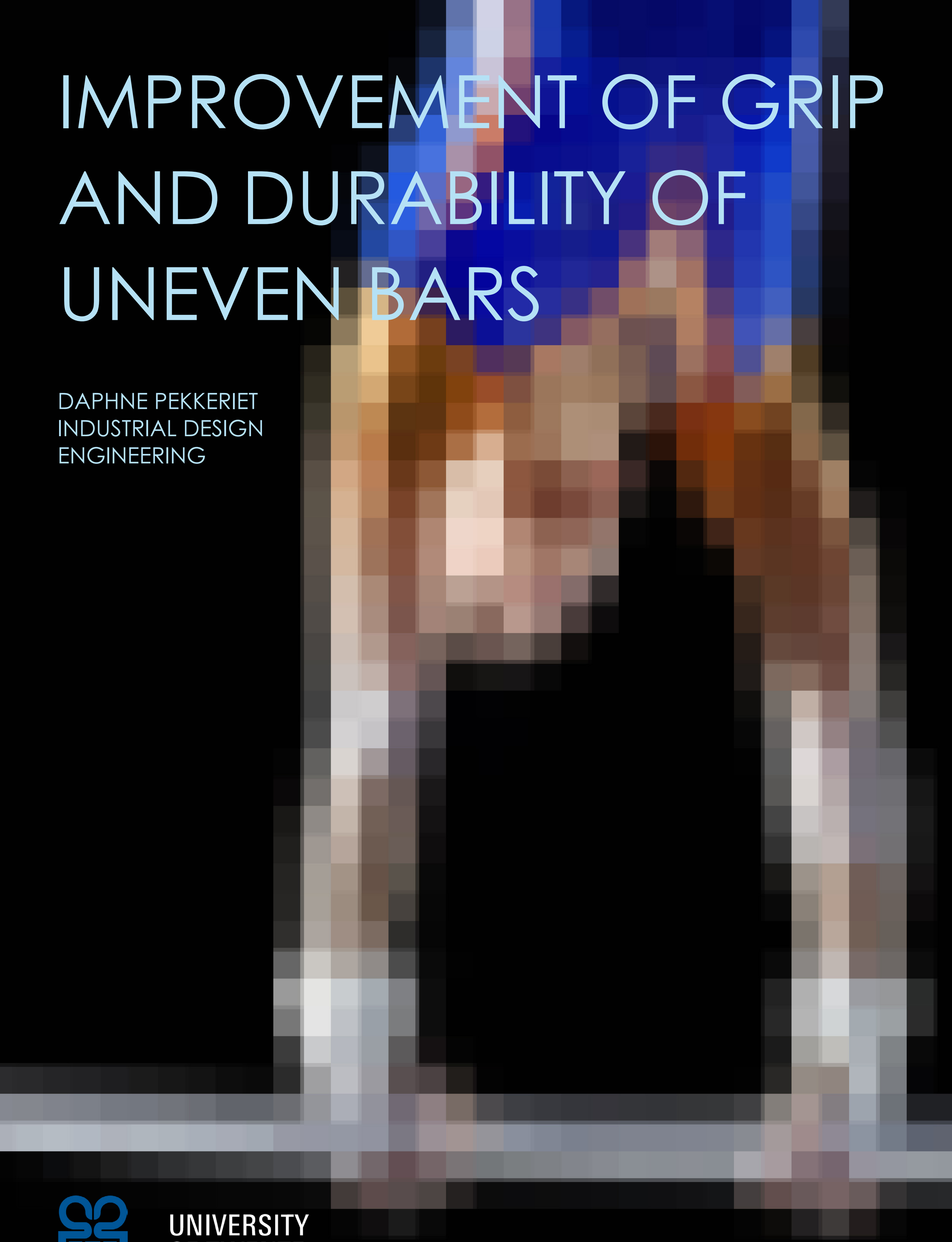
IMPROVEMENT OF GRIP AND DURABILITY OF UNEVEN BARS



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Master Thesis - University of Twente

Improvement of grip and durability of uneven bars

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Colloquium 08 January 2018

SUMMARY

The uneven bars is a woman gymnastic apparatus which has changed significantly since the introduction in the '30's of the past century. The bars or rails of this apparatus are made out of a fibreglass core with a wood veneer layer around it. The bars show an increase in wear, causing a decrease in grip. Where in previous years a bar could last five years [1], these days in some gymnastic halls the bars wear off within one to six months [1]. The wear of the wood leads to dangerous situations, because it can splinter or the inner fibreglass might be exposed. This fibreglass core is very slippery, leading to less grip. Due to the fast wear the perceived grip changes fast as well.

In this thesis both subjective and objective aspects of grip are investigated. A literature study was performed to understand grip and to understand the use of magnesium. Literature shows that grip is influenced by the coefficient of friction and the surface area. Magnesium does give higher coefficients of friction. A research to wear is performed based on a system analysis. The system analysis showed that the wear of the bars might have several causes. Both abrasive wear and fatigue wear were visible. The current research was focussed on abrasive wear. Grips cause abrasive wear and rub down the veneer evenly. Most forces are exerted at the dowels of the grips during the hanging phase of a swing. During the literature study the changes over the last decade for the bar, the grip materials and the routines were investigated. No changes were found. The last part of the literature study was focussed on the norms set by the International Gymnastic Federation (FIG) and NEN. Most important standards for this thesis are: The bar may not be slippery, too rough and should absorb water.

After a literature study three experiments were conducted. A bar was prepared to mimic the abrasive wear visible in the bars. Gymnasts were asked to make swings and to fill in a questionnaire about their perceived grip. The gymnasts graded the bars which do not have visible wear the best. The bar which showed the most wear, has the least grip according to the gymnasts. After the research to perceived grip, the objective part of grip is researched. First the roughness of the bar was examined with a confocal microscope. The data showed large differences for every measurement within the bar parts. Therefore no conclusion could be drawn about the specific roughness of the bar parts. However, a general surface typography was noticed. The surface of the bars is flat with deep steep valleys and little curvy peaks. The coefficient of friction was calculated after an experiment where the normal and friction force were measured. The three bar parts which were used in the grip experiment were used, as well as a never used bar and a bar which has been coated with a rubber coating. Four conditions were tested for every bar part, namely with a fingertip on the bar with and without magnesium and with a leather grip with and without magnesium. Higher coefficients of friction are calculated when magnesium was used. The contact of skin and the bar surface had higher friction coefficients than the contact of leather and the bar. The highest coefficients of friction are calculated for the rubber coated bar. The grip grade from the assessment of the subjective aspects is not comparable with the calculated coefficients of friction. Grip is thus dependent on more than just the coefficient of friction.

A programme of requirements has been made with the collected data of the previous research. New materials are searched that fulfil the requirements. The material that fulfils the requirements the best is Polyamide. However, the material is too slippery, and is therefore not usable. Some

coating did fulfil the requirements, however, it could not be applied due to high production temperatures. Another material would be PEBA, this is a synthetic rubber that has high elasticity. It was not possible to get a sample of the material. Therefore, no tests could be performed concerning grip and durability. To increase durability, but not grip, an extra layer of veneer is added to a bar. During testing cracks and wrinkles were noticed. The gymnasts did not like the added stiffness of the bar either. The last possible solution is a rubber coated bar. The experiment to objective data of grip show high friction coefficients of the bars. Trainers indicate they like the grip on a small test part. Gymnasts are concerned they would slip off the bar. More testing needs to be done to see if the rubber coating gives enough grip and resists wear.

Two possible solutions were tested with gymnasts. A double layer of veneer shows fast wear. The rubber coating should be tested further but has shown positive results on the first tests.

LIST OF ABBREVIATIONS

BW	Body weight
COF	Coefficient of friction
FIG	International Gymnastic Federation
NM	No magnesium / without magnesium
M	Magnesium / with magnesium
PA	Polyamide / Nylon
Ra	Centre-line average roughness
Rku	Kurtosis - Sharpness of surface
Rp	average peak height
Rsk	Skewness - Symmetry around the mean line
Rv	average valley depth
Rz	Average peak-valley distance
TON	Topturnen Oost Nederland (Top Gymnastics East Netherlands)
TPE	Thermal Plastic Elastomers

ACKNOWLEDGEMENT

I would like to thank prof. dr. ir. Emile van der Heide for his support and supervising role in this thesis and dr. David Matthews for his help in supervising. I want to thank Patrick de Moor and Gerrit ten Bos of Bosan who have made this assignment possible and helped me to plan the experiments and supported the research. I would like to thank Walter Lette and Ivo Vrooijink for their help with the experiments done at the university and especially Dmitrii Sergachev for building the test rig for the coefficient of friction tests. Thanks to Frank Louter who explained a lot about artistic gymnastics on high level and especially about the uneven bars. Also thanks to the gymnasts who helped with the grip tests and who have tested the double veneer bar. I would like to thank Clareyne and Aswin for their help with reading my thesis and improving the text where necessary. At last I would like to thank my family and friends for their support these months.

CONTENTS

INTRODUCTION

Artistic gymnastics is a sport with different disciplines. Men compete in six events, namely vault, floor exercise, pommel horse, still rings, parallel bars and high bar. Women compete in four events: uneven (parallel) bars, balance beam, vault and floor exercise. For this research, the uneven bars also known as the asymmetric bars is examined in more detail. This is a woman gymnastic apparatus which has changed significatnly since the introduction in the '30's of the last century. At the first introduction in 1936, the uneven bars were parallel bars with one lowered bar and one raised bar. The bars were made of wood in an egg cross-section shape, which later on changed into an oval cross-section shape. It was hard to make the wooden bars equal to each other, since the elasticity of the wood was not only depending on wood species, but also on the shape, thickness, age and amount of knots of the timber. These bars were replaced by fibreglass bars with wood veneer in 1975 and this was approved by the International Gymnastic Federation (FIG) in 1979. After the Olympic Games in 1988 the oval shaped bars were replaced by thinner round bars. These bars fit the hand of the female gymnasts better, and are still used today. [2]

The routines from the '30s would nowadays be classified as simple. Over the years, the bars were set further apart and the routines became more difficult. In the 60's and 70's the gymnasts slapped their pelvises to the lower bar when they swung from the higher bar, mostly continuing their routine with different rotations at the lower bar or going back to the higher bar [3]. The distance between the bars was then very important, so they would hit the bar with their pelvis with precision. In the 80's the bars would be even further away from each other [4]. This was the start of the routines that are used nowadays. Currently routines contain a lot of swings, like a giant swing, with sudden stops to perform for example handstands and a variety of flight elements from one bar to another or at the same bar. It is important to get instant grip and keep grip, to ensure that the gymnasts do not slip of the bar during their routines. Research is performed on the measurements or simulations of forces, torques and movements of specific joints of the body while doing exercises on the uneven bars [5] [6] [7] [8]. Less research is performed on the forces in the uneven bars and grip on this gymnastic apparatus. More research is performed on the men's gymnastics apparatuses, such as the high bar and the parallel bars. Information is available of forces exerted at the bars, such as a mathematical model [9], a calculation about the reaction forces at the hands [10], the estimation of reaction forces in high bar swinging [11] and the kinematic changes during learning a swing [12]. Even more research can be found about the kinematics and biomechanics for men's gymnastics. Since the high bar is made of metal and has a smaller diameter, not only the elasticity is different, also the grasping techniques are different.

A well-known and highly cited article is from Hay et al. from 1979 [13], where the forces exerted on a bar of the uneven bars during exercises are measured. These forces are still used as a basic assumption. However, back then, the bars were oval shaped, where currently the bars are round. Other grasping techniques or forces could be used with an oval shape bar, leading to different results in forces.

Figure 1 - Grips made out of leather.

In 1994 grips were invented and patented by Mark P. Goodson [14]. Grips are made out of leather and can contain a dowel. This is a small roll of leather that grasps over the bar, preventing the gymnast from slipping off. In 1995, a research was conducted to find the influences of these hand guards on the forces and muscle activity on the high bar [15]. The forces on the bar were larger when using grips than doing the swings bare handed. This research suggests that the grips allow greater forces to cross the wrist.

The last eight years problems with wear are noticed for the bars. The bars show worn patches, which uncover the fibreglass core. Where in previous years a bar could last five years [1], these days in some gymnastic halls the bars wear off within one to six months [1]. Due to the fast wear the grip perceived by the gymnasts changes rapidly as well. The wear is not only leading to a decrease of grip it also can lead to dangerous situation since the gymnasts will not have enough grip at the fibreglass and slip off the bar.

Till this point no research is performed on perceived grip on the gymnastic apparatus uneven bars or on the fast wear of these bars. In this master thesis both aspects will be researched. The main question that is investigated is: Could grip and durability be improved by changing the surface of the uneven bars?

Grip is a subjective matter. It depends on different senses and personal perception. Since every person is unique, grip is also perceived differently by every person. Durability is an objective matter and is depending on wear, forces, dynamics and material use. For both grip as well as durability, tribology is important. The field of tribology includes research on the behaviour of contacting surfaces of different materials at diverse circumstances. Important aspects of tribology are friction, wear and lubrication.

In this thesis a link between the subjective experience of grip and the objective data of the tribological system is examined. First a literature research is performed to find what grip is according to literature, what the influence of magnesium is, performing an analysis of the tribological system, the changes over the last decade in the routines, grip materials and bars and the norms set by the International Gymnastic Federation (FIG) and NEN. For the system analysis the wear of 16 bars which were send back with wear problems were investigated. Wear is system dependent and therefore two systems are drawn. These systems consist of the contact materials (the bar, skin or grips and magnesium), the environment and possible forces. In the analysis the wear problems will be analysed and more insight is given into different wear mechanisms and processes.

After the literature research three experiments are described in chapter 3. At first the experienced grip of gymnasts on a prepared bar with abrasive wear was examined. Gymnasts were asked about the grip they experienced and how they would describe grip. Thereafter, the bar is cut into smaller pieces and the objective aspects are assessed. The roughness of every bar part is investigated by using a VK 9700 Keyence confocal microscope. The coefficient of friction is calculated after an experiment were the normal and friction force were measured. Four different situations were tested for every part, namely: skin or leather with or without magnesium.

After the research a programme of requirements is described and a material search is performed.

A couple of boundary conditions are set for this thesis. Only the bars of the gymnastic apparatus uneven bars were taken into account. This means that the rest of the apparatus is outside the boundary conditions, as well are other bars such as the parallel bars or high bar for men. Within the boundary conditions are skin, leather grips, magnesium and sweat. Other sticky materials such as honey or sugar water are not taken into account. Also additional sprayed water is not taken into account in this research. The bar shows different kinds of wear. Only abrasive wear is within the boundary conditions.

This report has the following structure: First literature will be discussed, including the results of this research. Grip according to literature, as well the use of magnesium according the literature will be discussed first. Thereafter the system analysis is performed, followed by the research about the changes over the last decade. At the end, the norms set by the FIG and NEN are discussed.
After the literature research, the research methods of the experiments will be discussed, followed by their results and the discussions about every experiment. At last the results of this thesis will be discussed. These are the programme of requirements and the search for a new material. At the end an overall conclusion is drawn, followed by a discussion about the thesis and recommendations. Appendices can be found at the end of the report.

2 LITERATURE STUDY

A literature study has been performed to grip and magnesium. Followed by a system analysis and a research of the changes over the last ten years. At last the norms set by the FIG and NEN are investigated.

2.1 Grip

According to the Cambridge dictionary, the definition of grip is "to hold very tightly" or "a tight hold on something or someone". Meaning that grip causes gymnasts to hold onto the bar. Losing grip causes slip resulting in them falling off. When research is done concerning grip, it is mostly focussing on friction and less on perception.

Skin is soft and deforms easily, causing a different behaviour than when two hard materials move over each other. Skin is composed out of three layers, namely the epidermis, dermis and subcutaneous fat [16]. The outer layer is the stratum corneum, which determines the mechanical properties of the skin [16]. Most studies on the coefficient of friction (COF) with skin is performed with a subject's fingertips. Both the static as the dynamic friction coefficients for fingers are in the same range as for the palm of the hand [17].

Skin friction is influenced by different variables at the same time [18]. The main mechanisms of skin friction are adhesion, ploughing friction and energy return from the reformation of the skin [19]. All three mechanisms together create friction between human skin and an object. In dry condition, adhesion is caused by attractive surface forces at the skin-material interface [17]. Ploughing is caused by the deformation of the softer, viscoelastic bulk skin tissue [17].

Tomlinson et al. [19] found that at maximum friction, the ploughing is at its highest, whereas the adhesion is at a minimum. Derler and Gerhardt however mention that adhesion is considered as the main contribution to the friction of skin; deformation mechanisms play a minor role [17]. The difference which mechanism plays the key role can be caused by the roughness of the surfaces. On relatively smooth surfaces the dominant friction mechanism is adhesion which is directly related to contact area [20].

The ploughing friction is mainly caused by the deformation of the fingers, which is dependent on the normal force and the surface dimensions. Tomlinson et al. [19] did a research where they had surfaces with ridges in different heights and widths. The more spaced ridges give the skin the opportunity to deform over the ridges, causing more ploughing and therefore a higher friction. However, this spacing gives an inconsistent friction; when a consistent friction force is wanted, the spacing of the ridges should be narrow.

Uygur et al. [21] shows that the COF is higher is specialized grasping areas such as the palmar skin. This is confirmed by Derler and Gerhardt [17]. The skin of the fingertip and the palmar skin of the hand have a relatively thick stratum corneum compared to other body parts [22]. The differences between the skin areas could be based on both the frequent use of different skin areas for grasping and the importance of friction in manipulating activities in general [21].

The friction of skin strongly depends on the moisture content in the stratum corneum as well as on the presence of water in the interface between skin and a contacting surface. Moist or wet skin is characterised by significantly higher friction coefficients that increase strongly with decreasing contact pressure and are essentially determined by the mechanical shear properties of wet skin [17]. In a very humid climate or under wet conditions, the skin becomes completely hydrated, and the friction has been found to be 2-4 times higher than in dry sliding conditions [17, 22]. As levels of moisture initially increases friction force actually increases due to the reduction in the skin's modulus of elasticity which increases the contact area. As the moisture passes a critical level, however, there is enough present to form a film and then friction decreases [20]. Hendriks and Franklin [22] found a peak in the friction coefficient when there is no free water left on the skin surface but when the skin is still in a 'damp' state.

Not only the moisture content in the stratum corneum influences the COF, also the roughness of the surface has influence. The COF between a hard surface and dry skin decreases with an increasing material surface roughness [17, 18]. However, very rough surfaces are contrary. When the Rq value is up to 90 μm, the COF increases with an increasing surface roughness. This shift in COF is caused by the interaction with the friction ridges and ploughing. The asperities first start to interlock with the finger ridges and then deformation and hysteresis mechanisms start to dominate [20]. It has to be pointed out that the shape and the surface texture of the surface are important for skin tribology as well [17]. Skewness has a weak influence to the COF: surfaces with a positive skewness achieve low friction [22]. Different studies have shown that a lower surface energy leads to a lower coefficient of friction [17, 18]. The dynamic COF decreases with increasing skin temperature, decreasing age and for taller subjects.

The coefficient of friction has a positive effect on the needed hand grip force. A higher coefficient of friction causes a lower grip force [23]. The central nervous system changes the load force accurately to the changes in the load force without time delay [21]. When the fingers are longer and hand surface variables are greater than required for grasping an object, the fingers will spread less widely and grasping the object becomes more efficient and less exhausting [24]. Handgrip strength has a positive relationship with body height, body weight, body mass index, hand length, body surface area, arm and calf circumferences, skin folds, fat free mass, physical activity and hip waist ratio. [24]

As last, hand torque has an effect on the perceived grip. Handle diameter, grip force and the coefficient of friction are all associated with hand torque [25]. For gymnastics two types of hand torque can be distinguished, namely inward and outward torque. Torque towards the fingertips is called inward torque, whereas outward torque goes in the opposite direction, away from the fingertips. The fingertip force increases during inward torque, whereas for outward torque the fingertip force decreases even more than without torque [25]. Force is distributed differently for inward and outward torque. With outward torque more force is placed on the thumb and thenar. For inward torque the forces are highly concentrated on the tips of the fingers [25]. The load distribution differs for different cylinder sizes and per individual [26]. The load distributions inter-individual show similar distributions between the dominant and non-dominant hand [26]. The differences in load distribution between individuals could be explained by the different hand sizes and shapes [24].

Optimal grip can be achieved by a high coefficient of friction, a large surface contact area and a smaller diameter to make grasping easier. A higher coefficient of friction can be gained by a moist or damped skin, a low surface roughness or extreme high surface roughness, a negative skewness, a high surface energy and low skin temperature.

2.2 Magnesium

Magnesium carbonate, magnesium powder or powdered chalk are all the same, and are used in gymnastics. Gymnasts use magnesium on all apparatus, to prevent their hands from blistering and to increase torsion with the apparatus [27]. However, increased friction makes blistering also more likely [27]. The grip enhancement agent reduces or absorbs moisture such as sweat and/or increases grip through the adhesive properties of the agent [27, 28, 29]. Carré et al. [28] measured the moisture level of the fingers after applying magnesium carbonate. They found no effect of the moisture level of the finger. However, they did not include high levels of perspiration, which may have a different effect than just applying water. The same goes for the research of Li et al [29].

Carré et al. showed that chalk on dry skin on a dry steel surface reduces the COF [28]. Li et al. found a similar result on stone, where the coefficient of friction also decreased when magnesium was applied [29]. It is thought that the reduction of the coefficient of friction is caused by solid particles acting as a lubricant between two surfaces [28, 29]. When moisture is added to the finger, the COF increases. This increase is thought to be due to the chalk particles combining with water to produce a viscous solution [28]. Both Carré et al. [28] and Li et al. [29] mention that the coefficient of friction is higher for a clean dry hand on a dry surface than for a magnesium powdered dry hand on a dry surface.

Pušnik and Čuk [27] used thermal imaging to see if the temperature in the palm of the hand rose after doing some simple exercises on a wooden bar. They found that the temperature in the palm of the hand rose when magnesium was used. The temperature of the palm stayed about the same when no magnesium was used. Since friction causes the temperature to rise, the friction is higher when magnesium is used.

