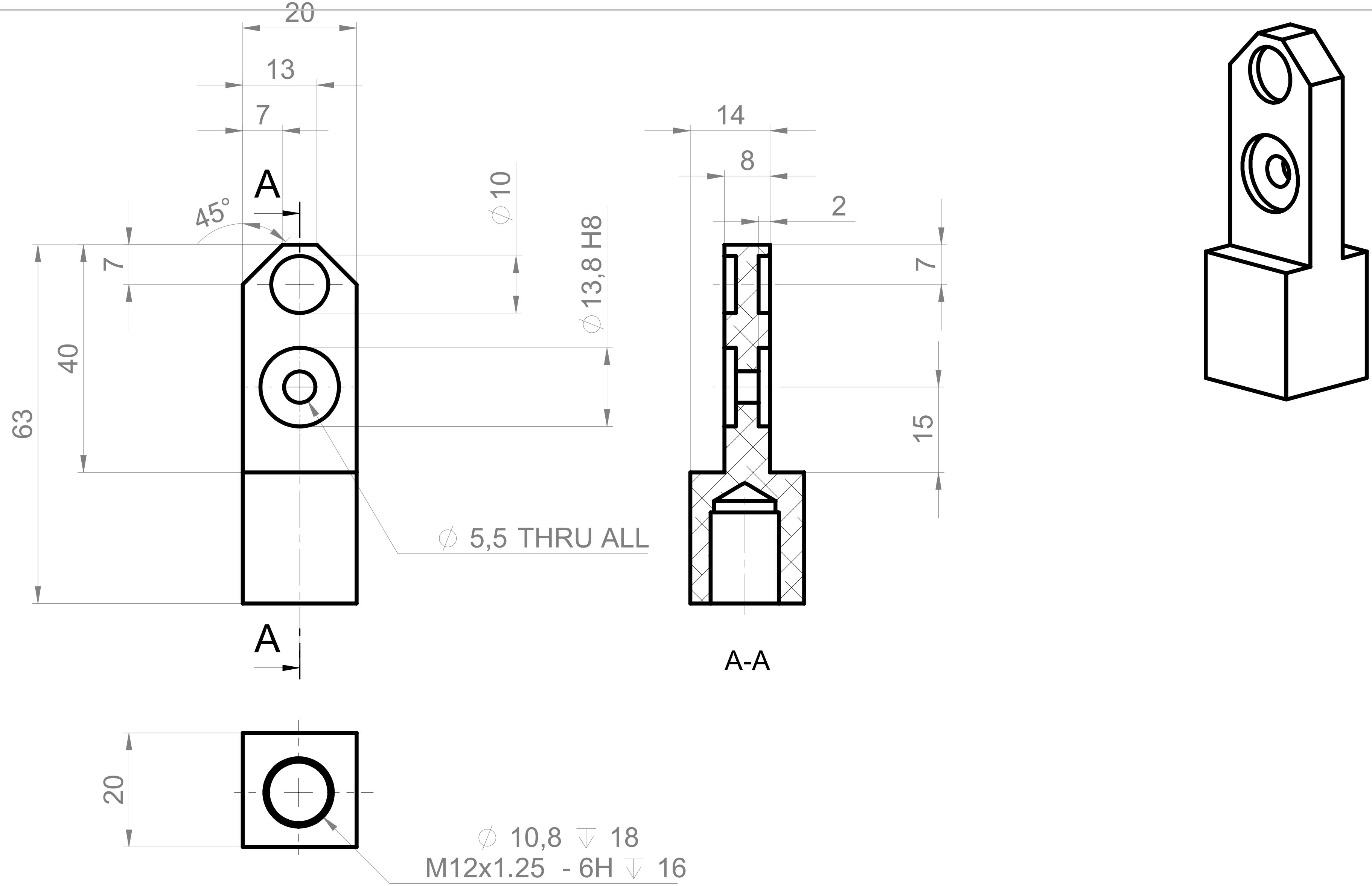

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