Amca et al. [30] also found that magnesium causes a higher coefficient of friction. They even have an explanation why the results of Carré et al. and Li et al. where contradictory to the hypothesis. The forces used in the previous mentioned research are relatively small in comparison to the real situation. Amca et al. let experienced rock climbers hang on blocks, which resulted in forces as big as their body weight. They reported a better performance when chalk was used [30]. There are a couple of possible reasons which can explain the better performances: modifications of the skin roughness, modification of skin elasticity which enables the fingers to best adapt to the hold shape and changes in water/sudation elimination behaviour [30]. Note: the climbers could be psychological biased, since they knew when magnesium powder was used and grew up with the notion that it should perform better.

According to literature, hands with magnesium powder in fact give more friction than hands without. Furthermore, the optimal use of chalk is important to keep the hand in the ideal moisture range [30].

2.3 System analysis

A system analysis is a thorough research to examine a situation at places where wear, friction or surface contact is possible. In a system analysis one will look at the system (materials, possible lubrications and environment) and the movements, forces and/or torques. The tribological system and boundary conditions are set and the input, output and results are discussed.

2.3.1 Tribological system

Two possible systems are discussed. These two systems operate in a dry environment, with a proper temperature and humidity to exercise in. Sweat of the gymnasts will be absorbed by the magnesium powder and is therefore not considered.

The first system, its situation is depicted in Figure 2, contains the hand(s) of a gymnast, the bar and magnesium powder. Figure 4 offers a schematic representation of the situation on a tribological level.

The second system contains a leather grip with dowel, magnesium powder and a bar. Figure 3 shows this system, Figure 5 shows a detailed overview. Other possible used materials are resin and sticky materials. These materials do not fulfil the boundary conditions and thus they will not be considered during the analysis. The leather grips are in contact with the bar, whereas in the previous situation the hands are in contact.

In Figure 2 and Figure 3 the nominal contact area is marked with an ellipse shape. In standing phase, the contact area is the palm of the hand or the grip which is placed over the palm. For the hanging phase, the contact is at the pads in the hand palm just below the fingers and at the fingers. For the situation with the

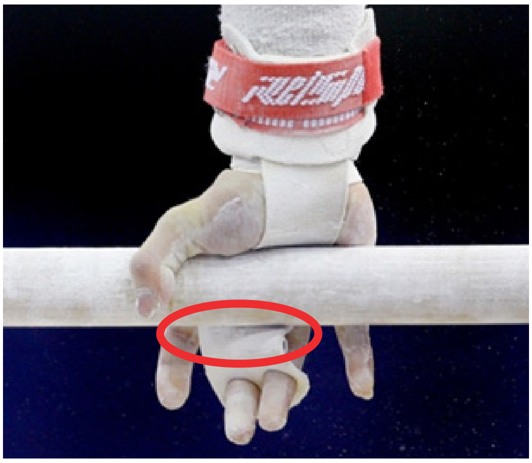

Figure 2 - Gymnast with bare hands on bar. The red ellipse indicates the nominal contact area.

Figure 3 - Gymnast with grips on bar. The red ellipse indicates the nominal contact area.

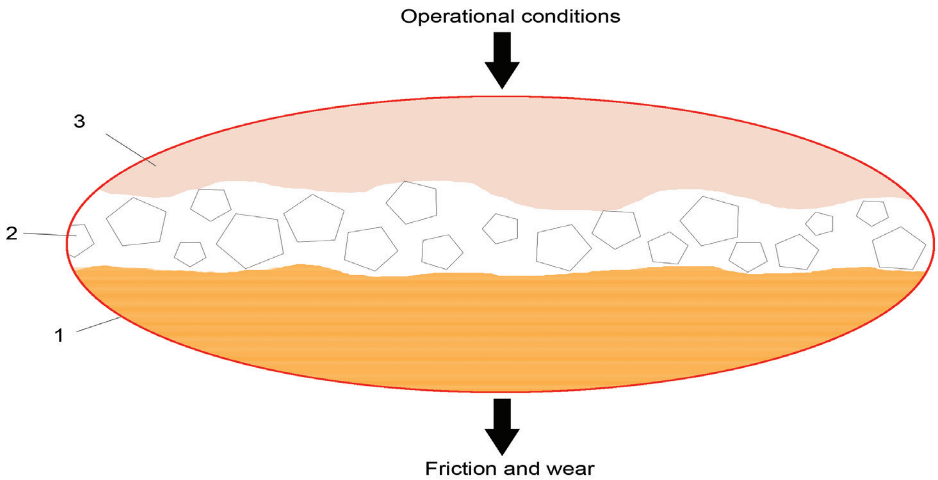

Figure 4 - Detailed view of the system with hand, magnesium and the bar. (1) Bar [birch or beech wood]; (2) Magnesium powder; (3) Hand [skin].

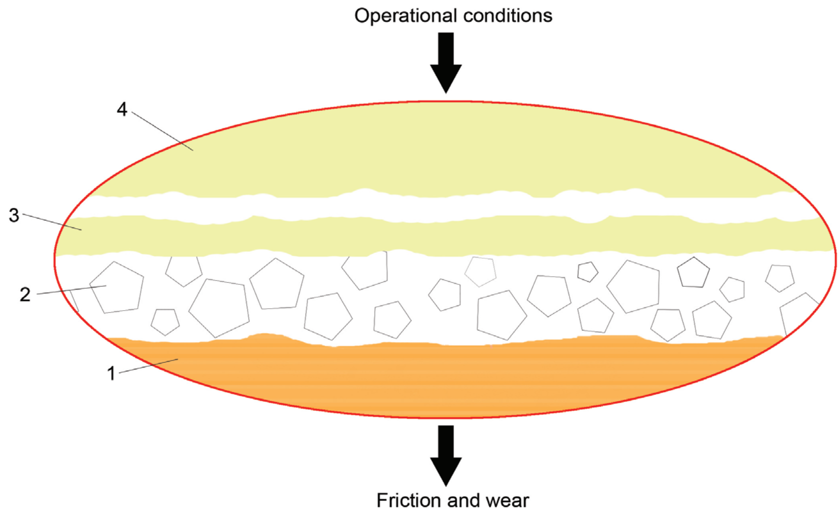

Figure 5 - Detailed view of the system with grip, magnesium and the bar. (1) Bar [birch or beech wood]; (2) Magnesium powder; (3) Grip made of leather; (4) Dowel of grip.

grips, it is at the dowel. The input and output of both systems will be discussed after the introduction of all system components.

2.3.2 Components

2.3.2.1 Bar

There are different manufacturers and distributers of bars. However, all bars consist of the same materials, namely a hollow glass fibre core which is covered by wood veneer. The kind of wood veneer, type and way of fabrication of the glass fibre and the gluing method are different per manufacturer. In Appendix A, the description by the manufacturers and distributors is described.

The bars are 39 to 40 mm in diameter. For this analysis, one bar is measured. Other bars may differ in dimensions. This bar has a diameter of 39.50 mm, with a veneer thickness of 0.75 mm. Including the underlying soft fabric layer the veneer is 1 mm thick. The glass fibre core is hollow and has an outer diameter of 37.5 mm and an inner diameter of 25.75 mm.
Observations showed that the wood can be glued to the core directly or on an in-between layer. How the wood is exactly glued or connected to the core is not clear. There is no information available on the production method of these bars. It is possible that the wood is directly glued to the core by high frequency glue. This glue is melted by the friction caused by the high frequent movements of both materials. However this is merely an assumption as to what the glue layer could be.

The wood veneer is made from beech or birch. The hardness of wood is measured on the Janka scale. In the Janka hardness test the force required to embed an 11.28 mm diameter steel ball halfway into the wood sample is measured. A higher Janka number means thus a higher hardness. Birch wood has a hardness of 6500 N (Sweet Birch), 5600 N (Yellow Birch, Iroko) and 4000 N (Paper Birch) on the Janka hardness scale. Beech wood has a hardness of 7500 N (Highland Beech) and 5800 N (American Beech) on the Janka hardness scale. [31]

2.3.2.2 Grips

A grip is a strip of leather with two openings at one end. Here is where two fingers can be placed (Figure 6). The leather strip will be strapped to the wrist, so the grips cannot slip off. Between the hand and the leather a small roll called a dowel is placed. This dowel has the same width as the grip and is approximately 1 cm in diameter and made out of leather. The dowel gives the gymnast more grip because it reaches over the bar as can be seen in Figure 3, causing less chance to slip off the bar.
Leather itself is stiff in comparison to skin. To

Figure 6 – Cross section of a bar. A core made out of glass fibre, with a thin wood veneer layer around it.

Figure 7 - Leather grips with two openings for fingers in one end and a dowel for better grip

shape the leather to the hands and make it more flexible the grip needs to be broken-in.

2.3.2.3 Magnesium

Magnesium is available in powder, block and liquid form [32]. A gymnasts' preference is person-dependent. The liquid form is better for health, since no particles can be inhaled during use, and better for the wooden apparatus [33], since less wear is noticed. However, it is more expensive and mostly not available in gymnasiums [32]. Most gymnasiums offer powdered magnesium which is therefore used the most.

Magnesium has a hardness of 2.0 on the Mohs hardness scale [34], which is quite low, considering the scale ranges from 1-10, where diamond is a 10. It has an average particle size of 44μm [35].

2.3.2.4 Hands

Skin has different roughness at various places. Different areas on the hand alone have different roughness. The index finger is almost double as rough as the edge of the hand [17]. In this case, the palm of the hand and the inside of the fingers have contact with the wood. There is no information of the roughness of the palm of the hand. However, due to the callous, the roughness will probably be as rough as the index finger (26.1 ± 6.1μm [17]).

Skin region	Ra [μm] range	Rz [μm] range
Index finger	26.1 ± 6.1 (19-33)	87.3 ± 17.1 (62-99)
Edge of hand	14.9 ± 6.7 (9-22)	54.1 ± 21.2 (33-73)
Back of hand	(23-28)	(138-144)
Volar forearm	(17-20)	(119-125)
Volar forearm	(12-13)	(82-92)
Forehead (temple)	(12-15)	(84-95)
Cheek	(11-15)	(33-45)

Table 1 - Surface roughness values of different skin sites of persons aged between 20 and 45 years, adapted from [17].

The COF of wood and skin for static friction is between 0.46-0.60 and for the kinetic friction is 0.22-0.42 [36]. These COF values are for raw Cherry, Maple and Pine. These are not the same materials as are used for the bars. However, COF will be assumed at 0.32 for kinetic friction, as the mean value of the outer two values.

2.3.3 Input

For a system analysis the black box principle can be used. The input for this black box is the maximum force and the velocity; the output is wear and friction. The maximum force of the higher bar is 2140 N on the bar [13]. Comparing this with the subject's bodyweights (BW), the maximum forces exerted on the higher bar are about 3.5 BW [13]. This force is measured during the giant swing, when the body is in the 'hanging' phase. Note: these forces are measured on an old oval shaped bar, while nowadays round shaped glass fibre bars are used. The forces may differ slightly. However, it is assumed to be in the same range. Much higher forces (3500 N) are measured on the lower bar during the research of Hay et al.. However, these forces are measured when the gymnast slapped her thighs to the lower bar [13]. This element is not used any more since the bars are moved further apart from each other. The forces of men on a horizontal bar while doing backward giants are 1188 N per hand for bare hands and 1267 N per hand for dowel grips [15]. These forces are about 2.2 BW on each hand [15]. Figure 9 shows that the bar bends when a gymnast is

Figure 8 - Black box of system analysis. Input are force and velocity, output is wear and friction.

Figure 9 - Giant swing in hanging and supporting phase. The bar is bended in the hanging phase.

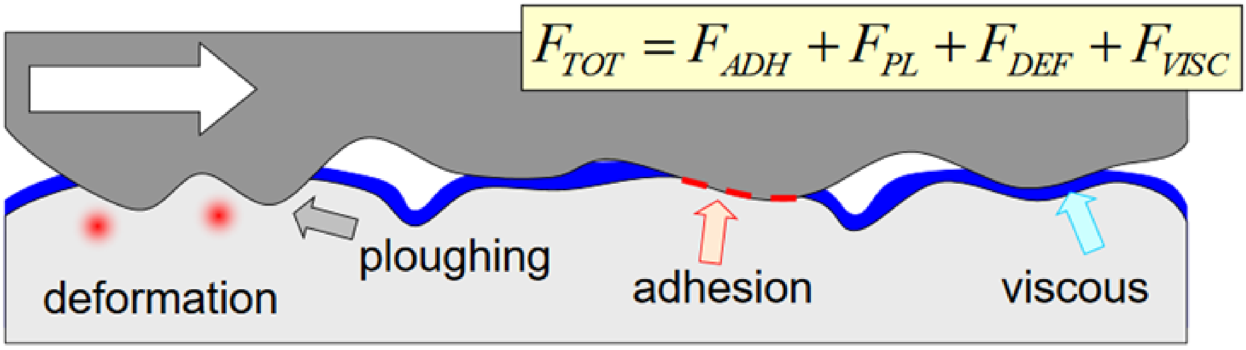

Figure 10 – Four friction mechanisms: deformation, ploughing, adhesion and viscous and the formula to calculate the total friction. FTOT = total friction; FADH = adhesive friction; FPL = ploughing friction; FDEF = deformation friction; FVISC = viscous losses friction. [38]

in the hanging phase and stays straight in the supporting phase.

Since the swing time of the giant swing of men is measured by Neal et al. [15], the angular velocity could be calculated. The angular velocity for men doing the backward giant swing is 3.062 rad/s (0.043 m/s at a swing time of 2052 ms) with bare hands and 3.293 rad/s (0.046 m/s at a swing time of 1908 ms) with doweled grips.

2.3.4 Output

The output of these systems are friction and wear. Friction is caused by different friction mechanisms and wear is caused by different wear mechanisms.

2.3.4.1 Friction mechanisms

Friction makes it harder to create velocity and can lead to blisters on the hand. Friction can be caused by several mechanisms, including adhesion, ploughing, deformation and viscous losses. The adhesion causes shear at the interface; the ploughing mechanism causes mechanical interaction (for instance by roughness); deformation can be plastic or visco-elastic; and viscous losses might be related to shear of a lubricant film. The total friction is the sum of all friction mechanisms. Figure 10 shows four different mechanisms and the formula to calculate the total friction.

2.3.4.2 Wear mechanisms

There are four wear mechanisms that can occur in a system. These are adhesive wear, abrasive wear, surface fatigue and tribochemical wear. Adhesive wear is a transfer of material due to cold welding, the adhesion is temporarily or permanent. Abrasive wear is removal of material due to interaction with a hard counter body.

Abrasive wear of a surface could be caused by the opposite surface or by an additional third body. Three body abrasive wear is caused by external particles. Surface fatigue is the removal of particles by fatigue due to cyclic stresses. Due to substantial number of load cycles and high contact pressure, cracks can occur below surface. Within time, the crack will grow to the surface. Eventually material particles will break off. At last tribochemical wear is the removal of reaction products. Figure 11 shows an overview of the four wear mechanisms.

2.3.4.3 Wear processes

The wear mechanisms are caused by different processes. These are sliding, oscillating, flowing, impacting and rolling. Sliding is the movement of an object with a velocity and a normal force. Oscillation is the same as sliding, however, the velocity of the object changes direction. Flowing is gas which moves along the object with a certain velocity. Impacting is when an object collides with a certain force at the surface. Last is rolling which is the rotational movement of an object over a surface. Figure 12 shows the wear processes with the direction of the forces and velocities.

2.3.5 Wear analysis of used bars

Sixteen bars have been sent back from a gymnasium with wear problems, of which nine were examined. There are different manufacturers of these bars. Of all nine bars an individual report was made, with photos and explanation of the wear problems. These reports can be found in Appendix B. The seven bars that are not examined in detail, had in general the same kind of wear problems as the nine that were examined. A summary and conclusion based on the nine examined bars will be given.

Since the bars have different manufacturers, all the bars have different properties. Various kinds of woods are used, different fibreglass cores are visible and different ways for gluing the wood to the core are used. Some bars have a coating. One kind of bar has a red layer in between the wood and the fibreglass which indicates when a bar has worn off (see Figure 13, picture 5). Others have fabric-like material in between the wood and the fibreglass to glue the veneer to the core (Figure 13, picture 4). At other bars the wood is directly glued to the core (Figure 13, picture 2 and 3). How the wood is glued to the core, results in different kinds of wear patches.

The cores were also different in texture. Some cores are very smooth and shiny (Figure 13, picture 4 and 5), while others are very rough and have a green appearance (Figure 13, picture 2 and 3). The smooth core is more pleasant to touch with the hands; however, it also causes a more slippery feel. The rough texture gives higher friction due to the deformation of the skin. However, if it is too rough, it can tear open the skin.

Overall there are two main aspects of wear present in the bars, namely abrasive wear and fatigue.

The abrasive wear is gradual and is mostly seen at the edges of the wear patches, when there is a layer in between the wood and the fibreglass (Figure 13, picture 4). The bar with the soft layer in between showed more abrasive wear than fatigue. It is also less splintery in the width direction. The lower layers underneath the wood all show abrasive wear.

During a visit to a gymnasium, it was very clear where the worn patches are. When the gymnast swings around the bar, most forces are transferred during the hanging phase. The gymnasts will tighten their grip when coming from the support phase to the hanging phase. The dowels of the grips are then at the side of the bars, where the worn patches can be found. See Figure 14. At this place, most wear is noticed. Here too, the main wear visible is abrasive wear.

In Figure 15, an overview of the problems of the different bars is depicted. In the length

Figure 11 - Wear mechanisms: (1) Adhesive wear; (2) Abrasive wear; (3) Surface fatigue; (4) Tribochemical wear. [38]

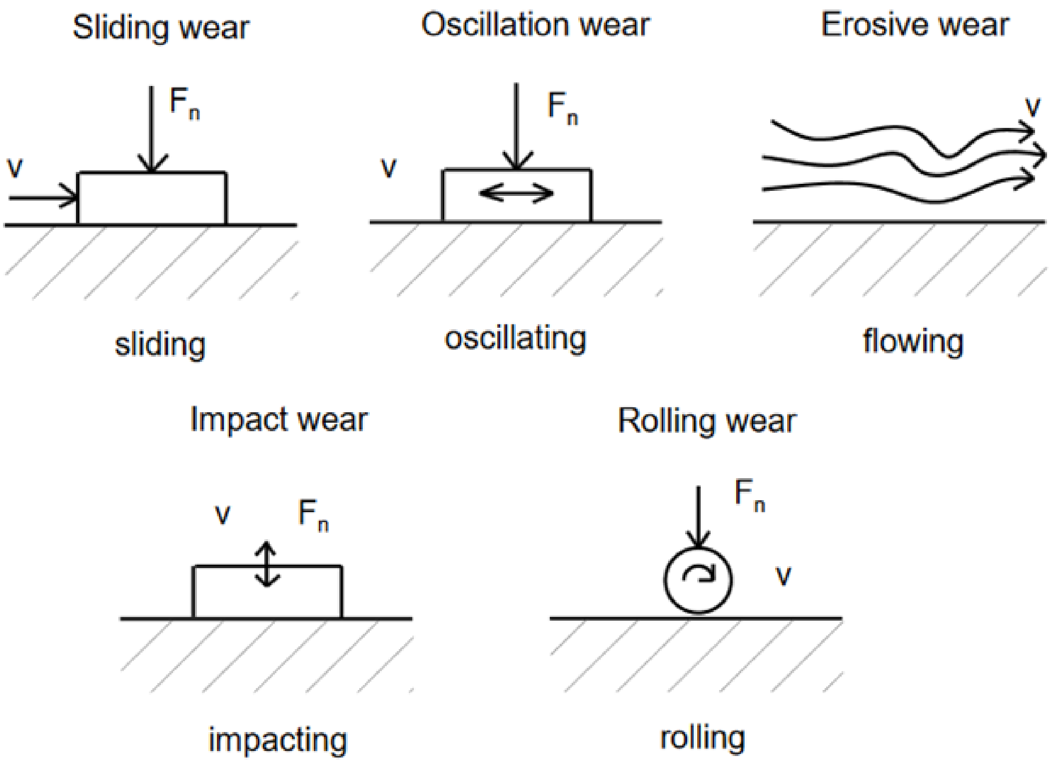

Figure 12 - Wear processes (from left to right). Above: sliding wear, oscillation wear, erosive wear. Below: impact wear, rolling wear. [38]

direction, splintery edges are visible. The ellipse shape in the middle of the worn patch shows the core of fibreglass. The shape around the ellipse is the layer between the wood and the core. This could be a soft fabric-like material or glue. Figure 16 shows worn patches of the nine different bars. These are plotted in a graph of abrasive versus fatigue wear. Mostly the bars show severe fatigue or severe abrasion wear. Most times the other type of wear is also present, but to a lesser degree.
Almost all worn patches are found at the same places, one at the left of the middle of the bar and one on the right. These worn patches are sometimes connected. In some cases, there are two patches above each other (Figure 17). This is caused by turning the bars and by gymnasts that have routines where they change positions during the routine. Since fatigue wear is mostly caused by wrongly glued bars, it will not be taken into account in this research.

2.3.6 Causes

The different wear problems are caused by different movements and materials. Gymnasts use magnesium powder and grips made of leather to gain better grip. These materials gradually rub down the wood and underlying layers. From a certain level, all gymnasts use doweled grips. These dowels give the gymnast a better and

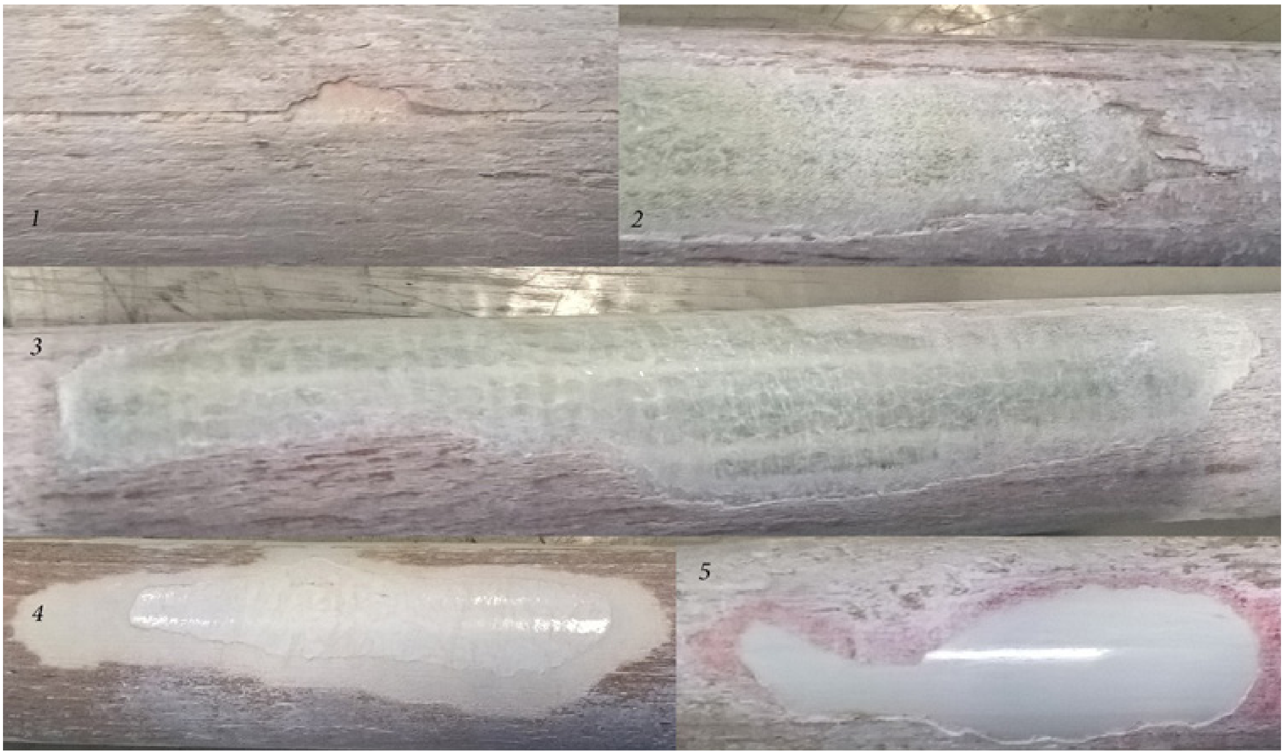

Figure 13 - Worn patches of different bars. (1) Chipped off wood at seam; (2) Splintery at the side and abrasion at the rest of the bar; (3) One big worn patch, with fatigue and abrasive wear; (4) Abrasive wear, with smooth and shiny core; (5) Abrasive wear with red at the edges to show there is wear, and smooth and shiny core.

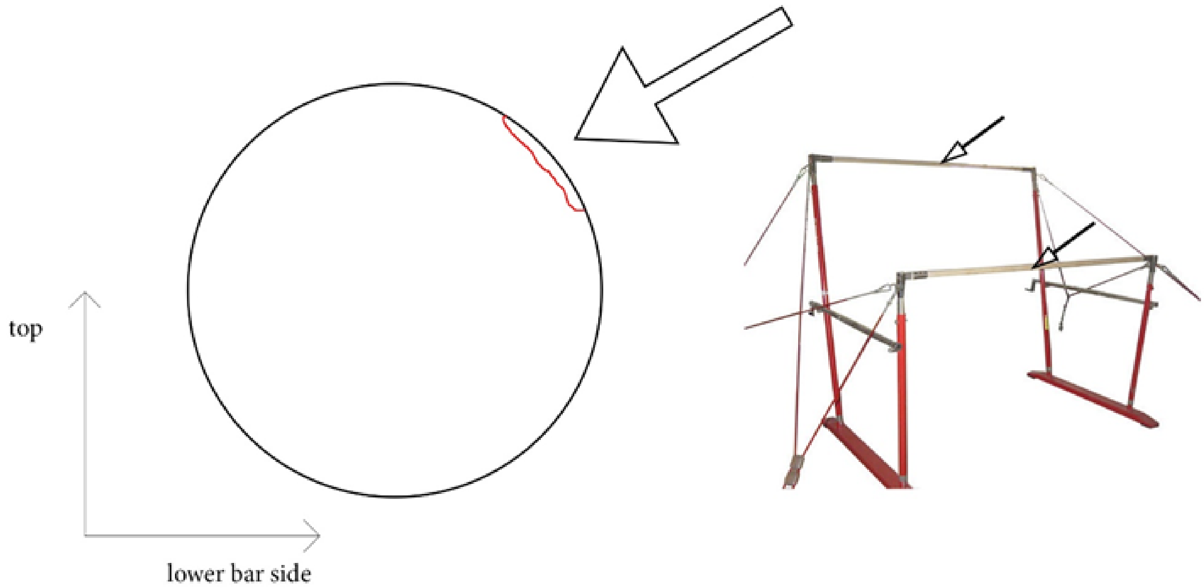

Figure 14 - Cross section of bar and side view of uneven bars [39]. The arrow points out the place of wear.

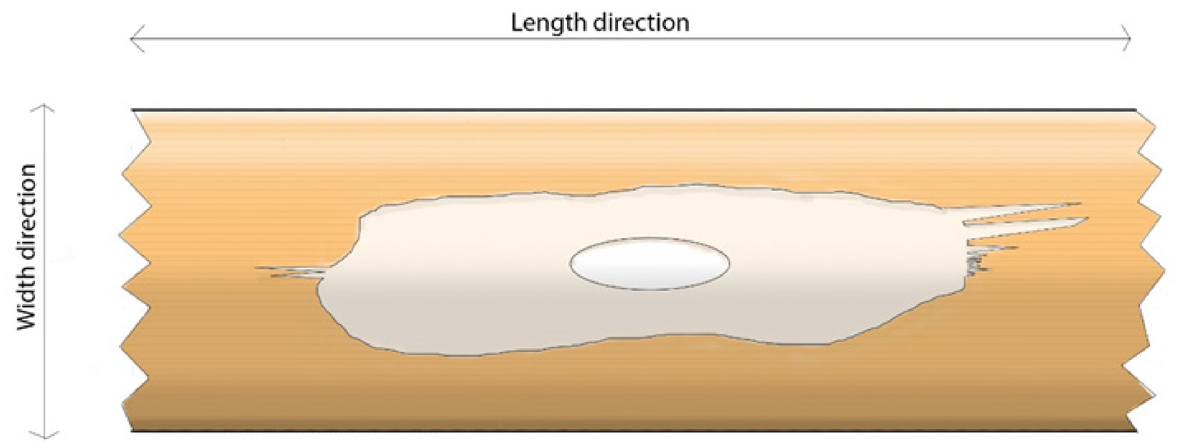

Figure 15 - Overview of worn patches of different bars. Splintery at the edges, abrasive wear in the width direction. Core is visible in the middle.

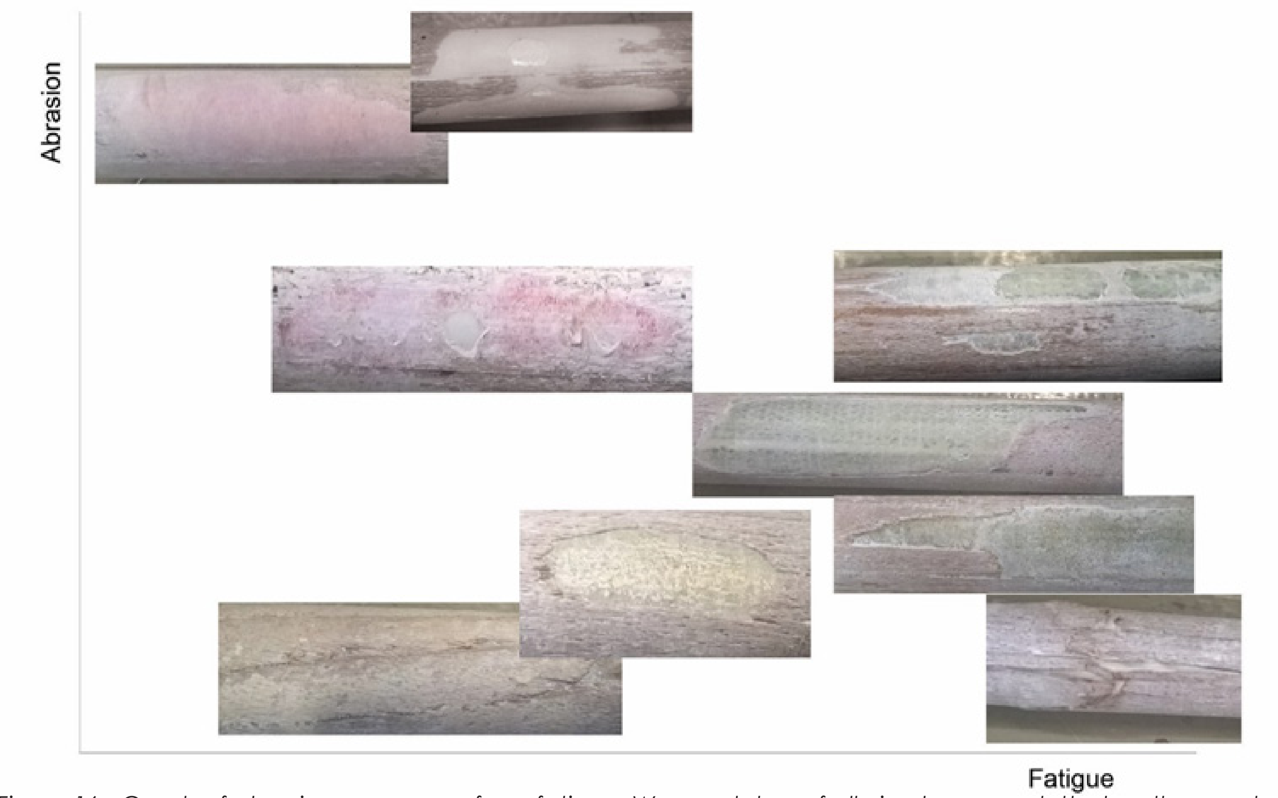

Figure 16 - Graph of abrasion wear vs. surface fatigue. Worn patches of all nine bars are plotted on the graph based on the type of wear.

Figure 17 - Worn patches at four places (left and right), marked in red.

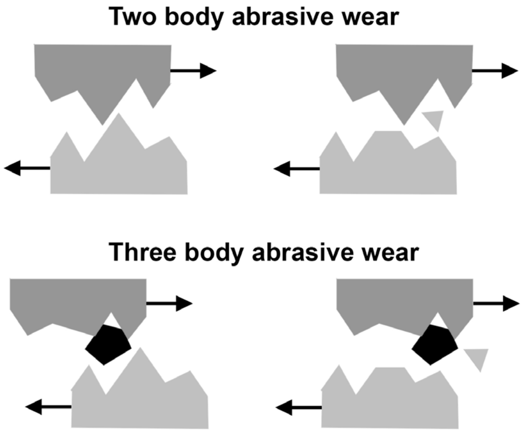

Figure 18 - Two and three body abrasive wear. In both systems two body abrasive wear is present.

more secure grip [40], however, they also exert a high pressure at the bars on a small contact area. Next to that, some gymnasts also use resins, honey, water and other materials that help them stick to the bar.

Abrasive wear is present due to the higher forces exerted on the bar by the dowels. The leather rubs down the wood on the places were the dowels are during the hanging phase of swings. A three body abrasion is not possible in this system, since magnesium has a low hardness.

At the end the sticky making materials could adhere to the loosened materials and tear off these materials. The sticky materials will induce wear of the bar. However, they will not be the main cause of the wear.

2.3.7 Potential solutions

To reduce the abrasive wear two rules could be applied. The first is to reduce the penetration depth of the abrading particle by reducing the roughness of the hard surface or to increase the hardness of the softest surface. For this system the leather is softer than the wood. However, the wood wears off fast. The hardness of the bar could be increased, unlike the decrease of the hardness for the dowels. The second rule is to introduce an intermediate layer. This layer will be a sacrificial layer, which will abrade instead of the main material.

From this current research, the main solution would be to use no grips anymore. However, this is not a preferred solution by the gymnasts. Therefore, the solution should be found in changing the bars. The amount of potential solutions will reduce, when one looks at the rules set by the International Gymnastics Federation (FIG).

2.3.8 Conclusion system analysis

Different bars with worn patches which were send back from a gymnasium were investigated. It was observed that the worn patches were all at the same place, namely, where the dowels of the grips are in the hanging phase of a swing. The grips cause abrasive wear. Most forces are transferred at the dowels of the grips during the hanging phase of a swing. The grips gradually rub down the wood.

2.4 Changes over the past years

Grip perception changes rapidly with the current bars. Due to abrasive wear, the grip decreases during use. Leading to too little grip. Before a good solution can be found for the problem of reduced grip due to abrasive wear, the changes in the past decade are investigated.

2.4.1 Routines

In the years that the uneven bars has been a gymnastic apparatus for women on big events like the Olympics, a lot changed. When starting, the uneven bars were just parallel bars for men which were set to different heights [41]. The bars were egg shaped instead of round and a shoulder width apart from each other. Therefore, the routines were very simple compared to nowadays routines. Within the years the bars became round and the width between the bars became bigger. In the 60's and 70's the gymnasts slapped their pelvis to the lower bar when they swung from the higher bar, mostly continuing their routine with different rotations at the lower bar or going back to the higher bar. The distance between the bars was important, so they would hit the bar with their pelvis with precision. In the 80's the bars would be even further away from each other. [4] The elements became harder with the years, however, the last ten years little has changed. These days most routines contain many swings, with sudden stops to perform for example handstands and many flight elements. [3]

It can be concluded that much has changed in the routines since the introduction of the uneven bars. However, these changes have not taken place during the last decade, when the wear rate increased.

2.4.2 Grip materials

These days gymnasts use all kind of different materials to get a better grip on the bars. Well known is magnesium powder. Magnesium is probably used since the beginning of the uneven bars. Also leather grips are well used and liked materials of gymnasts. The grips are invented and patented in 1994 [42]. Last decade (and even longer) they are used by the gymnasts. In the earlier days the gymnasts sometimes used honey, sugar water and syrup. This was mostly used by gymnasts from without acces to magnesium and grips [1]. Nowadays still some gymnasts use it, but most use just magnesium and grips. The use of grip materials has thus not changed significantly the last decade. The change in grip materials can therefore not be the only problem.

Figure 19 - Uneven bars at the Olympics of Helsinki in 1952. Two men are holding the uneven bars to secure from falling. [41]

2.4.3 Bars

At the first Olympics where women could compete in uneven bars in 1954 the contestants broke 39 bars. In the 60's the uneven bars as known now were invented. The apparatus was better secured because the bars became round with fibreglass cords. Due to its new construction no bars were broken, in the Olympics of 1972. [41] In later years the bars have changed from wood with a fibreglass cord to fibreglass cores with wood veneer.

2.4.4 Discussion

Due to the fact that the bars are not made in own factory but are all purchased at competitors, no information about production processes etcetera is available. Hence, a lot of assumptions are made. The changes in the bars are not clear. Therefore, it could be possible that the bars or the production processes did change the last couple of years. Since no changes were found in the routines and the used materials, the only solution direction was to change the bar.

2.4.5 Conclusion changes

The quality of the bars deteriorated and specific craftmanship was possibly replaced by cheaper production methods and/or materials. However, these are all speculations by the author and no direct link was found between the change of perceived grip due to fast wear and changes with respect to quality over the last decade.

2.5 Norms

The international Gymnastic Federation and the NEN have set norms to assure the quality of the gymnastic apparatus and to make the apparatus as safe as possible. These norms need to be taken into account in the design process.

Both the International Gymnastics Federation (FIG) as NEN has set norms for the uneven bars. In Appendix C a couple of tables can be found with the norms set by the FIG and NEN. One table contains the comparison of these two sets of rules. Most rules are set by the FIG, which are more performance-oriented, while the NEN-EN norms are more aimed at safety. The most important rules for now are:

- The bar surface must provide a good glide and turn capability but may not be slippery (FIG);
- To ensure grip stability, the bars' surface must absorb moisture (FIG);
- Rough surfaces should not present any risk of injury (NEN-EN);
- The bars retain the natural colour of wood. They are neither lacquered, nor polished (FIG);
- The diameter of the bar is 40 mm (±1 mm) (FIG & NEN-EN);
- When the bar is pulled down vertically, with a tractive force of 1350 N ± 20 N, the maximal deflection is 70 ≤ x ≤ 100 mm. (FIG) | For NEN-EN: minimum = 40 mm, maximum = 100 mm.

The FIG has more rules which are important to take into account. However, these specifications have to be determined by a specific way of testing. These norms will therefore be taken into account in a further stadium of the design process.

A couple of the norms regulate the properties of the core, while others are based on the surface of the outer layer. It is very likely that the core already has the right properties related to the deflection of the bar.

The outer layer should provide the bar with a good glide and turn capability while not being slippery. Next to that, it cannot be too rough, causing any injuries. It also has to absorb moisture. Last but not least the bar should look like it is made out of wood. However, the bars do not have to be made out of wood.

When visiting the top gymnastic hall, Frank Louter, the top coach of the gymnasts, was asked how the bars should be changed and what should be the same. He mentioned that the stiffness of the bar should be kept the same, since gymnasts are used to this stiffness. This means that the fibreglass core should stay. Next to that, the surface should give enough grip, so the gymnasts can make difficult moves without losing their grip, but should not lead to blisters.

2.5.1 Discussion norms

Some norms set by the FIG are strict, however, they serve no higher goal. For example the absorption of water is said to be important, however, the magnesium which is used by all gymnasts absorbs the water. The bar also should look like wood. Both norms are described vaguely in comparison to the norms set for the deflection of the bar. Both norms are obsolete and should be replaced by norms which are more up-to-date, so gymnastics will improve even more.

2.6 Conclusion literature research

2.6.1 Grip

According to the Cambridge dictionary, the definition of grip is "to hold very tightly" or "a tight hold on something or someone". Meaning that grip causes gymnasts to hold onto the bar. Losing grip causes slip resulting in them falling off. When research is done concerning grip, it is mostly focussing on friction and less on perception.

Optimal grip can be achieved by a high coefficient of friction, a large surface contact area and a smaller diameter to make grasping easier. A higher coefficient of friction can be gained by a moist or damped skin, a low surface roughness or extreme high surface roughness, a negative skewness, a high surface energy and low skin temperature.

2.6.2 Magnesium

Gymnasts use magnesium on all apparatuses to prevent their hands from blistering and to increase torsion with the apparatus [27]. The grip enhancement agent reduces or absorbs moisture such as sweat and/or increases grip through the adhesive properties of the agent [27, 28, 29].

Pušnik and Čuk [27] found that the temperature in the palm of the hand rose when magnesium was used. Since friction causes the temperature to rise, the friction is higher when magnesium is used. Amca et al. [30] also found that magnesium causes a higher coefficient of friction.

2.6.3 System analysis

Different bars with worn patches which were send back from a gymnasium were investigated. It was observed that the worn patches were all at the same place, namely, where the dowels of the grips are in the hanging phase of a swing. The grips cause abrasive wear. Most forces are transferred at the dowels of the grips during the hanging phase of a swing. The grips rub down the wood gradually.

2.6.4 Changes with time

No differences were found in the past ten years with respect to the bars, grip materials and routines. It is possible that small changes which are not noticed in this research combined caused the bigger problem leading to grip problems. Another possibility is that the quality of the bars deteriorated and specific craftmanship was replaced by cheaper workers. However, these are all speculations and no direct link can be found between the change of perceived grip due to fast wear and changes over the last decade.

2.6.5 Norms

The international Gymnastic Federation and the NEN have set norms to assure the quality of the gymnastic apparatus and to make the apparatus as safe as possible. The outer layer should provide the bar with a good glide and turn capability while not being slippery. Next to that, it cannot be too rough, causing any injuries. It also has to absorb moisture. Last but not least the bar should look like it is made out of wood. However, the bars do not have to be made out of wood.

The top coach of Topturnen Oost Nederland (TON) Frank Louters mentioned that the stiffness of the bar should be kept the same. Next to that, the surface should give enough grip, so the gymnasts can make difficult moves without losing their grip, but should not lead to blisters. These norms and wishes need to be taken into account in the design process.

3

EXPERIMENTS

The amount of grip and the amount of friction were experimentaly assessed, with and without magnesium.

3.1 Perception of grip

3.1.1 Introduction

Grip changes over the course of time due to abrasive wear. To test how this experienced grip changes over time, an subjective experiment was performed with gymnasts.

3.1.2 Experimental

Two gymnasts of TON (Topturnen Oost Nederland) and six gymnasts of Linea Recta (gymnasts of the University of Twente) helped to perform this test. For this test a new bar was sanded off in three different ways. One part was sanded off lightly, almost not visible or tangible (Figure 20). The second part was sanded of more, however, it was not visible in comparison to a new bar (Figure 21). The last part was sanded down till the fibreglass was visible and felt slippery (Figure 22).

3.1.2.1 Preparation bar

The used bar was not new, however, the bar has never been used or had no user marks. The bar has been divided in six longer parts of 12,5 cm and 5 smaller strips in between of 3 cm. The larger parts start at respectively 56 and 57 cm from the socket of the bar. The measurements were conducted with a flexible steel rule and were marked with a pencil. All bigger parts were marked with numbers 1 till 3. These numbers were noted at the smaller strips and were placed at both sides of each strip. The bar was fastened with a clamp at the workbench.

Numbers 3 were sanded down first since these had to be sanded off the most. Consequently, it could be tested how long one should sand before the core was visible.

Different types and orders of sanding paper are used per category; 1, 2, & 3. For parts with the number 3, a 60 grit sandpaper was used to start the sanding. The sandpaper had a length of approximately 50 cm and was about 3 cm wide. The bar is sanded as shown in Figure 24. The paper is moved up and down so the bar will be sanded for a little less than half the circular

Figure 20 - Sanded bar before testing, part 1, lightly sanded down. Not tangible and visible noticeable.