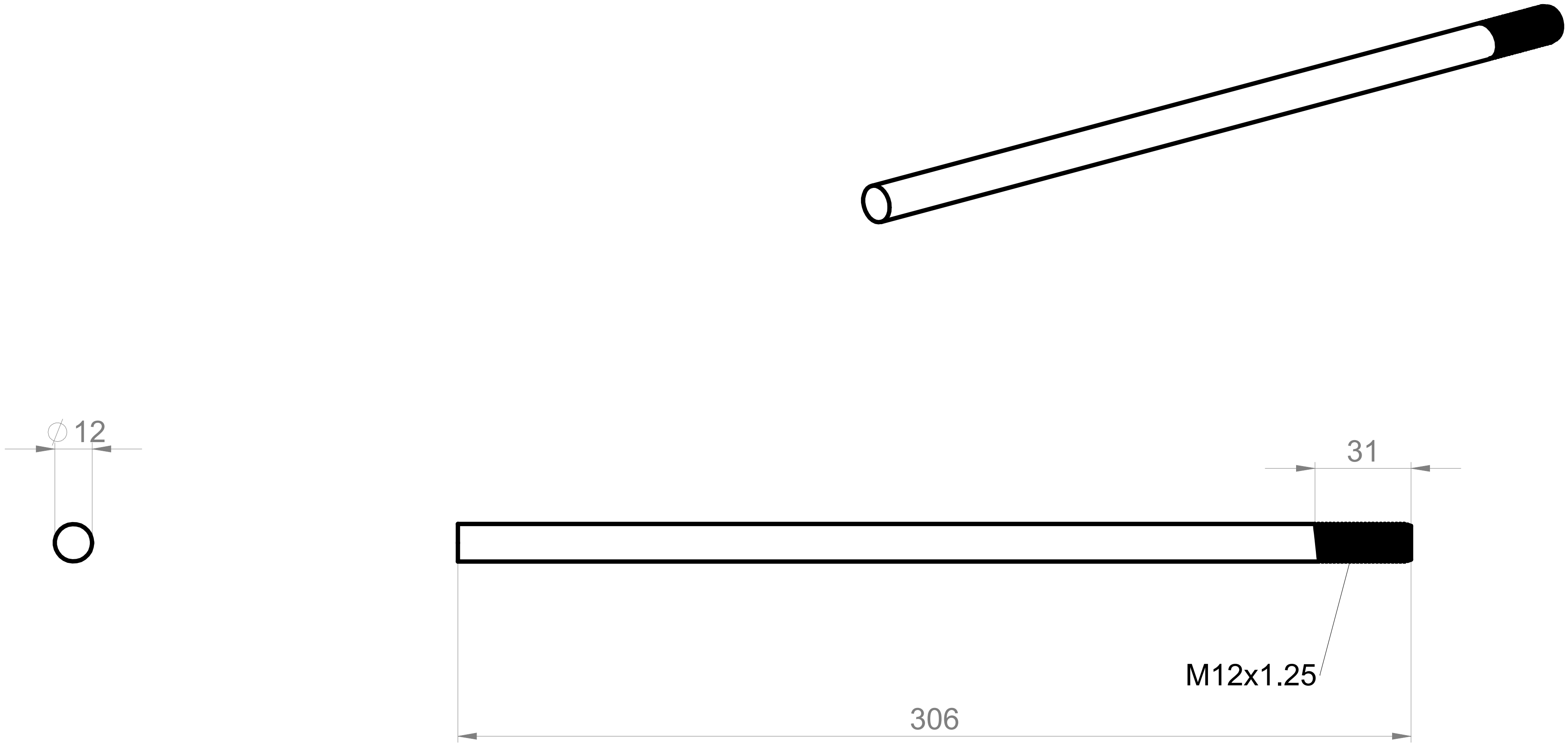

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