Figure 21 - Sanded bar before testing, part 2, medium sanded down. Tangible noticeable, not visible.

Figure 22 - Sanded bar before testing, part 3, heavily sanded down. Tangible and visible noticeable.

contour of the bar. The bar has been rotated to make sure the whole perimeter is sanded evenly. This method is used for the other categories as well. When the core was visible at different places, the part was finished by using sandpaper with a 600 grit. This is very fine sandpaper, to mimic the magnesium powder.

For the parts with number 2, sanding was started with a grit of 320, followed by 180 grit. The bar was slightly sanded down, so the bar felt smooth. When the part felt smooth, the strip was finished ones again with a 600 grit sandpaper. For the parts with number 1, the sanding was only lightly done with 320 grit sandpaper and finished with 600 grit sandpaper.

Each part was compared by touch to the other part with the same number. When both felt the same, the parts were done. Also it was made sure if the strips had an even feeling over the perimeter. The bar is made dust-free with a dry cloth, followed by a wet cloth.

3.1.2.2 Test setup

Every gymnast makes five giant swings or swings several times at each marked part. It is important that they know if they have enough grip and whether it is comfortable or not. After swinging at a marked part they have to fill in a questionnaire. All gymnasts first do all parts without magnesium and then the same routine with magnesium. At the end they are asked to fill in an additional questionnaire to discover how they describe grip and comfort. Both questionnaires can be found in Appendix D. All answers from the questionnaires are combined in a data sheet (Appendix E). All answers from the additional questionnaire can be found in Appendix F.

3.1.3 Results

Figure 27 till Figure 30 show the roughness and grip perception of the gymnasts. Figure 27 shows the perception of each tester regarding the roughness of the bar. Bar 2 without mag-

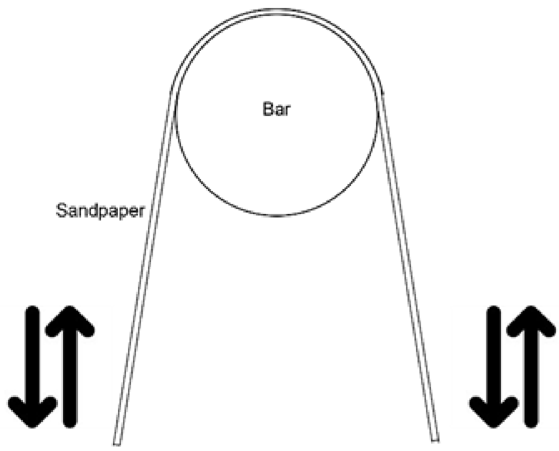

Figure 24 - Method of sanding bar

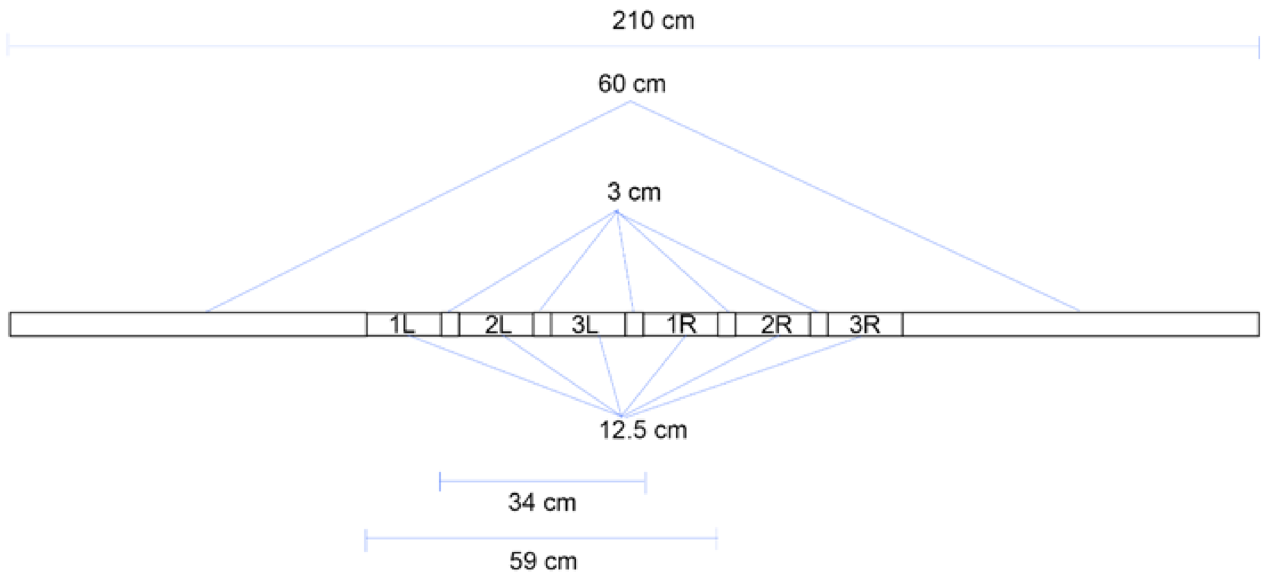

Figure 23 - Placement and dimensions of every sanded off part.

Figure 25 - Gymnast during test, preparing the bar with magnesium

Figure 26 - Gymnast during test, making giant swings with magnesium.

nesium and bar 3 with and without magnesium are perceived the smoothest. Bar 1 with and without magnesium and bar 2 with magnesium are averagely perceived rougher. However the perception per person differs a lot and the differences within the averages between parts are small. Therefore, no hard conclusions can be drawn from this. A similar experiment with more participants can be carried out to investigate if grip can be generalized.

Figure 28 shows the grip grade given by each gymnasts and the average for all gymnasts per condition. The perception of grip is higher when magnesium is used. Bar 1 and 2 have the highest grip grades when magnesium is used. Without magnesium bar 1 scores best.

Figure 29 shows how many subjects feel like they have enough grip to do 5 (giant) swings and Figure 30 shows if they feel like they have enough grip to do a whole routine. For both bar 1 and 2 with magnesium 6 out of 8 gymnast have enough grip to do 5 swings. Without magnesium bar 1 scores best. Bar 3 scores the least, with only 3 participants who have enough grip for 5 swings. A whole routine is best at bar 1 with magnesium. It is interesting that someone did not think it was possible to do 5 swings, however it is possible to do a whole routine. The other bars with and without magnesium score much less.

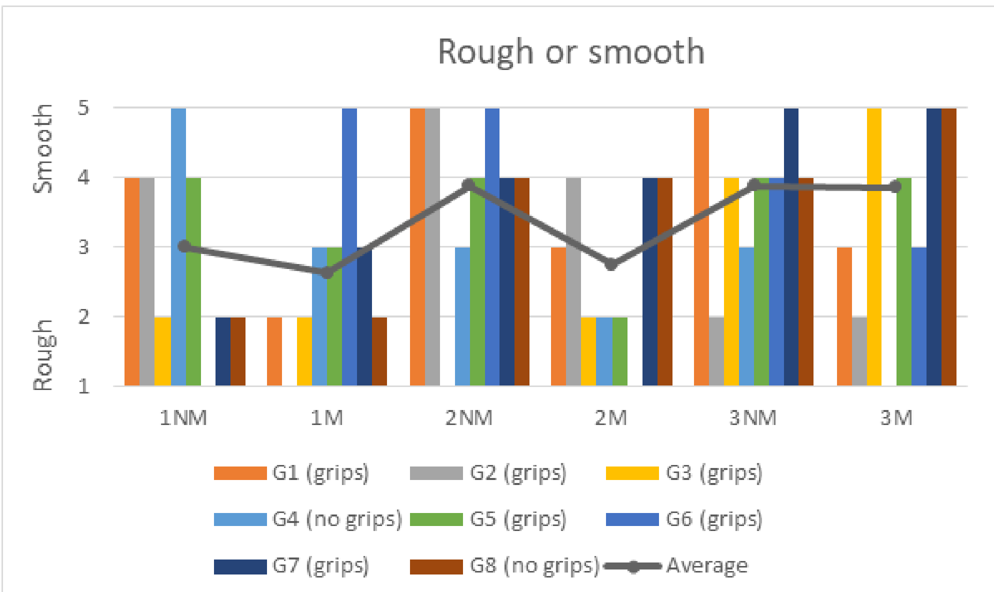

Figure 27 - Experience of roughness of the bar per person and the average. 1 till 3 = part number; NM = no magnesium; M = with magnesium. Smoothest surfaces are perceived in 2NM; 3NM and 3M.

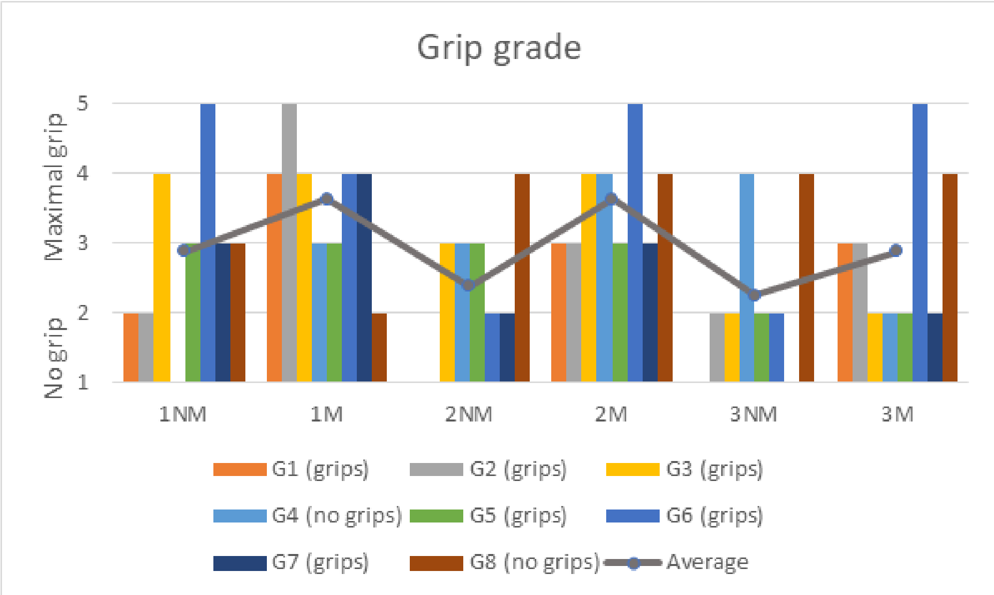

Figure 28 - Grade of amount of grip experienced by every gymnast and the average. 1 till 3 = part number; NM = no magnesium; M = with magnesium. Most grip experienced in 1M and 2M.

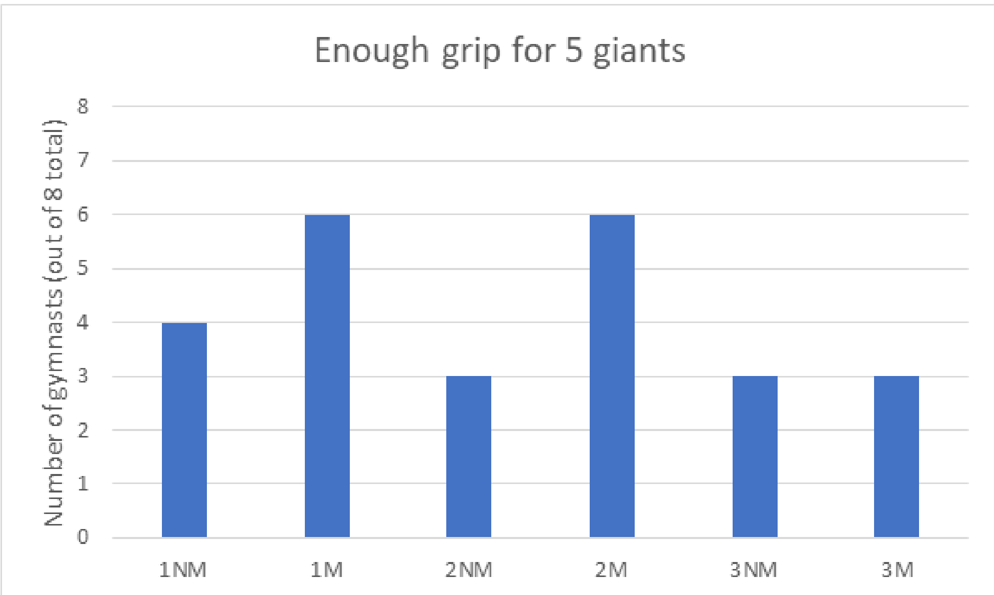

Figure 29 - Amount of gymnasts who had enough grip to preform 5 (giant) swings. There were 8 gymnasts who did this test. 1 till 3 = part number; NM = no magnesium; M = with magnesium. Most grip experienced in 1M and 2M.

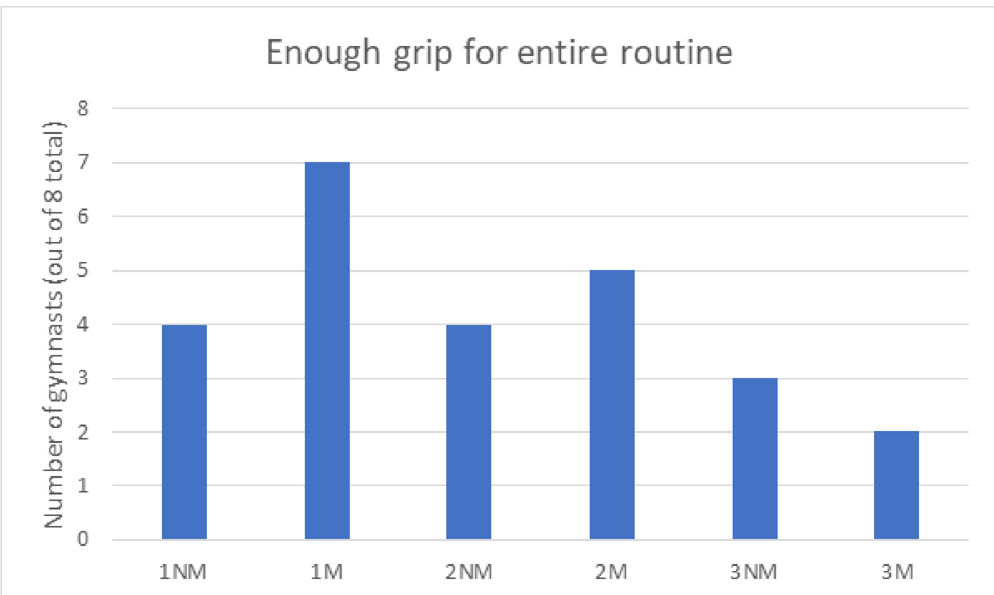

Figure 30 - Amount of gymnasts who thought would have enough grip to perform a whole routine on this bar. 1 till 3 = part number; NM = no magnesium; M = with magnesium. Most grip experienced in 1M and 2M.

At the end of the test the gymnasts were asked to fill in an additional questionnaire, which contained more questions specific off a new design. The gymnasts prefer more grip over speed for a new bar. The more grip gives the gymnasts the possibility to accelerate more. Grip is according to the testers given when the bars diameter is small enough so they can grasp it, with a rough surface so the grips stick better and the use of magnesium. An uneven bar is better than the men's high bar, since this surface is rougher. They would also like to have the same training bar as the competition bar, to get used to it.

3.1.4 Discussion

On the basis of the answers given by the gymnasts, part 1 with magnesium is found the best. Part 2 is runner up, with almost the same points. The gymnasts gave the highest grip grades to bar 1 and bar 2. However, bar 1 scored higher grades when no magnesium was used.

It is possible that the gymnasts are influenced by the order of the experiment. All gymnasts started with bar 1 without magnesium. The less experienced gymnasts had sore hands after a few rounds of experiments, but still had to do the last rounds. Therefore, their grip could be less than when they did the experiments in another order or on several days/timeslots.

It is noticed that not all gymnasts were consistent with their grip grades. It is possible that they find it hard to compare to different parts with each other when they cannot compare them at the same time. To generalize these results, more gymnasts should participate in a similar research and trained to assess grip.

3.2 Surface roughness

3.2.1 Introduction

It is thought that the experienced grip is influenced by the surface roughness of the parts. A large contact area is created by a very smooth (low roughness) counter surface or by a very rough counter surface. High surface roughness causes the skin to deform over the peaks, and creates a larger contact area.

3.2.2 Literature study

For this research, six roughness parameters are interesting to look at. Ra is the centre-line average and gives more information about the average roughness. However it does not say anything about the heights or depths of the peaks and valleys or the shape of these. Rz measures the average peak-to-valley distance of 5 peaks and valleys. This says more about the height differences, however, it does not say anything about the height of only the peaks or only the valleys. The skewness measures the symmetry around the mean line. When Rsk is 0 the surface is symmetrical, values higher than 0 mean sharp tops and values lower than 0 mean that the surface has flat planes with deep valleys (Figure 31). Kurtosis measures the sharpness of the surface. If Rku is 3, the surface is symmetrical, lower than 3 means the surface is curvy and over 3 it means it is spiky (Figure 32). Rp measures the average peak heights and Rv the average valley depths.

3.2.3. Experiment

After the subjective test with the gymnasts, the used bar is cut in pieces. Every part which has been used during the grip test is properly numbered 1 till 3 according to the previous test. The parts that will be investigated are: 1 left, 1 right, 2 left, 2 right, 3 left, 3 right and side. All parts are viewed under a confocal microscope (VK 9700 Keyence, 50x magnification) to measure surface roughness. Different photos taken by the confocal microscope are stitched together to create a bigger picture of one area. The following roughness parameters have been taken into account: Ra, Rz, Skewness, Kurtosis, Rp and Rv.

On every photo two or three line roughness measurements were performed perpendicular to the grain and parallel to the grain. Figure 33 shows an example of a measurement. All measurements can be found in Appendix G. Since every set of measurement has some outliers, the maximum value and the minimum value are

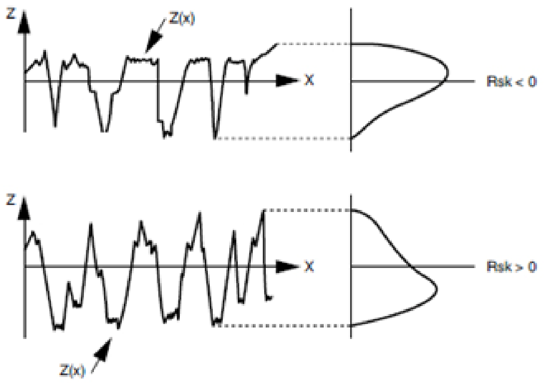

Figure 31 - Skewness. Rsk < 0: Flat planes with deep valleys; Rsk > 0: Sharp peaks; Rsk = 0: Symmetrical surface.

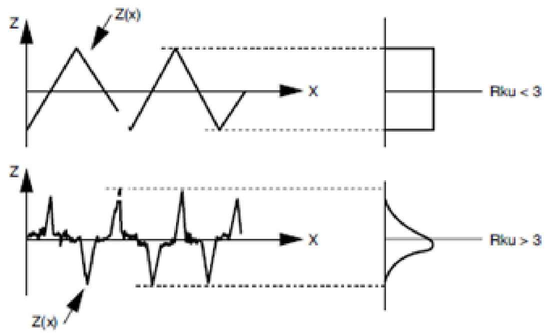

Figure 32 - Kurtosis. Rku < 3: Curvy surface; Rku > 3 Spiky surface; Rku = 3: Symmetrical surface.

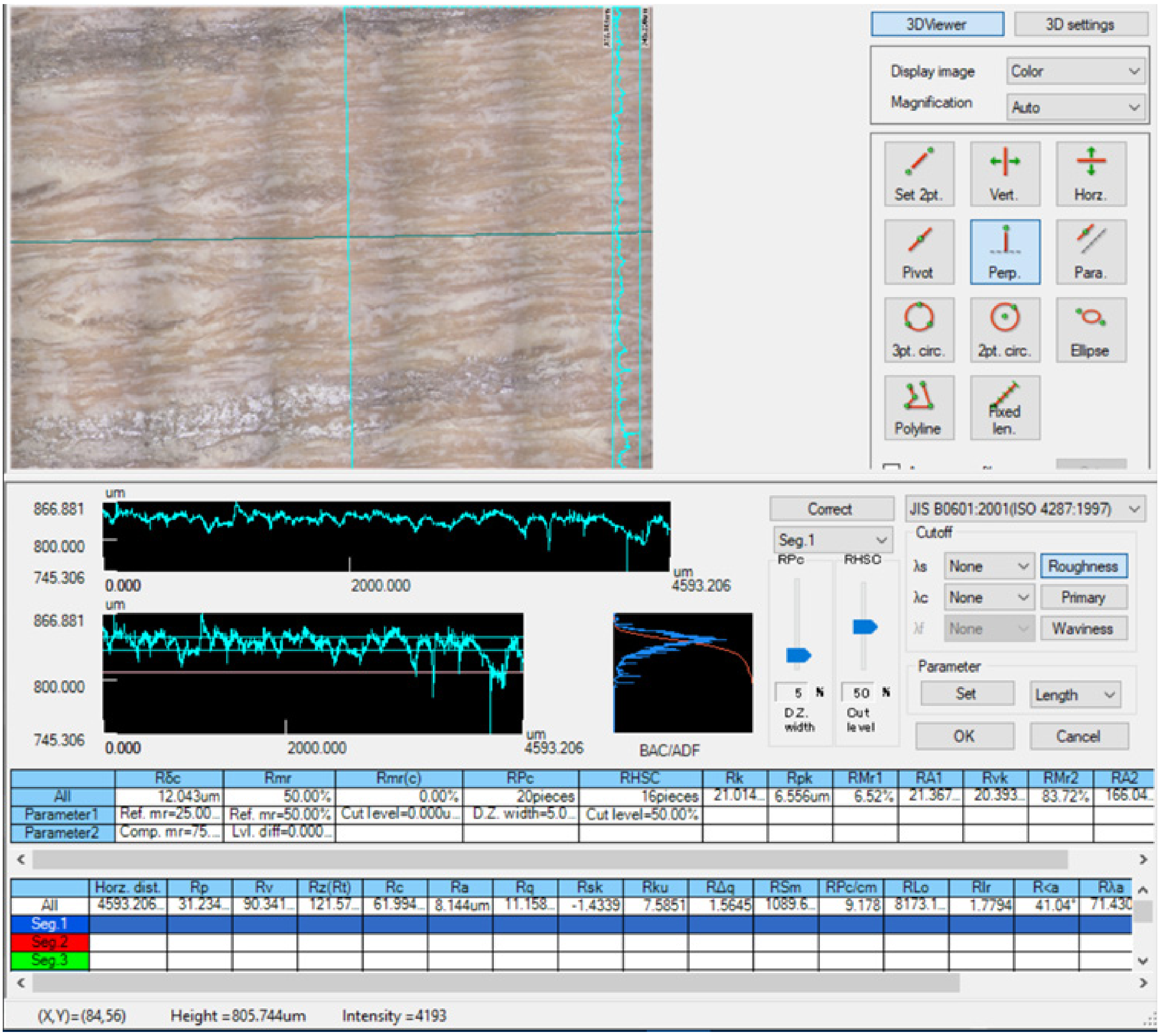

Figure 33 - Line roughness measurement of part 2 right. The darker line is parallel on the grain, the light blue line is perpendicular to the darker line, and therefor perpendicular to the grain. The roughness is calculated for the light blue line. The shiny lines on the bottom and top are pencil strikes to mark the area that needed to be scanned.

distracted from the average calculation. Giving a more accurate average.

3.2.4. Results

The averages of the roughness values Ra, Rz, Skewness, Kurtosis, Rp and Rv perpendicular to the grain can be found in Table 2. It can be seen that the roughness of part number 2 is the lowest for the centre-line average (Ra). The Rz value is about the same for all three parts. However, part three has an extreme measured differences between left and right. This can be caused by the differences in the surfaces measured since the third part is not evenly sanded down.

Figure 34 - Photo of a measured surface. The darker stripes show the stitching lines. The white lines look like they are valleys or peaks.

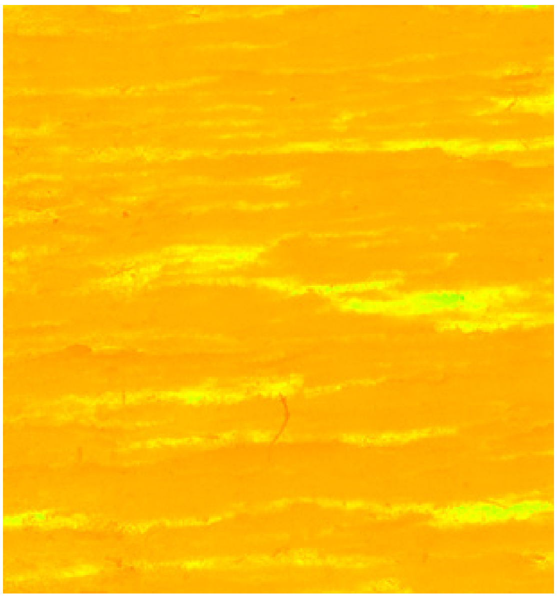

Figure 35 - Height profile of the surface of Figure 34. The more red the colour the higher the surface is. As can be seen, the surface is mostly flat with valleys. No high peaks are visible. The valleys are mostly narrow and probably steep, since no smooth transition in colour is visible.

Almost all values of the skewness are lower than 0, meaning that the surface looks like a flat plane with deep valleys. The differences between left and right is big for all parts. Only part 1 left has a value of approximately 0, meaning this surface is more symmetrical. The value of kurtosis is everywhere higher than 3. This means that the surface is very spiky (See Figure 32). Overall the surface of the bars are flat surfaced with deep spiky valleys. These valleys look like long narrow lines, which are approximately 400-800 µm away from each other. The lines are parallel to each other, however, the length and start and end points are not the same.

The previous data shows that the surface now looks like a flat surface with deep spiky valleys. Or at least for the roughness perpendicular to the grain. Since the depth of these values are important, the Rv value is taken into account. The Rp value was observed to be larger in some cases than the Rv value or was approximately the same. This is contradictive to the previous findings which predicted a flat surface with deep valleys. To ascertain whether the magnesium is hiding in the valleys of the wood or causing peaks, the results of parts 1 till 3 are compared to the side bar. The peaks of the side bar are a bit lower, however, not significantly lower. The valleys are indeed deeper for the side bar than for the other three parts. This means that the magnesium is filling the valleys and creating small peaks in the parts numbererd 1 till 3. The structure of the wood is drawn in Figure 36.

3.2.5 Conclusion

A couple of conclusions can be drawn after the surface roughness measurements. The rough-

		Ra ⊥ to grain		Rz ⊥ to grain		Skewness ⊥ to grain		Kurtosis ⊥ to grain		Rp ⊥ to grain		Rv ⊥ to grain	
		Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
1	Average	9,213	9,000	100,040	83,780	0,067	-0,287	6,003	3,892	52,182	43,901	47,809	39,880
		9,107		91,910		-0,110		4,947		48,041		43,845	
	Average -MIN&MAX	8,861	9,084	93,233	85,306	0,038	-0,311	5,555	3,735	45,428	43,766	44,570	36,475
		8,940		87,916		-0,145		4,660		44,726		41,932	
	Median	8,229	9,066	85,129	85,905	0,031	-0,481	4,930	3,514	38,130	44,406	42,392	34,892
	sd	4,576	1,097	46,808	17,181	1,386	0,692	2,987	1,180	32,778	14,906	22,920	13,079
	Median	8,699		85,517		-0,363		3,849		43,969		38,005	
	sd	3,230		35,213		1,078		2,456		25,066		18,557	
2	Average	7,520	8,408	80,451	91,283	-0,703	-0,086	5,533	6,026	33,582	47,077	46,868	44,208
		7,964		85,867		-0,395		5,780		40,330		45,538	
	Average -MIN&MAX	7,335	8,047	77,290	89,412	-0,709	-0,292	5,527	5,462	30,487	42,183	45,312	39,390
		7,809		84,670		-0,502		5,502		38,004		43,768	
	Median	7,863	8,144	71,780	81,173	-1,051	-0,230	5,867	4,963	28,722	36,392	47,529	36,492
	sd	2,123	2,411	23,362	24,503	0,959	1,290	1,251	3,546	15,854	22,506	13,166	18,967
	Median	8,118		75,045		-0,534		5,452		32,934		40,942	
	sd	2,251		23,884		1,147		2,592		20,121		15,898	
3	Average	7,852	15,190	71,838	128,027	-0,516	0,030	4,329	5,155	34,604	65,323	37,234	62,703
		11,521		99,932		-0,243		4,742		49,963		49,969	
	Average -MIN&MAX	7,701	14,254	73,291	127,011	-0,506	-0,161	4,362	4,290	34,231	60,426	37,326	61,378
		10,848		96,667		-0,338		4,313		45,994		47,815	
	Median	8,420	12,203	75,562	129,660	-0,645	-0,595	4,388	2,877	30,028	48,378	37,884	60,248
	sd	3,660	6,813	22,993	39,981	0,630	1,179	0,602	4,192	13,081	34,815	13,265	28,687
	Median	9,621		90,948		-0,598		4,287		44,224		41,847	
	sd	6,442		42,492		0,946		2,859		29,539		24,989	
Side	Average	10,224		92,815		-0,649		4,240		35,955		56,861	
	Average -MIN&MAX	10,264		92,775		-0,655		4,018		34,482		55,347	
	Median	10,264		92,775		-0,655		4,018		34,482		55,347	
	sd	0,394		10,462		0,191		0,872		6,017		9,423	

Table 2 - The average roughness parameters for parts 1 till 3 left and right and side. Only perpendicular is showed, since the movement of the hand is perpendicular to the grain.

Figure 36 - Estimation of the side view of how the surface looks like. Visible are curvy peaks and deep steep valleys.

ness of the bars are different for each bar part and each line measurement. The overall shape is determined, however, no exact dimensions for a new surface could be given . The surface consists of curvy peaks and deep steep valleys. These bumps and valleys create a larger contact area with the skin or leather, since the skin or leather deforms to the shape. The valleys also store magnesium powder.

Overall this means that the new surface should be flat with steep narrow spikey valleys and no or little peaks. Since the measurements are so different for all bars, grip is not compared to the roughness of the surfaces.

3.3 Coefficient of friction

3.3.1 Introduction

It is hypothesized that the grip experienced by gymnasts is influenced by the coefficient of friction between the bar and the hand or grip. The coefficient of friction is thought to be higher when magnesium is used, as is mentioned earlier in the literature research.

3.3.2 Contact area

The forces exerted on a bar by a gymnast in a hanging phase on the high bar are 2140 N [43]. On a hand of a gymnast a load of approximately 1070 N can exist. For one fingertip this could be as high as 70 N (estimation). The speed of a giant swing made by a male on a high bar with grips is 30.6 rpm [15].

The contact area of the finger and leather strip are calculated with the Hertzian Contact equation [44]. The finger is first modelled as a plane for reasons of simplicity. The Poisson's ratio and elastic modulus of glass fibre (v = 0.2; E = 75 GPa) are used for the bar, and for the hand and leather both a Poisson's ratio and elastic modulus of 0.5 are used [45]. The weight of the finger is 11 N and for the leather 13 N. This difference is due to a lower weight of the finger guide than the metal holder for the leather. The line contact length is 13 mm for the finger and 16.3 mm for the leather. Both are measured in an un-squeezed situation. The rectangular contact area width is 0.351 mm for leather and 0.361 for skin. Since the length of the finger contact area and the leather contact area are different the following contact areas are calculated. Contact area for leather is 5.44 mm^2; the contact area for the fingertip is 3.61 mm^2. As can be seen, the contact area for the leather is much higher, which can affect the calculated coefficient of friction.

3.3.3 Experiment

Since the bar is large and cylindrical, a new test rig is to be built by Dmitrii Sergachev to measure the normal and frictional force to calculate the coefficient of friction. Figure 38 shows the setup of this test. The bar is clamped in on an axis. This axis was connected to a DC motor, which was hooked on a control unit, to set the speed. The control unit could control the direction of the rotation and had 12 velocities to select. Under the stabilizing plate three gauges were placed to measure the forces in different directions.

Before the tests were performed a set of test experiments were done to determine the speed and weight. Since the velocity which gymnasts can achieve is much higher than the motor can achieve (12.9 rpm), the maximum speed of the motor is used. The coefficient of friction did not change significantly after a certain load . Since high loads are painful on the fingertip and the loads do not change the coefficient of friction much, a load of 10 N is chosen. The total load is about 0.5 N higher due to the weight of the finger guide.

The tests are being performed in the following order: Day 1 Skin – Bar no magnesium, Day 2 Skin – Bar magnesium, Day 3 Leather – Bar no magnesium and magnesium. Between the second and third day the bars will be cleaned with a wet cloth to remove the magnesium.

The same bar that is used in the experiment with gymnasts and to measure the surface roughness will be used. The parts are: 1 left, 1 right, 2 left, 2 right, 3 left, 3 right and side. The side bar has not been used during the experiment with gymnasts, however, it can tell more about a new bar. For this experiment one small part of another bar (same manufacturer) has been coated with four layers of rubber coating (Plasti Dip). Since rubber has high coefficients of friction with skin, the coating is used to test if it could increase the friction. More information about this choice will be explained in chapter 4.2 New material.

3.3.3.1 Measurement method

The bar is spinning at a velocity of 12.9 rpm with inward torque [25]. The finger is placed under the finger guide, with the end of the tip of the finger at the end of the guide but is not touching the bar yet. The arm is resting on the arm rest. When the 10 N weight is placed, the finger will be placed on the bar and the measurement will be started. After 30 seconds the measurement finishes automatically. The finger is lifted of the bar for a few seconds and will be again placed on the bar and the next measurement will be started.

The measurements for leather are a bit different. The used leather is from the inside of a strap of a used grip. This part had no to little visible wear. Figure 39 shows the set up for a leather strip. To keep the measurements as similar as possible, the leather will also be lifted off the bar when the measurement is finished and placed again, starting the new measurement.

When magnesium is used, the finger will rub over a magnesium block before every measurement. Figure 37 shows how the finger looks just after applying magnesium powder and after doing a measurement. The leather strip will be rubbed

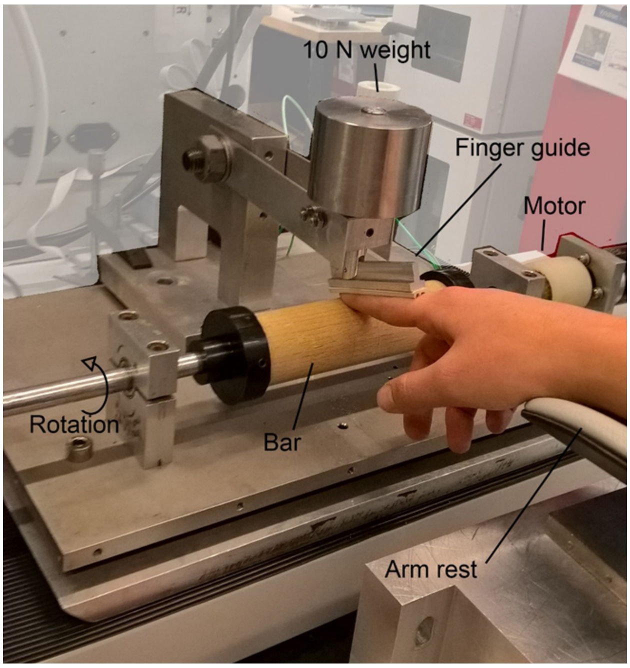

Figure 38 - Test set up: A bar is rotated by a motor with a constant speed. The finger is kept in place by the finger guide and the arm is rested on the arm rest. A 10 N weight is applied on the fingertip.

Figure 37 - Finger after applying magnesium before and after experiment.

Figure 39 - Test setup for leather.

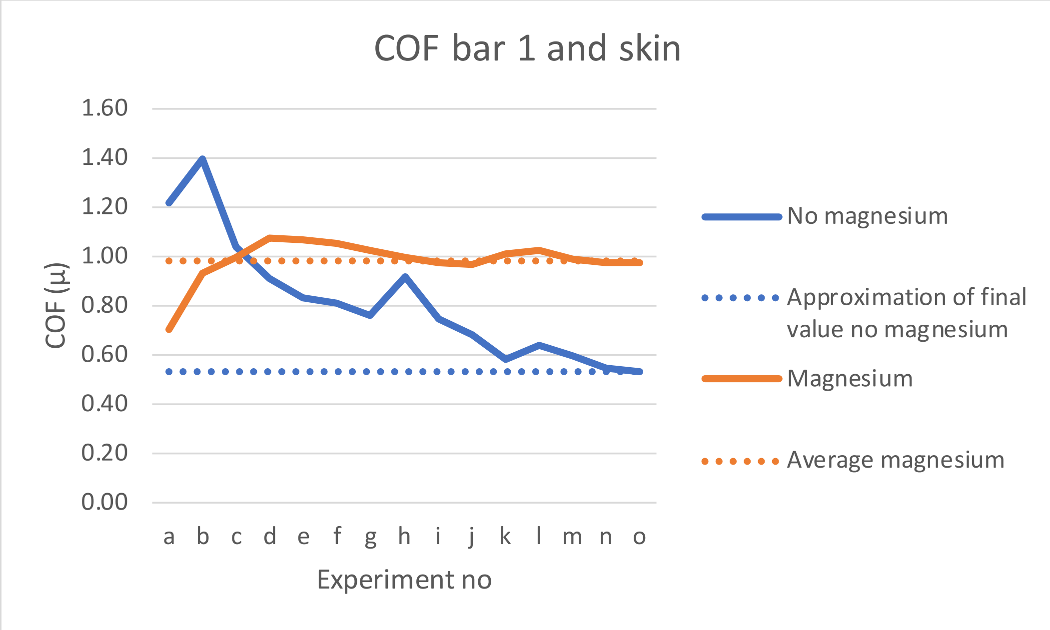

Figure 40 - Comparison of COF with and without magnesium for bar 1. Without magnesium the COF drops during the experiments. With magnesium the COF rises till a certain point and then stays relatively constant. The average COF with magnesium (μ = 0.98) is significantly higher than the approximate final value no magnesium (μ = 0.53). The peak at point h for no magnesium is caused by the extra rest time to let the finger recover.

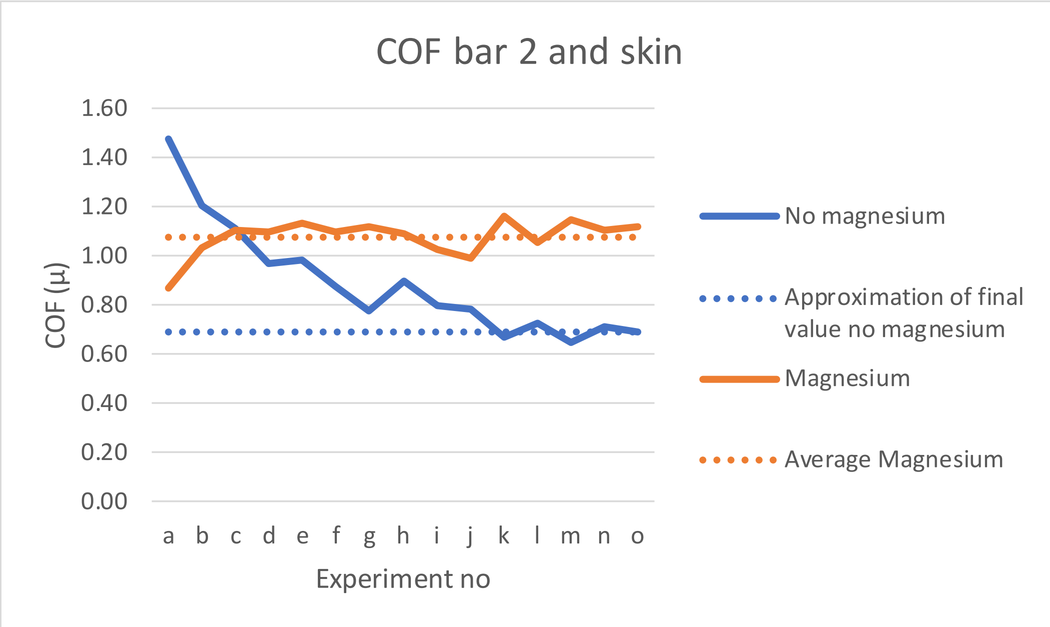

Figure 41 - Comparison of COF with and without magnesium for bar 2. Without magnesium the COF drops during the experiments. With magnesium the COF rises till a certain point and then stays relatively constant. The average COF with magnesium (μ = 1.08) is higher than the approximate final value (μ = 0.69). The little peak at point k for magnesium can be caused by a little rest to let the finger recover.

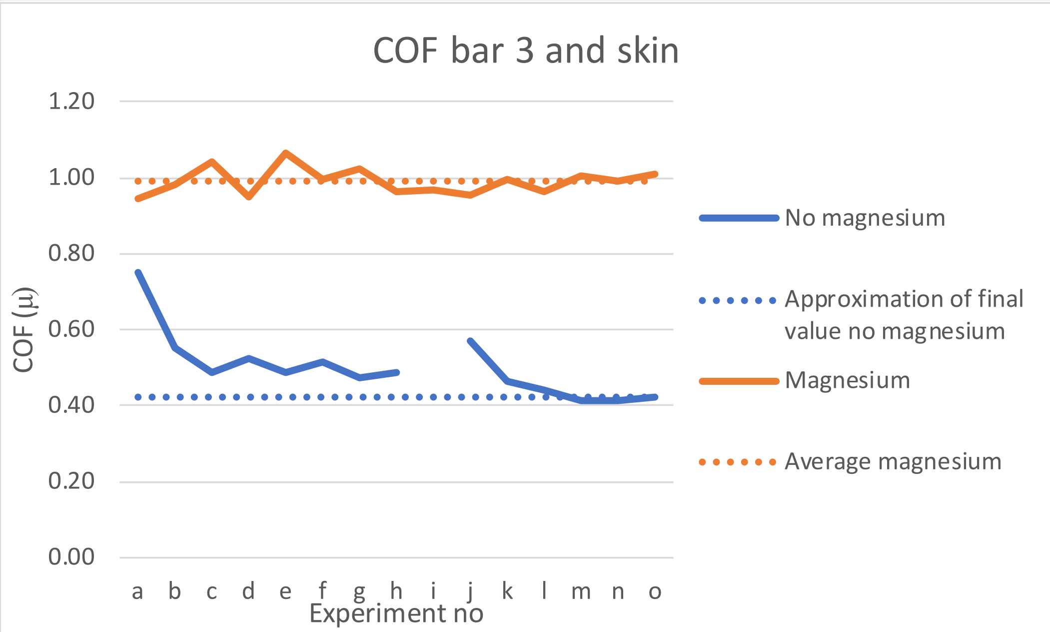

Figure 42 - Comparison of COF with and without magnesium for bar 3. Both the COFs with and without magnesium are relatively constant from the beginning, with a little drop for the COF for no magnesium. The missing data point for no magnesium is a failed measurement. The COF for magnesium (μ = 0.99) is more than twice as high as without magnesium (μ = 0.42).