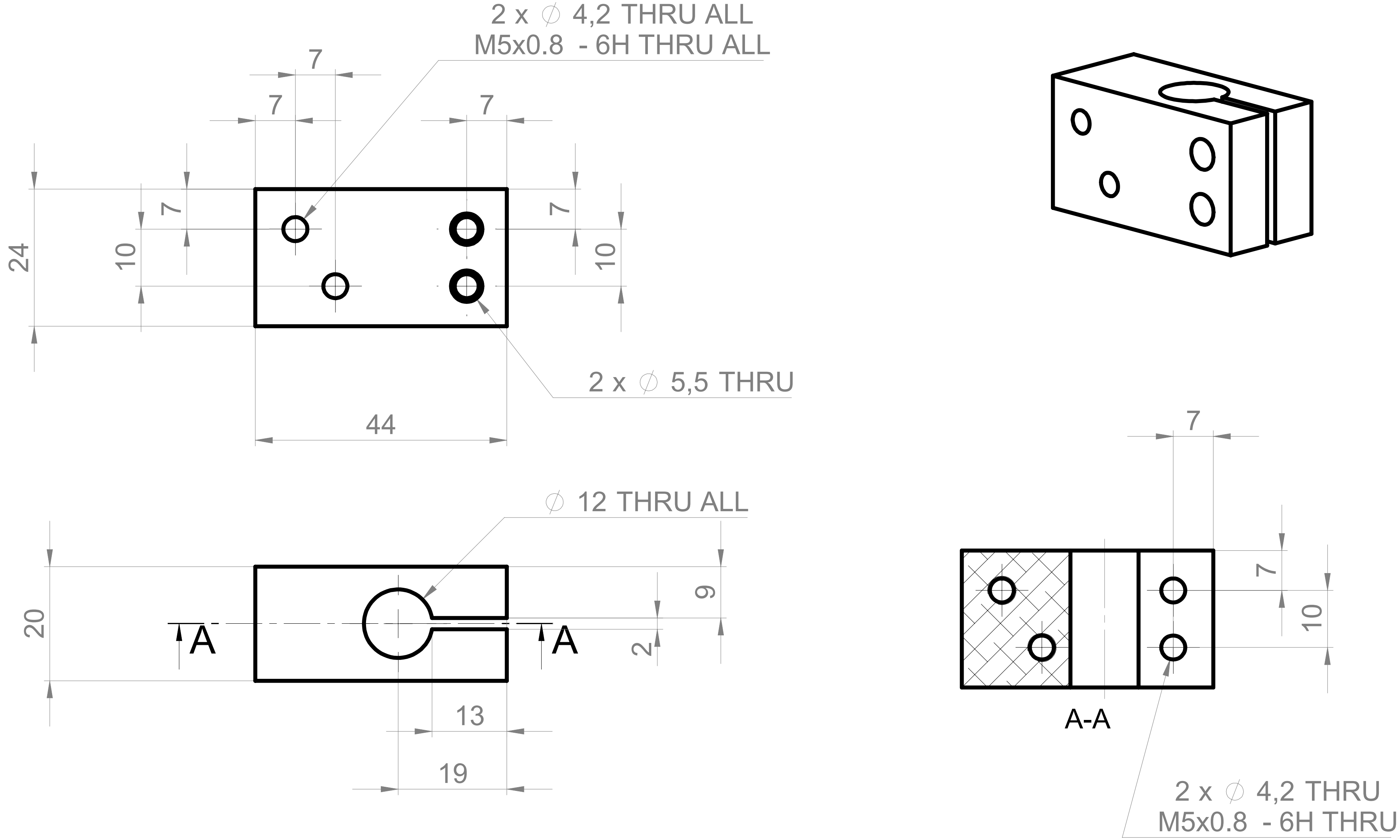

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