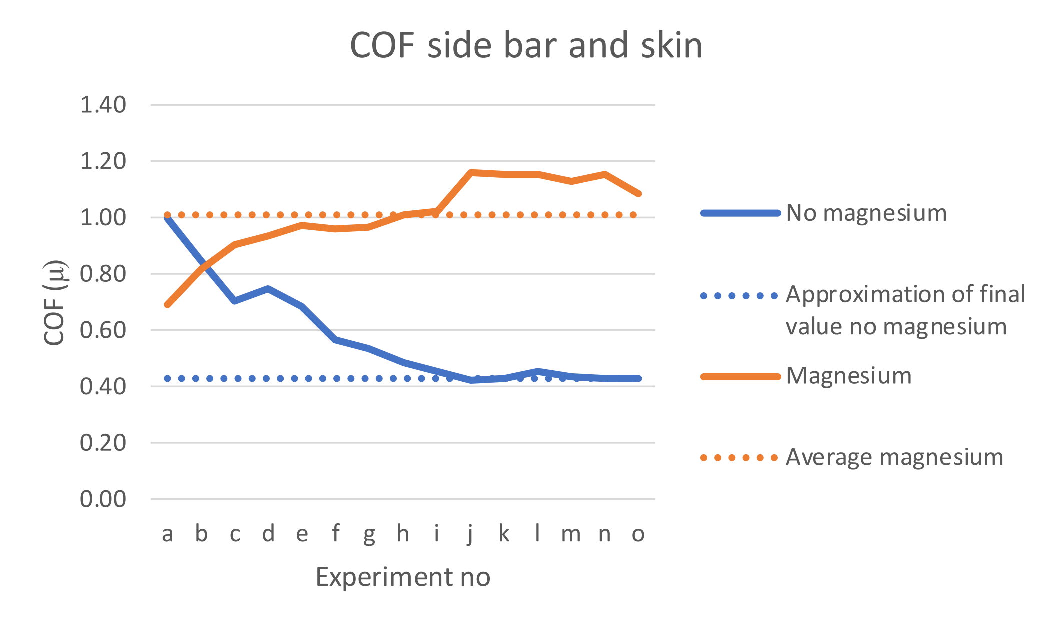

Figure 43 - Comparison of COF with and without magnesium for the side piece of the bar. The COF for no magnesium decreases during the experiments, the COF for magnesium increases during the experiments. The approximated final value (µ = 0.43) is lower than with magnesium (µ = 1.01).

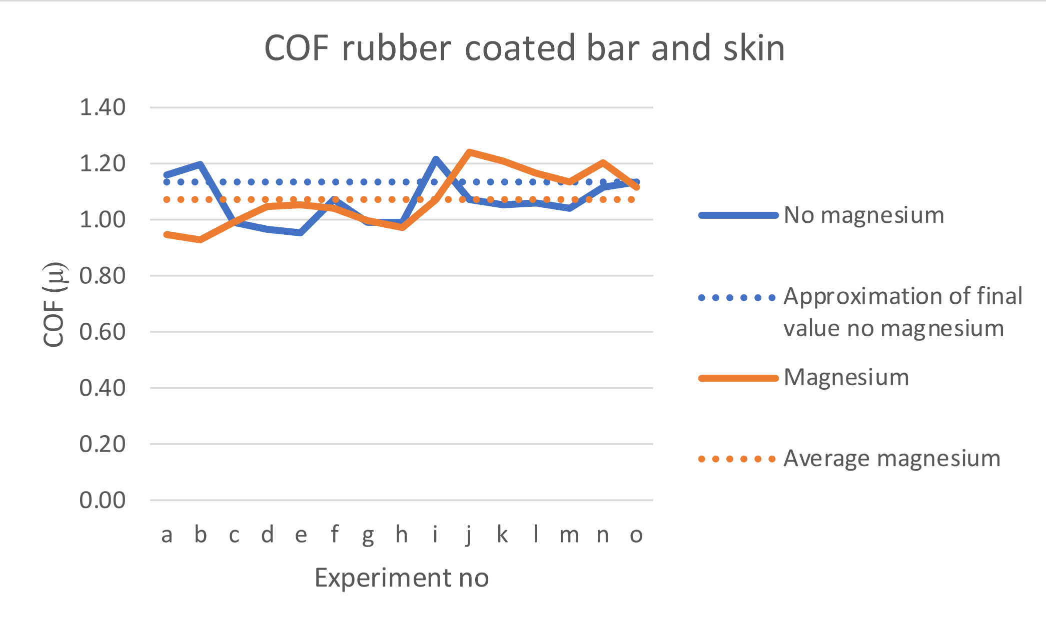

Figure 44 - Comparison of COF with and without magnesium for a rubber coated bar. The COFs for both experiments are inconsistent. However the COF when no magnesium (approximated final value µ = 1.13) is used has a slight higher value as when magnesium (average µ = 1.08) is used.

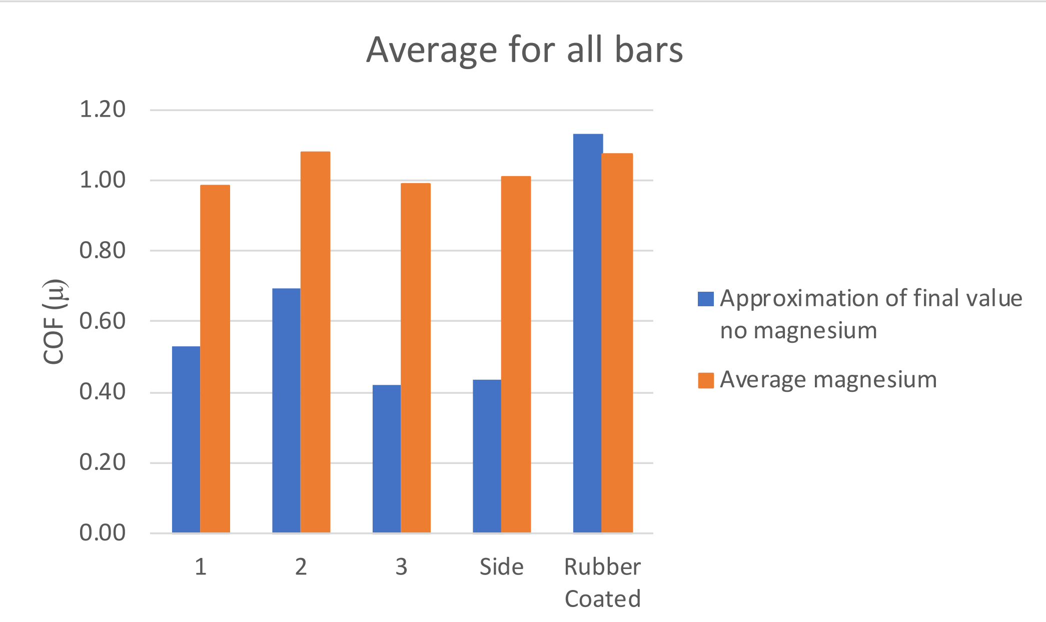

Figure 45 - Comparison between bars for the average with and without magnesium. A much lower COF can be found in bars 3 and the side part than in the other bars without magnesium. With magnesium, this decrease of COF is not as clear and the values are even relatively the same. The values for magnesium are significant higher than for no magnesium.

with the magnesium block. The leather is not cleaned between the different bar parts. The finger is cleaned between the different parts. After approximately 5 rounds of experiments the bar was covered with magnesium.

For every condition 15 measurements are done. All measurements will be done on one spot of one bar part (only left or right). Therefore, the differences within a bar part and between the left and right bar parts are not taken into account. After the first set of measurements the spot will be marked, so all measurement are done at the same spot.

Note: The COF during the experiments is tested with a rotating bar. Normally the COF is tested with a small flat piece of material. The COF can therefore be different than tested under normal circumstances.

Every 0.1 second the normal load and friction force is measured. All this data is saved in a .csv file. The coefficient of friction of each point is calculated by dividing the friction force by the normal load. The average coefficient of friction is calculated and used in processing the data.

The data is processed in Microsoft Excel 2016.

3.3.4 Results

3.3.4.1 Coefficient of friction of skin

Figure 40 - Figure 44 show the coefficients of friction during the 15 experiments for all bars with skin with and without magnesium. The COF of the bars 1,2, 3 and the side bar increase significantly when magnesium is used. The COF decreases over time when no magnesium is used. The COF increases at first when magnesium is used and then stays relatively constant.

The bar coated with a rubber spray shows a different trend. The COF without magnesium is high from the start. With magnesium the friction coefficient does not increase. The averages for both are about the same, however, the trend of the graphs are not consistent.
Figure 45 shows the averages of all experiments per bar part. It shows that the friction coefficient of bars 3 and side are much lower than the rest. However, when magnesium is used, the coefficient of friction is about the same as bar 1 and just slightly lower than bars 2 and rubber coated.

COF Skin	No magnesium					Magnesium				
	1	2	3	Side	Rubber Coated	1	2	3	Side	Rubber Coated
Average	0.81	0.89	0.50	0.58	1.07	0.98	1.08	0.99	1.01	1.08
Median	0.76	0.80	0.49	0.49	1.06	0.99	1.10	0.99	1.01	1.05
SD	0.24	0.22	0.08	0.18	0.08	0.09	0.07	0.03	0.13	0.10

Table 3 - Averages, medians and standard deviations for all bars with and without magnesium. A lower standard deviation can be found when magnesium is used.

COF Leather	No magnesium					Magnesium				
	1	2	3	Side	Rubber Coated	1	2	3	Side	Rubber Coated
Average	0.27	0.28	0.30	0.30	0.38	0.68	0.62	0.55	0.52	0.57
Median	0.27	0.28	0.30	0.30	0.39	0.68	0.63	0.54	0.52	0.57
SD	0.02	0.02	0.01	0.02	0.02	0.03	0.02	0.04	0.04	0.03

Table 4 - Averages, medians and standard deviations for all bars with and without magnesium. A higher SD is visible for magnesium.

Table 3 shows the average, median and standard deviation of all bars. This is calculated with the averages of each set of measurements. The standard deviation show lower values when magnesium is used. It was seen during the experiments that the skin became wet when no magnesium was used. When magnesium was used the finger stayed dry. In both situations the finger looked squeezed.

3.3.4.2 Coefficient of friction of leather

The measured friction coefficients for the bar with the leather of a grip can be found in Figure 46 till Figure 50. The friction coefficients of magnesium are higher for all bars. Sometimes the COF is even double when magnesium is used. When no magnesium is used, the coefficient of friction is constant. The coefficient of friction for magnesium is irregular, however no increase or decrease over time is shown. Only the side bar shows a small increase during the first few experiments.

Figure 51 shows the averages of COF between all bars and leather with and without magnesium. The COF when no magnesium is used is relatively the same for bars 1 till 3 and the side bar. The rubber coated bar has a higher coefficient of friction. Comparing the magnesium coefficients of friction shows a different distribution. Bar 1 and 2 have the highest friction coefficients, whereas the COF dips with bar 3 and the side bar. The rubber coated bar is in between bars 2 and 3. The rubber coated bar shows the least increase of friction when magnesium is added.

3.3.4.3 Comparison skin and leather

Figure 52 shows the averages of coefficient of friction for all bars with both skin and leather. The blue columns show the coefficients of friction without magnesium, the orange show with magnesium. The coefficient of friction with and without magnesium is higher for skin than for leather in all situations. Even though the contact area of the leather is higher. In some cases the friction coefficient is even higher for a finger without magnesium than for leather with magnesium (bar 1, bar 2, side bar and rubber coated bar). Table 3 and Table 4 show the standard deviations for skin and leather. The standard deviation of leather is lower than for skin.

3.3.5 Discussion

The COF between skin and the bar decreases over time when no magnesium is used. This can be caused by the wetness of the finger due to transpiration and therefore, the increased contact area.

The COF of the bar and skin increases at first

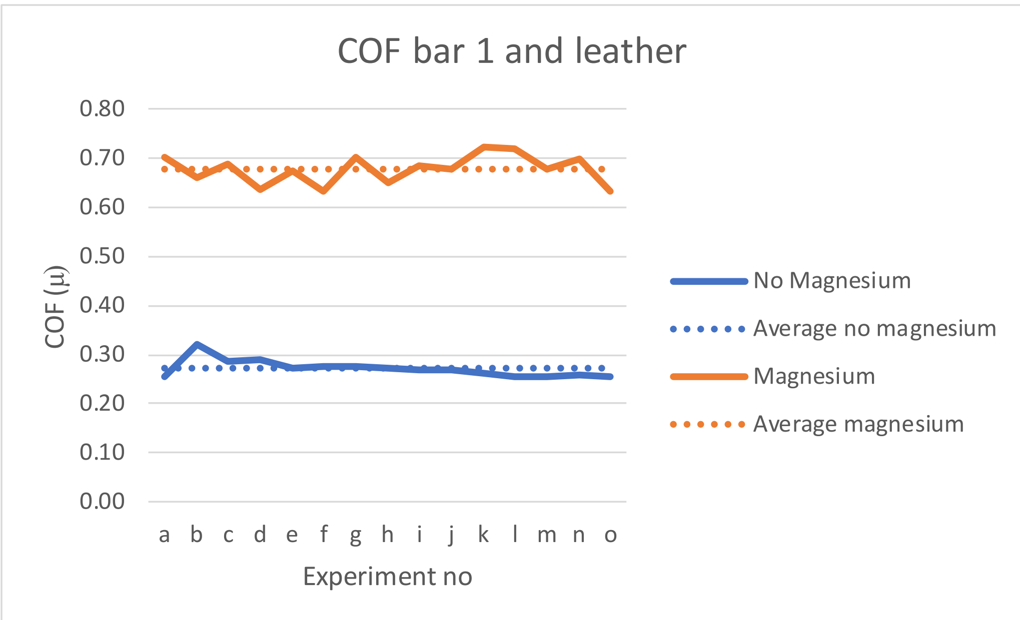

Figure 46 - Coefficient of friction for bar 1 and leather. The COF is more than doubled when magnesium ($\mu = 0.68$) is used in comparison to no magnesium ($\mu = 0.27$). It is also noticeable that the COF is more inconsistent when magnesium is used.

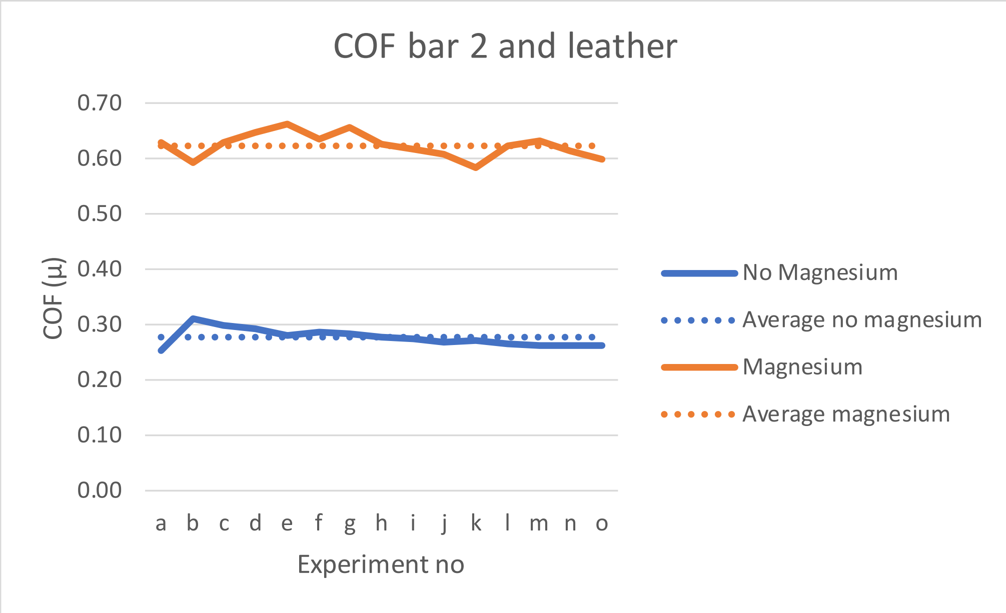

Figure 47 - Coefficient of friction for bar 2 and leather. The COF is again more consistent when no magnesium is used. The average COF for magnesium (μ = 0.62) is double as no magnesium (μ = 0.28).

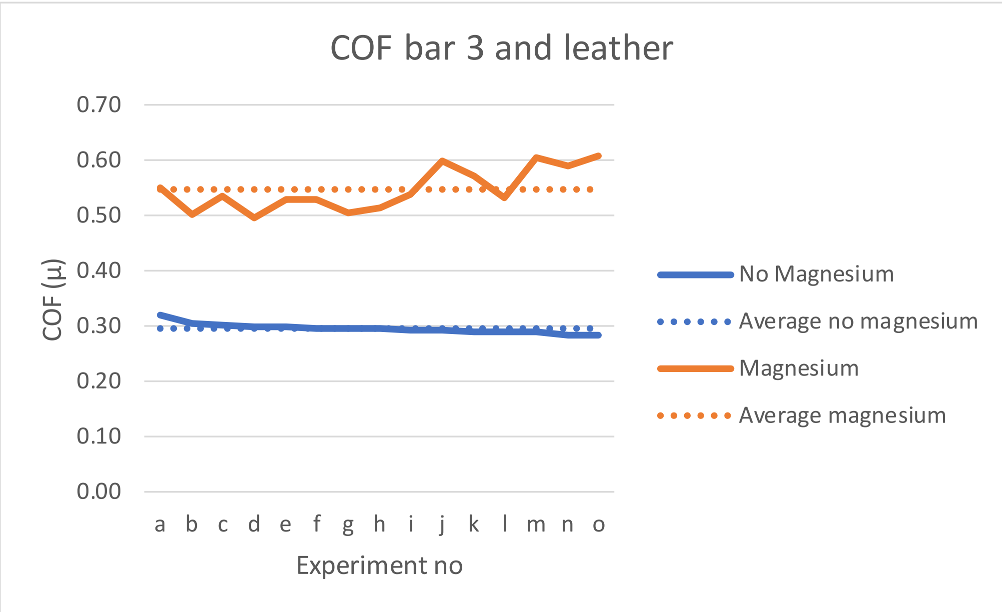

Figure 48 - Coefficient of friction between bar 3 and leather. The friction coefficient for no magnesium is extremely consistent and is almost the same as the average. The magnesium again gives an erratic course. However the COF is much higher (μ = 0.55) than when no magnesium (μ = 0.30) is used.

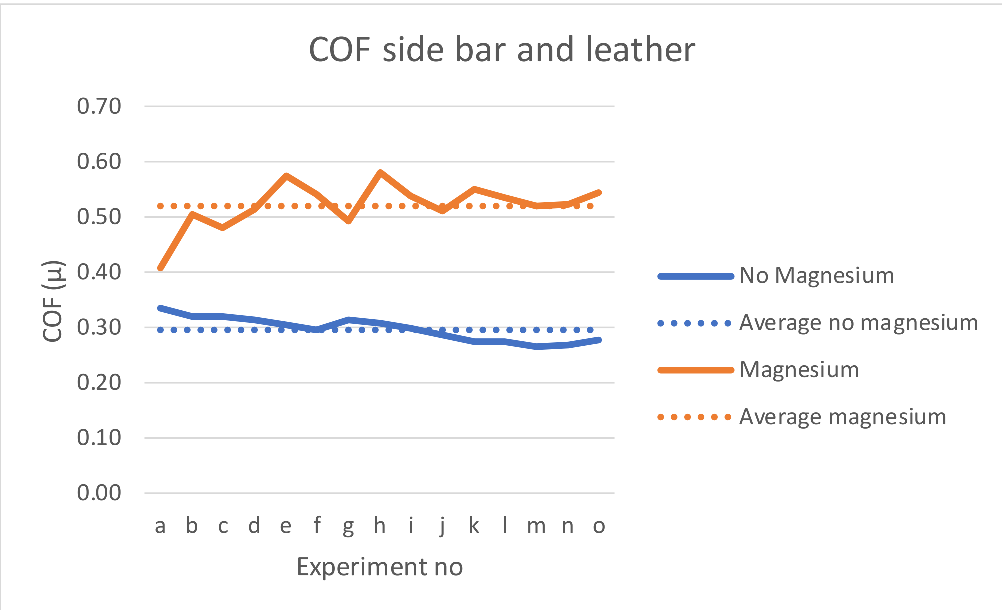

Figure 49 - Coefficient of friction of the side piece of the bar and leather. The COF when no magnesium is used is less consistent as at the bars discussed before. However, it is still more consistent than the magnesium. Differences are smaller between the friction coefficients. $\mu_{no\ magnesium} = 0.30$; $\mu_{magnesium} = 0.52$.

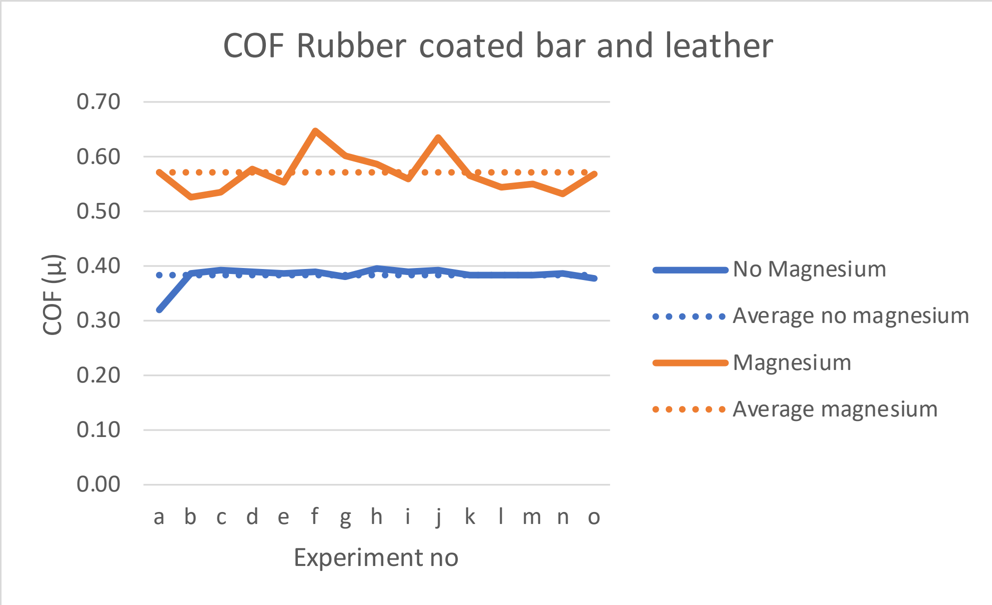

Figure 50 - Coefficient of friction between rubber coated bar and leather. There is a difference between the friction coefficients, whereas with skin these friction coefficients where the same. The average coefficient of friction for no magnesium is 0.38 and with magnesium is 0.57.