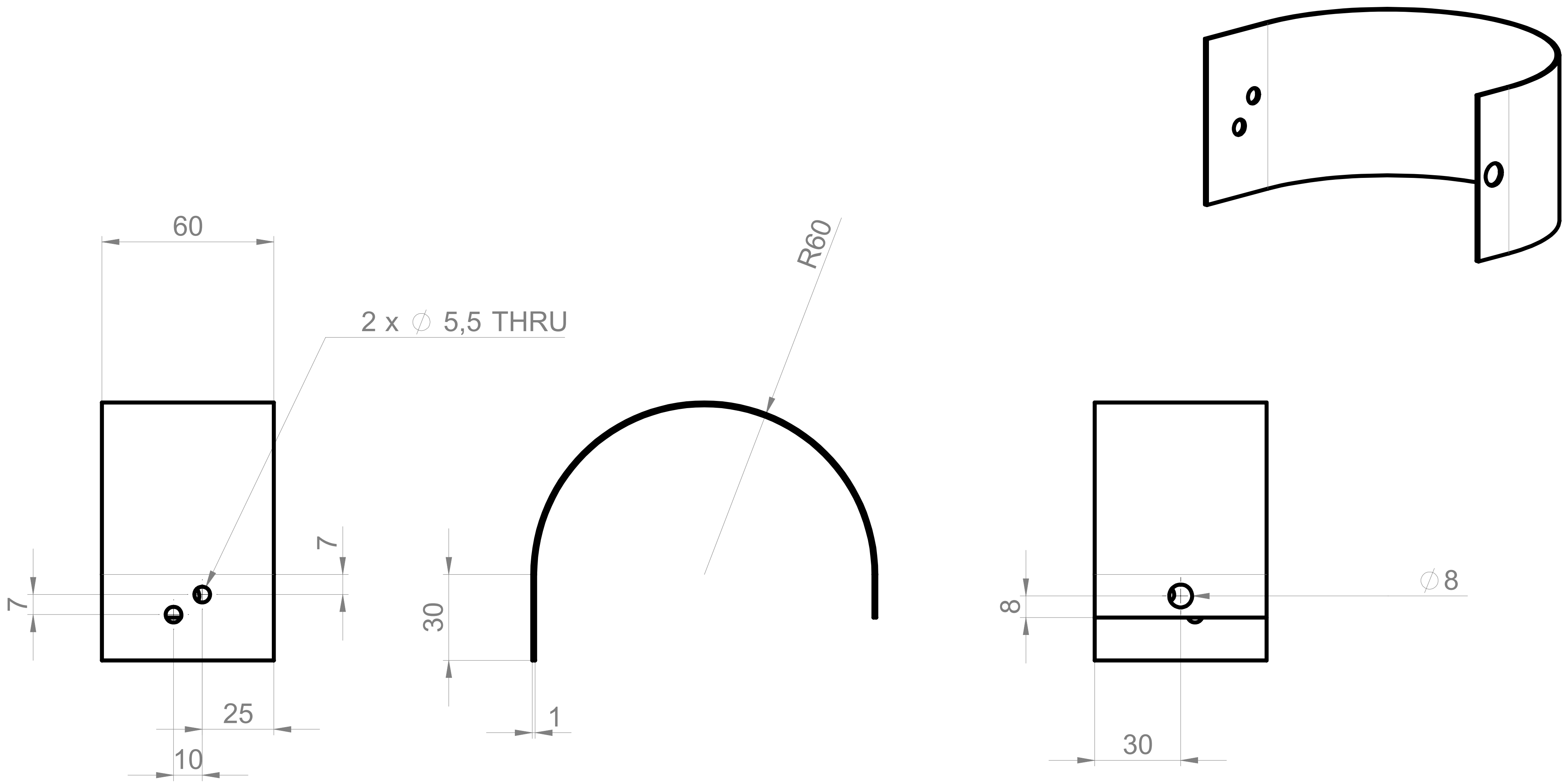

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