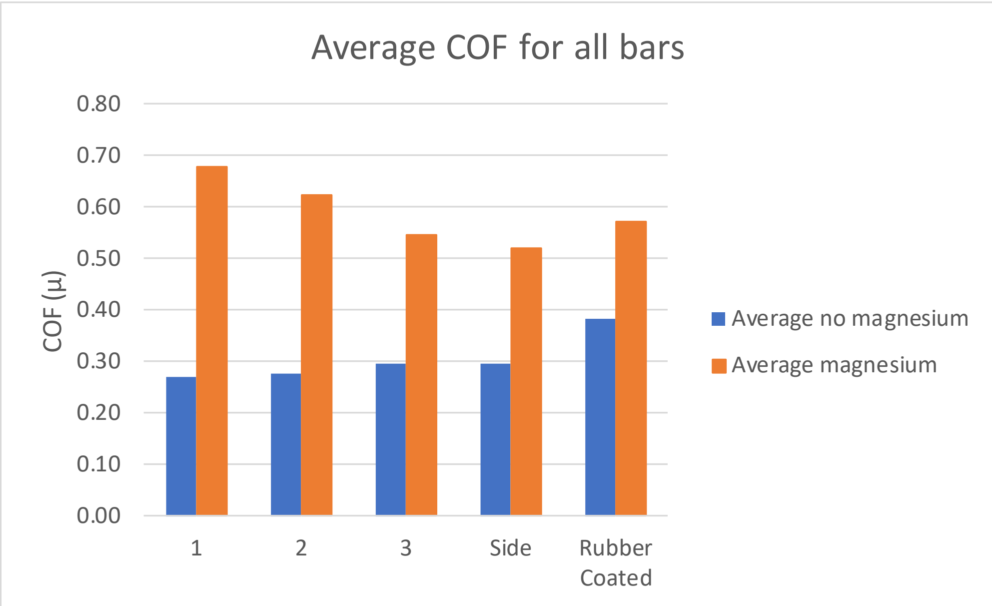

Figure 51 - Averages of the coefficients of friction. All bars show higher coefficients of friction when magnesium is used. Little differences are shown between the bars when no magnesium is used. Only the rubber coated is slightly higher. Also the third and side bar have little higher values than bars 1 and 2. Which is the opposite of skin. When magnesium is used however, the coefficients of bars 1 and 2 are higher than for the other bars.

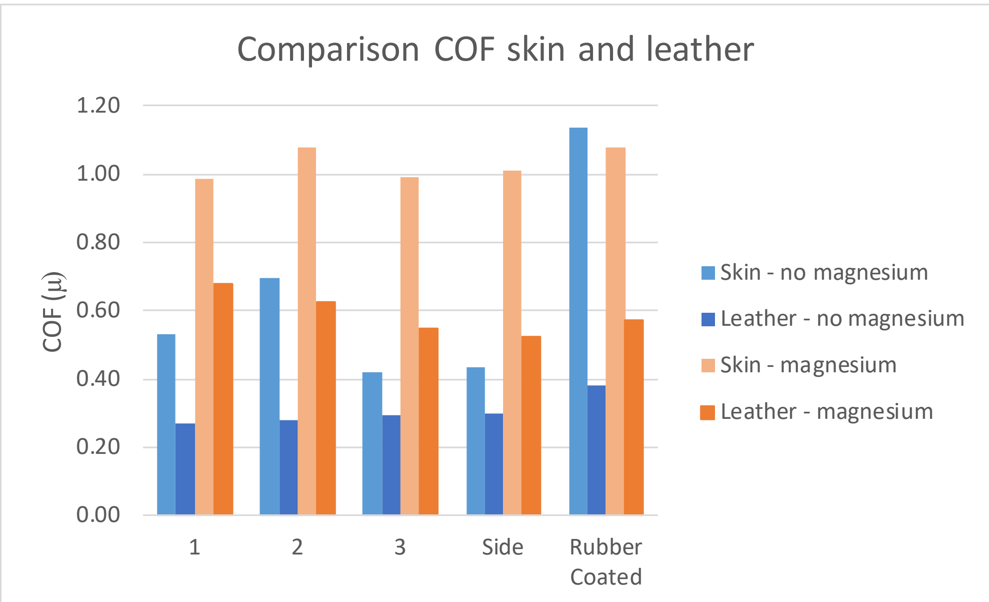

Figure 52 - Comparison of the coefficients of friction for skin and leather with and without magnesium. It is visible that the COF is in all situations much higher for the finger than for leather. In some cases the friction coefficient is even higher for a finger without magnesium than for leather with magnesium (bar 1, bar 2, side bar and rubber coated bar).

when magnesium is used and then stays relatively constant. The increase can be allocated to the fact that the bar is not covered with magnesium yet. During the experiments, more magnesium sticks to the bar, which leads to covering the bar.

When all coefficients of friction between bars and skin are compared the friction coefficients of bar 3 and side are much lower than the rest. However, when magnesium is used, the coefficient of friction is about the same as bar 1 and just slightly lower than bars 2 and rubber coated. This shows that magnesium causes higher coefficients of friction and that the use of magnesium is more important for the coefficient of friction than the surface roughness.

The standard deviation show lower values when magnesium is used. The lower standard deviation can be caused by the magnesium, which absorbs all the water, giving less different contact areas and thus coefficient of friction. Other possibility is that the time it took to put on some magnesium, gave the skin enough time to un-squeeze, leading to more standardized fingertip in comparison to no magnesium.
The coefficient of friction stayed constant for leather and the bar when no magnesium was used. This could be due to no or little deformation of the contact area. When magnesium is used the COF was highest for bar 1 and 2, while those had the lowest friction coefficients without magnesium. The magnesium may create a larger contact area when it sticks into the valleys of the veneer surface.

The standard deviation of leather is lower than for skin. This is most probably caused by the less or no changing contact area.

3.3.6 Conclusion

The coefficient of friction increases when magnesium is added. This is in correspondence with literature [30]. This is for both skin as for leather grip. The highest coefficient of friction is callculated for the rubber coated bar. Another interesting finding is that the coefficient of friction is much lower for leather than for skin. However, gymnasts have no interest in giving up the grips. Most heard is that the gymnast get more blisters when they do not wear the grips. This could be caused by the higher friction at the skin. The skin is also more protected by the leather which can give a more comfortable feeling. For this experiment the flat smooth side of the grip is used. This has the same properties as new grips. Grips which are used for a longer period of time in contact with a bar surface could have different coefficients of friction.

3.4 Grip and COF

3.4.1 Results

As can be seen in Figure 53, the magnesium causes that the gymnasts give higher grip grades. The magnesium causes also higher COF (Figure 54 and Figure 55). However, the grades were not consistent with the COF for skin. As can be seen in Figure 54 the COF for bar numbers 1 and 3 with magnesium is about the same. However the grade given by the gymnasts differs significantly. Bars 2 and 3 without magnesium however get almost the same grades (respectively 2.38 and 2.25), but have COFs which differ a lot from each other (respectively 0.90 and 0.50). The opposite is happening between bar 1 and 2 (no magnesium). The COFs are almost the same, however, the grip grade differs much more than between bars 2 and 3.

A contradiction is found when one considers the grip grade in comparison to the coefficient of friction of the leather. The highest COF is measured in bar 3, however this bar gets the lowest grip grade. Bars 1 and 2 have almost the same COF and have slightly lower values for friction than bar 3, however the grip grade is higher for bar 1. The grip grades for magnesium are more consistent with the COFs. Both bar 1 and 2 show the same grip grade. The COF is slightly lower for bar two but is still in the same range. Bar 3 has a little lower coefficient of friction and also a lower grade.

The grip grade for bar 1 without magnesium is the same as bar 3 with magnesium. The coefficient of friction with leather is however more than twice as high for bar 3.

3.4.2 Discussion

The perceived grip is not consistent with only the coefficient of friction. Grip is thus a factor which is described by more parameters. Roughness could be a parameter which influence the perception of grip. However, the data in this research was too irregular to compare with the grip grade. Secondly, not only physical parameters such as the coefficient of friction and roughness are important, also some mental parameters should be kept in mind. The gymnasts had a high preference to use magnesium. This is consistent with the outcome of the coefficient of friction measurements. However, the looks of the bar had a large influence on their choices. Hence, it can be concluded that the currently selection grip grade is inconsistent in comparison to the friction coefficient.

3.5 Discussion experiments

The bar used in the experiments is sanded down by hand. This led to uneven sanded areas on each part. This could be improved if the bar rotated constantly and a sandpaper of the exact width would sand down the bar for a precise amount of time. Due to the length of the bar, no roughness data and coefficients of friction were available before the experiments started. It could be interesting to see if the coefficient of friction and the roughness of the bar changed during the experiment with the gymnasts. However, this will always be difficult because of the length of the bar.

3.5.1 Grip grade

The results about the experience with each bar part differ a lot for all gymnasts. Only eight subjects did this test. More gymnasts should participate in this test to see if the results would become more consistent or stayed inconsistent. At this moment the questionnaires between the swings were long. It could cause the gymnasts to forget how the previous bars felt. Also could it be helpful if the gymnasts could compare the different bar parts with each other. Or instead of giving a grade for grip, they could compare the bar parts with each other and rank which bar gives most and which the least grip.

At last, the gymnasts are biased by the look of the bars and the use of magnesium. The bar which looked the most bad (bar 3), scored lower than the rest. However, it is hard to do the experiment blind. The gymnasts can be lifted to the bar, preventing them to see the bar. However, the use of magnesium will be felt.

3.5.2 Roughness

The roughness of the bar needed to be measured in the rotational direction. This made it hard to measure the surface roughness, since normally the surfaces are flat. The only possible way of measuring this surface roughness was with a confocal microscope. Only small pieces could be measured due to the time needed per piece. The roughness was different for all measurements, making it hard to compare the bars with each other. A general description is given for the surface topography. However, this is based on the average data from the measurements. To see if the surface actual looks like the description, more research should be performed.

No relation is found between the grip grade and the roughness. Therefore, the roughness and surface topography could be ignored when searching for a new material.

3.5.3 Coefficient of friction

The results from the experiment to determine the coefficient of friction were clear and in line with each other. However, the experiment is performed with only one finger of one subject (no gymnast) on one spot of the bar. For a more average result related to gymnasts, more subjects, preferably female gymnasts, should be tested. At this moment also one spot of each bar is tested. This is done to have a more constant result. If different spots and both the left and right bar part would have been examined, more could be told about the bar part in general.

It would have been better if there was more time in between the experiments to let the finger recover from the previous measurement. The finger was sometimes still squeezed when the next measurement was started. Also, the sweat is not been removed between the measurements. The measurements are now 30 seconds long. This is quit long, since normally a routine during competition takes about 50 seconds. During this time they regularly make flight elements, leaving the bar. A better time for the experiments would be 10 seconds.
The coefficient of friction measured is much higher for the fingertip than for the leather. Hence, it would be better for their grip if gymnasts did not use grips. However, the gymnasts will not stop using the leather grips, since they give more protection to blisters. For these measurements, the layer under the leather is made out of metal, instead of a finger. This could have influenced the measured COF, since little deformation was noticed.

The coefficients of friction measured in this research are different then when measured under normal circumstances. When one wants to compare the COFs with other measurements, a test should be performed to see what the differences are for the COFs measured with this machine and with a flat surface. Ones it is known what the differences are, the COFs can be compared.

3.6 Conclusion experiments

On the basis of the answers given by the gymnasts, part 1 with magnesium is found to be the best. Part 2 is runner up, with almost the same points. The gymnasts gave higher grip grades when they used magnesium. The roughness measurements are inconsistent and cannot be compared to the experienced grip. It is however possible to describe the surface as flat with small curvy peaks and deep steep narrow valleys. The coefficient of friction is highest when magnesium is used. The coefficient of friction between the bar and skin is higher than between the bar and a leather grip. The coefficient of friction is not the only parameter that influences the experienced grip.

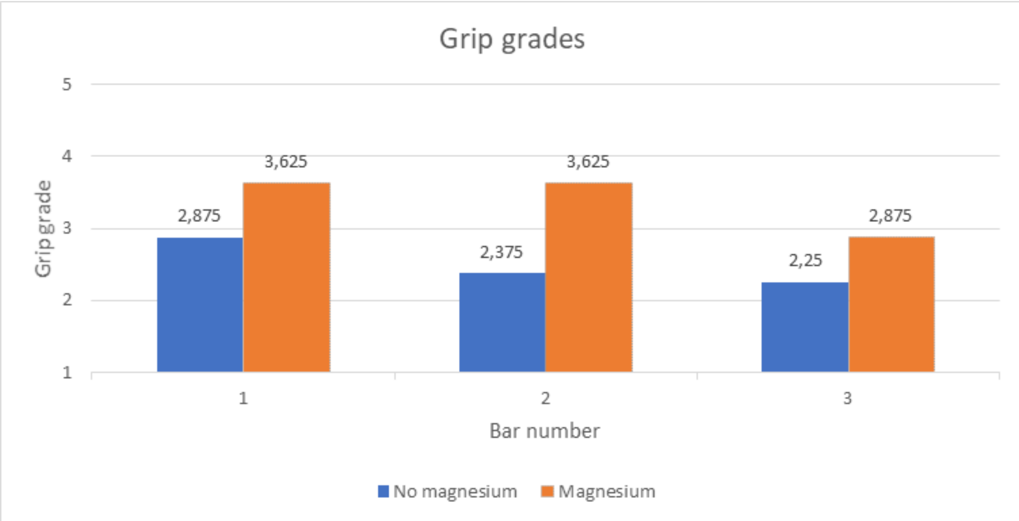

Figure 53 - Average grip grades given by the gymnasts. 5 is maximum grip; 1 is no grip. All bars have higher grip grades when magnesium is used.

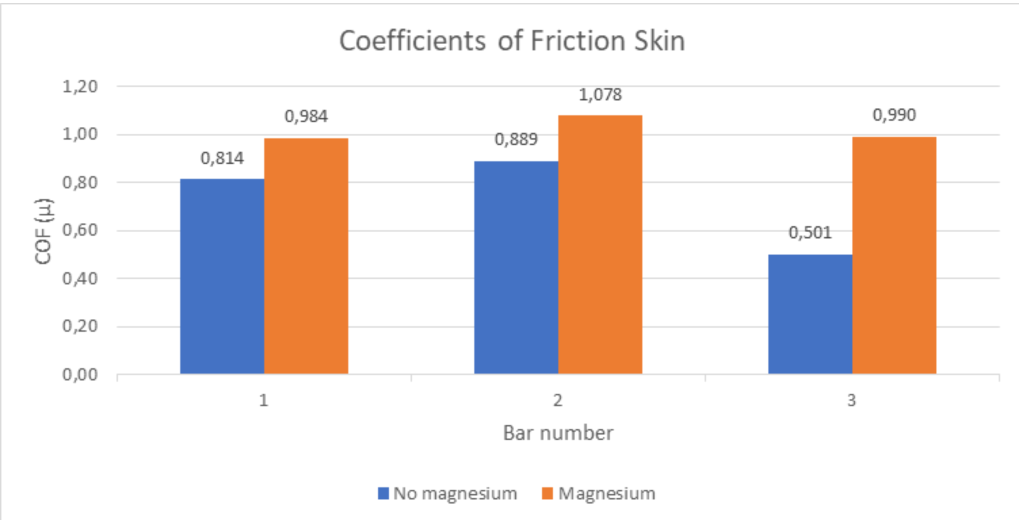

Figure 54 - The coefficient of friction between skin and bar measured for all bars. The COF is for all bars higher when magnesium is used.

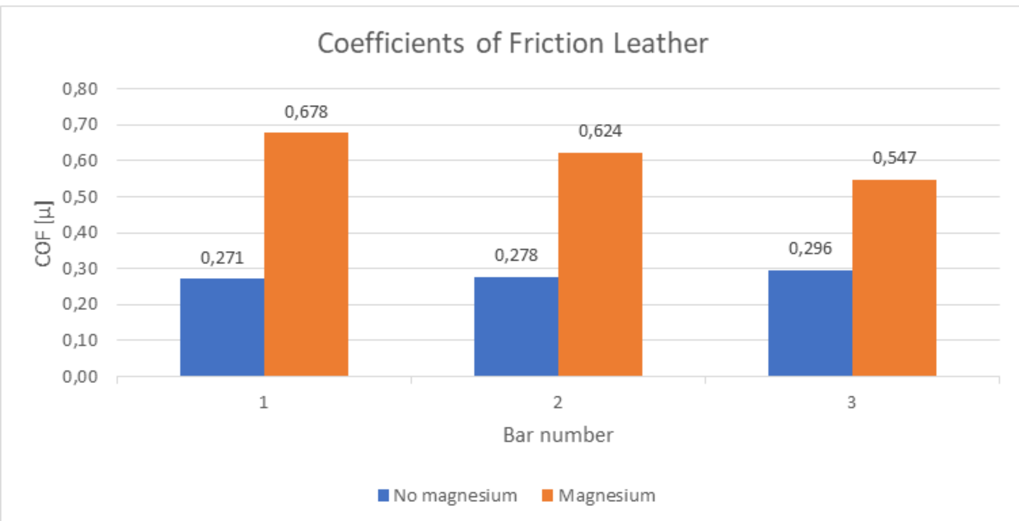

Figure 55 - Coefficients of friction for leather. Higher coefficients of friction are noticed when magnesium is used.

RESULTS

4

THE RESULTS FROM THE DIFFERENT STUDIES ARE TAKEN INTO ACCOUNT TO MAKE A PROGRAMME OF REQUIREMENTS AND TO SEARCH TO A NEW MATERIAL.

4.1 Programme of requirements

Based on the analysis a programme of requirements was set. These requirements were based on the norms set by the FIG and NEN-EN, the demands of the trainer of TON, and properties of bars from articles. Also some general requirements and wishes are set according to the wishes of the company.

4.1.1 Measurements

- The diameter of the bar is 40 mm ± 1 mm. (According to FIG & NEN-EN 915 norms)
- The length of the bar is 2400 mm ± 10 mm. (According to FIG & NEN-EN 915 norms)
- The distance between the sockets must be at least 200 cm ± 1,0 cm. (According to FIG norms)

4.1.2 Appearance

- The bars retain the natural colour of wood. They are neither lacquered, nor polished. (According to FIG norms)
- The bar has a core of fibreglass.

4.1.3 Grip

- The bar surface must provide a good glide and turn capability but may not be slippery. (According to FIG norms)
- The surface cannot be too rough, leading to injuries. (According to NEN-EN 913 norms)
- The bars' surface must absorb moisture, to ensure grip stability. (According to FIG norms)
- [Wish] No magnesium powder or grips are needed to have enough grip.

4.1.4 Surface roughness

- The surface should be flat with deep steep valleys.
- The valleys should be deeper than that the peaks are high

4.1.5 Wear

- The bars can be used twice as long as now.
- [Wish] The bars can be used for at least a couple of years of extreme use[1], before wear is too large.
- The outer layer does not splinter off while using the bar for gymnastics.
- Within 6 months, the core should not become visible, due to wear.

4.1.6 Safety

- The bars must be secured (reinforced) against breaking through. (According to FIG norms)
- The bar will not break, during normal use[2].

4.1.7 Mechanical properties

- When the bar is pulled down vertically, with a tractive force of 1350 N ± 20 N, the minimal deflection is 40 mm and the maximal deflection is $70 \leq x \leq 100$ mm. (According to FIG & NEN-EN 915 norms)
- When a pendulum from horizontal position is released the maximal positive vertical deflection is $80 \leq x \leq 120$ mm. (According to FIG norms)
- When a pendulum from horizontal position is released the maximal negative horizontal deflection is $-41 \leq x \leq -26$ mm. (According to FIG norms)
- When a pendulum from horizontal position is released the maximal positive horizontal deflection is $46 \leq x \leq 71$ mm. (According to FIG norms)
- When a pendulum from horizontal position is released the maximal force must be $1500 \leq x \leq 1800$ N. (According to FIG norms)
- The bar should withstand a maximum force of 4 times body weight or 4205 N. [43] [46]
- When a pendulum is pulled vertically downwards with an initial tension of 1000N ± 30 N the maximum frequency of oscillation is $2.50 \leq x \leq 3.50$ Hz. (According to FIG norms)
- When a pendulum is pulled vertically downwards with an initial tension of 1000N ± 30 N the half amplitude interval is $350 \leq x \leq 5700$ ms. (According to FIG norms)

1 Extreme use: the bars are used more than 4 hours a day, for almost every day of the week all year around.

2 Normal use: using the bars as they were intended to, not for improper use.

4.1.8 Norms

- The bar fulfils all norms and specifications set by NEN-EN.
- [Wish] The bar fulfils all norms and specifications set by NEN-EN and FIG.
- Bar is usable for trainings, with about the same specifications as the competition bars.
- [Wish] The bar can be used for competitions at high level. (Related to fulfilling FIG requirements)

4.1.9 Costs

- [Wish] The selling price should be in the same price range as the current model.

4.2 New material

4.2.1 Introduction

Research is performed on the cause of the problem, the current experiences of grip and bar characteristics. The outcome of this research will be used in the search for a new, improved material. The material should fulfil a couple of requirements to fit for the job. A complete list of requirements can be found in the programme of requirements. A couple of these requirements are material based, such as water absorption, hardness and flexibility. Some others are depending on the surface or on both surface and material, such as surface roughness, surface typography and coefficient of friction. Things such as appearance and surface roughness are not taken into account in this material search. Both can be adjusted later in the process.

4.2.2 CES

To start the search for a new material, the material properties of both beech and birch transverse are investigated in more detail. The program CES Edupack 2016 level 3 is used to investigate these properties. Since it was not clear which species of beech and birch are used in the bars, the averages of all birch and beech are calculated. The average of all properties can be found in Table 5.
Grip is perceived higher when the surface energy of a material is higher [18].

4.2.2.1 Production methods

Not only the material properties take a role in the material selection, also production methods influences the selection. Since the sales numbers are low; and the bar is long, 2.2 m, little automated high series production processes are suitable. There are a couple of possibilities for the production process. It is possible to adjust the existing bar by adding things such as a coating or to make a bar from scratch, where a top layer will be added over a glass fibre core.

Options for adding the top layer are: (1) Bending sheet material around the core; (2) Using a sleeve which will be slid over the core; (3) Attach material directly to the core; (4) Adjust the standard bar. Example production methods are: (1) Buying standard sheet material and bend it around the bar, such as the current veneer; (2) Extrude, mould or print a tube or pipe or buy standard pipes with correct diameters and slide it over core; (3) Spraying material over core (such as coating) or mould over core directly; (4) Add coating or extra layer over the

	Birch average	Beech average
Density	681 kg/m3	694 kg/m3
Young's modulus	1.74 GPa	2.19 GPa
Poisson's ratio	0.03	0.03
Hardness Vickers	5.46 HV	5.77 HV
Compressive strength	7.27 MPa	7.04 MPa
Flexural strength	6.01 MPa	5.57 MPa
Fatigue strength at 10^7 cycles	1.80 MPa	1.67 MPa

Table 5 - Properties of birch and beech wood. The average of different kinds of birch and beech wood is used in this table.

wood veneer.

4.2.2.2 Material selection

From Table 5 the minimum values of the new material(s) are determined. The most important property that has to be improved is the hardness. Therefor the minimal hardness is set on 5.5 HV[3] and the maximum is 30 HV, since a too hard surface may cause problems during gymnastics. The fatigue strength should be over 1.8 and the maximum price per kg is set to €15. The maximum flexural modulus is set at 1.1 GPa. Under 1 GPa materials are mentioned as flexible materials, which is important for the bending of the bar. A number of processing and durability properties are set as usable. The following properties are set on limited use; acceptable and excellent: Polymer injection moulding, polymer extrusion, polymer thermoforming[4], water (fresh) and weak alkalis. See Table 6.

All materials that have passed the criteria set in Table 6 are showed in the chart in Figure 56.

3 Not all materials have a hardness which is measured in Vickers. All the materials which did not have a HV hardness are therefore not selected.

4 Due to the settings of polymer forming, only polymers were selected by the program.

Hardness	5.5 - 30 HV
Fatigue strength	> 1.8
Price	< €15/kg
Flexural modulus	< 1.1 GPa
Polymer injection moulding	Limited use, acceptable, excellent
Polymer extrusion	Limited use, acceptable, excellent
Polymer thermoforming	Limited use, acceptable, excellent
Water (fresh)	Limited use, acceptable, excellent
Weak alkalis	Limited use, acceptable, excellent

Table 6 - Set criteria the new material needs to meet.

Water absorption is an important factor to take into account. However, it is not possible to set this requirement in the first material selection. The selected materials (beginning with the lowest density), are looked into to find the water absorption and the surface energy. The higher the surface energy the better grip is perceived [18]. Table 7 shows the values of water absorption and surface energy for the materials. Since PA has the best values for both water absorption and surface energy, this material will be looked into closer. Since different kinds of PA

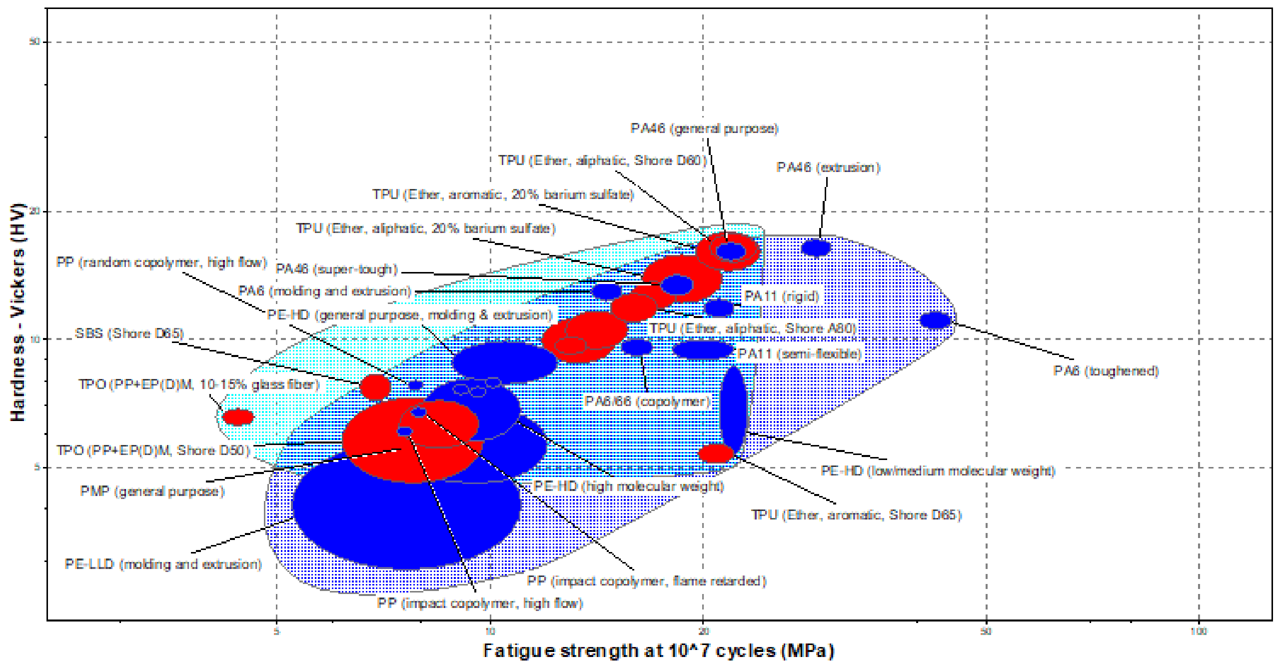

Figure 56 - All materials which past the set requirements. The materials are placed in a diagram with on the x-axis the fatigue strength and on the y-axis the hardness. Best materials which fulfil the set requirements could be found at the right upper corner.

Material	Water absorption	Surface energy
PMP	0.0091-0.011%	24 mJ/m^2 [47]
TPO	0.0136-0.0165% 0.00907-0.011%	25.8-38 mJ/m^2 [48]
PP	0.0195-0.0205%	30.1 mJ/m^2 [49]
SEBS	0.05-0.06%	Not found
PE	0.005-0.01%	35.3-35.7 mJ/m^2 [49]
PA	0.59-0.96%	40.7-46.5 mJ/m^2 [49]
SB	0.07-0.09%	Not found
COC	0.001-0.01%	Not found
TPU	0.07-0.09% 0.7-0.9% *	Not found

*Table 7 - Water absorption and surface energy of the selected materials. * All types of TPUs have water absorption values between 0.07-0.09%. Only TPU (Ether, aromatic, 20% barium sulfate) has 0.7-0.9% which is ten times higher than the other values. This could therefore be a mistake in the data of CES Edupack 2016.*

	Price (€/kg)	*Density (kg/m^3)*	*Young's modulus (GPa)*	*Yield strength (MPa)*	*Tensile strength (MPa)*	*Flexural modulus (GPa)*	*Poisson's ratio (-)*	*Hardness Vickers (HV)*
PA46 (extrusion)	9,64	1180,00	1,00	55,05	72,00	0,90	0,41	16,50
PA46 (general purpose)	9,64	1200,00	1,00	54,05	54,65	0,90	0,39	16,20
PA46 (super-tough)	8,79	1095,00	0,60	45,05	45,90	0,55	0,41	13,50
PA6 (moulding and extrusion)	3,60	1140,00	1,06	43,40	36,55	0,85	0,35	13,05
PA6/66 (copolymer)	3,48	1090,00	0,78	32,15	40,20	0,78	0,35	9,63
PA6 (toughened)	4,12	1085,00	0,88	37,20	106,20	0,37	0,35	11,15
PA11 (rigid)	14,10	1030,00	1,20	39,75	52,50	1,20	0,41	11,90
PA11 (semi-flexible)	14,40	1035,00	0,48	29,50	50,00	0,48	0,41	9,50

Fatigue strength at 10^7 cycles (MPa)	*Water absorption (%)*	*Polymer injection moulding*	*Polymer extrusion*	*Polymer thermoforming*	*Water (fresh)*	*Water (salt)*	*Weak alkalis*
28,80	3,45	Acceptable	Acceptable	Limited use	Acceptable	Acceptable	Acceptable
21,85	3,45	Acceptable	Acceptable	Limited use	Acceptable	Acceptable	Acceptable
18,35	3,00	Acceptable	Acceptable	Limited use	Acceptable	Acceptable	Acceptable
14,60	2,50	Excellent	Acceptable	Limited use	Excellent	Excellent	Limited use
16,10	2,20	Excellent	Acceptable	Limited use	Excellent	Acceptable	Limited use
42,40	2,15	Excellent	Acceptable	Limited use	Excellent	Excellent	Limited use
21,00	0,89	Excellent	Acceptable	Limited use	Excellent	Excellent	Excellent
20,00	0,30	Excellent	Acceptable	Limited use	Excellent	Excellent	Excellent

Table 8 - All sorts of Polyamide with their properties.

materials exist, the material will be investigated further to see the possible processes and the best materials. Only PA materials are filtered to see which materials would fulfil all these requirements.

These materials are sorted by water absorption percentage. As can be seen, PA46 has the best water absorbing capabilities. PA46 super though has the lowest flexural modulus of these materials, meaning that it is the less stiff.

4.2.2.3 Quest

Instead of looking at the material properties, the experienced grip between skin or grip and the material is most important. However, there are no programs such as CES Edupack with this kind of data. It has to be noticed that water absorption is not used as a requirement anymore. The main purpose of magnesium is to absorb water. Therefore, this requirement is no longer considered a priority but as a wish.

In general rubbers and silicones have higher coefficients of friction and could give more grip. A set of materials which is replacing natural rubbers more and more are Thermal Plastic Elastomers (TPEs). These are thermoplastic elastomers which are mostly low modulus, flexible materials which can stretch a lot [50]. There are different types of TPEs, traditional and new entrants. The traditional TPE classes are: Styrenics (S-TPE's), Copolyesters (COPE's), Polyurethanes (TPU's), Polyamides (PEBA's), Polyolefin blends (TPO's) and Polyolefin Alloys (TPV's). New entrant TPE classes are Reactor TPO's (R-TPO's), Polyolefin Plastomers (POP's) and Polyolefin Elastomers (POE's) [50]. All TPE classes have their own properties.

All these materials are individually investigated with the program CES Edupack. PEBA material can be bended and stretched easily without damage. Using PEBA D40, the Vickers Hardness is between 10.2 and 10.8 HV. This is harder than the used wood veneer. No coefficient of friction can be found between PEBA and skin. The material is also known for its stretch abilities and soft feel. The material needs to be ordered to see if it can fulfil the requirements.

Since there are little production methods possible or feasible, the possible production method should also be taken into account. The best way to add the material on the core is to use a sheet of PEBA and bend it. However, this is dependent on the flexibility of the material. It is also possible to 3D print with PEBA [51]. The top layer should be divided in multiple pieces and be connected to each other to achieve the length.

4.2.2.4 Coatings

After the quest to a completely new material, the quest has continued to coatings to apply at the wood or directly at the core. A coating which could fulfil the requirements is called Rilsan [52]. The coating absorbs water and has the properties of Polyamide. However, the processing temperature to apply the coating is too high for the fibreglass. A coating which needs lower processing temperatures, is a PPA coating. However this coating has a hardness which is too low. There has been no research to coatings without the water absorbing ability.

4.2.2.5 Existing solutions

Pommel horse handles

Apart from researching completely new materials, also already existing materials which are used in different products and different fields are reviewed. The handles of the pommel horse (men's gymnastics) used to be of wood. Since a couple of years a hygroscopic coating is used on aluminium handles. The coating is appreciated by the gymnasts since they have more grip. The material was quickly tested by grabbing the handle and rotate the hand around it. Due to small particles in the coating which give more grip, the handle did not feel comfortable for rotating movements. Also some water was added to the handle. The water was not absorbed directly, while the handles of wood directly absorbed the water.

Plasti Dip coating

Plasti Dip coat is a coating which is used to spray on cars. The coating is rubbery like and can be easily pealed of a car whenever one wants. Plasti Dip has a hardness of Shore A 70, which is lower than wanted. This layer will be a sacrificial layer, which will abrade instead of the main material. The coating can easily be added again, leading to a longer life time. Applying the Plasti Dip coating can easily be done in the factory and is cheap for individual bars.

Thicker veneer layer

Another possible solution is to endure the life time of the bar. If the veneer layer is twice as thick, the bar should be resistant to abrasive wear twice as long. However, thickening the veneer layer is not as easy as it sounds. If the veneer is to thick, it is hard to bend around the core without cracking the wood. Therefore, two layers of thinner veneer can be placed on the wood. Different problems could appear. The shear and cleavage stresses will most likely increase, leading to fatigue. Another problem which could appear is when the first layer of wood is worn off and the glue layer in between the veneers gives grip problems. The process of adding veneer is individual process and cannot be fabricated at the factory at this moment.

Other materials

Other options which were explored are Kevlar, a shrink film and adding non-slip grit to epoxy. All these options are not possible to use. The Kevlar is strong, however, to make it stiff epoxy need to be added. It is also known for its delamination. The epoxy makes the material slippery. The non-slip grits are relatively large. This gives an uncomfortable feeling, which is about the same as the feeling with the hygroscopic coating of the pommel horse. The materials of the shrink film are not suitable to use.

4.2.3 Experimental

From the materials which fulfilled the first set of requirements, PA has the best values for both water absorption and surface energy. To see if this material is as good in practice as it is in theory, a sample is ordered. After receiving the sample it was quickly clear that this material would not give the gymnasts enough grip. The material felt extremely slippery and did not absorb water immediately. The water made the material even more slippery.
After a long quest, no samples of PEBA were found to order. The material is only available in raw material to use in the production. Hence, no sample is ordered and no tests could be done.

The Plasti Dip coat was added on a small part of a bar. It was expected that the bar would feel like a silicone material. However it felt much less sticky. The coefficient of friction has been tested in the coefficient of friction test described before. These tests show that the coefficient of friction is higher than for normal wood. The rubber coated bar part will be brought to the gymnasts of TON. They will be asked if they like the feeling, if they think it gives enough grip and if it does not give too much friction.

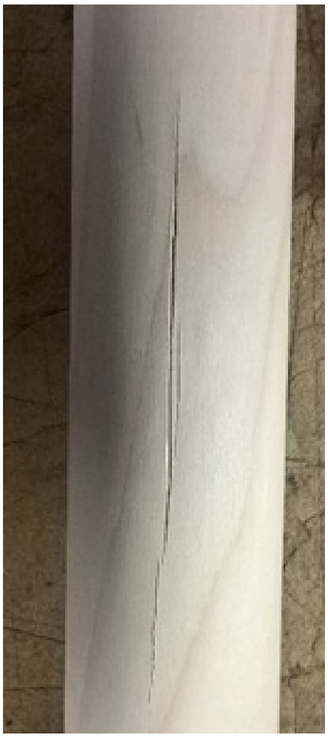

Figure 57 - Cracks in newly added veneer layer

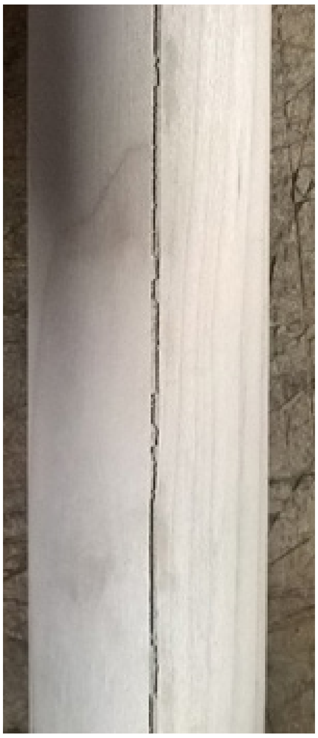

Figure 58 - Seam of the newly added veneer layer. A big irregular gap visible at the seam.

To test the idea of a double veneer layer, an extra layer of veneer is added by a woodworker on a standard bar. As shown in Figure 57 the extra layer of veneer shows cracks before use. The seam has a gap between both ends of the veneer (Figure 58). If this solution does work, the veneer has to be applied by someone who is more specialized in adding veneer on bars. The bar with an extra layer of veneer was tested by the gymnasts of TON. During the tests the gymnasts were asked for their experiences and the wear was monitored during use.

4.2.4 Results

4.2.4.1 Double veneer

The gymnasts indicate that the bar feels more slippery than a normal bar. However, after a few rounds of exercises they are used to the feeling. This slippery feeling can be caused by the use of another wood species than usual. Most do not feel that the bar is slightly thicker than normal. When asked, the gymnasts indicate that the bar is slightly stiffer than normal. After about an hour the bar shows a crack in vertical direction. This started just after some heavier exercises were performed. The crack bended outward during the rest of the exercises, leading to a bump. As is shown in Figure 59. After approximately two hours, the bar showed some wrinkles (Figure 60). Both the crack (right hand) as the wrinkles (left hand) showed at the places where the hands hold the bar. It could be possible that these faults are due to production mistakes. Therefore, the bar is further tested during practice at TON. The trainer observed the wear during the practices and kept in contact to give feedback about the wear. After another day of testing, the bar is not used anymore due to the slipperiness, dimension differences and higher stiffness.

4.2.4.2 Rubber coating

The trainers were positive about the feel aspects of the coating. The gymnasts were concerned that they would slip off the bar. Since the trainers and the coefficient of friction measurements were positive, it will be discussed within the company to test an entire bar with Plasti

Figure 59 - Vertical crack after an hour of routines. The crack is bends outwards, creating a bump.

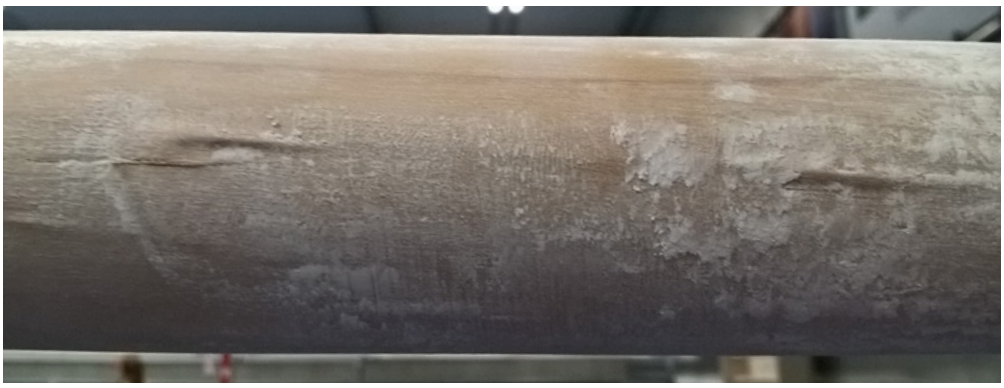

Figure 60 – Wrinkles at the bar appeared after approximately two hours of use.

Dip coating. This bar can be tested in the near future in the same way as the double veneer bar.

4.2.5 Conclusion new material

Polyamide or Nylon is not a suitable candidate to replace the wood material. PEBA could be able to fulfil the requirements, however, since no sample could be ordered, no tests could be performed and thus no hard conclusions can be drawn.

The slipperiness of the double layered veneer bar could be caused by the use of another wood. This wood had approximately the same hardness. The top layer came out slipperier than expected. It was expected that the gymnasts would feel the small difference in diameter. However, only when they were informed of the differences, did they not like the feeling anymore. The stiffness of the bar was a big problem. Even though the bar was just a little bit stiffer, the gymnasts did not like the stiffness. After just two hours, wear was already visible. Even though it was not abrasive wear, it could not be used for a longer period of time.

The rubber coated part had good grip according to the trainers. However, the gymnasts thought that they would slip off. The trainers held the part without any grips or magnesium. The gymnasts held it when they just finished training on a normal bar wearing grips and with magnesium on their hands. Since just a little part was coated, no gymnast could test the bar in a normal situation. To test this possible solution a standard bar should be coated with the Plasti Dip.

In Appendix H the possible solutions are compared with the programme of requirements. The extra veneer layer fulfils the requirements set by the FIG. However, after testing it became clear that the lifetime of the bar heavily decreased. No abrasive wear was found, however, grip decreased due to the fatigue wear and wrinkles in the top veneer layer. The rubber coating should be tested if it gives gymnasts more grip and if the hardness is high enough to increase lifetime.

4.3 Discussion

4.3.1 Programme of requirements

At this moment a couple of norms and requirements are in the programme of requirements, which should not be there. For example the norms set by FIG about the deflection of the bar are not interesting for this research. Some requirements set by the FIG could become wishes, such as the colour of the bar and the water absorption.

4.3.2 New material

The possibilities of searching a new material are quite low due to the measurements of the bar and the low production numbers. During the quest to a new material to much attention is spend to the set requirements, causing that to little research is done to other options. Some selected production processes led to only plastic materials. The hardness in Vickers led that some materials were not selected, since no Vickers hardness was known in the program. Both mistakes came up after the research, when no time was available anymore to start a new quest. For a follow up study it is recommended to fill in not only Vickers hardness, but also other hardness values. Also the production processes and water absorption should kept out of the settings.

Three options are mentioned as possible solutions. All need to be tested further before a conclusion can be drawn about the solution. The extra veneer layer does not have a harder surface and the lifetime decreased. The rubber coating should be tested if it hard enough and if the friction is not to high, causing blisters. This could be easily done by spraying another bar with Plasti Dip coating and test it in the same manner as is done with the double veneer bar. PEBA is a different story. It is hard to find a sample to test the material for coefficient of friction and tactility. Therefore, it is not considered as a possible solution. However, when a sample is available, it could be tested to see if the material would fulfil the requirements. The COF test should take place on the same machine for good comparison.

4.4 Conclusion

A programme of requirements is made with the norms set by the FIG and NEN and the wishes from the trainer. The search to a new material to replace the wood to improve grip for a longer period of time has been done. The best grip is experienced with Plasti Dip coating. The hardness of the coating is low, and therefore a test should be done to see if the Plasti Dip resists abrasive wear.

A solution to double the lifetime of the wood veneer and thus a larger perceived grip for a longer period of time did showed difficulties in the application part of the production. The second layer of wood started cracking after an hour and wrinkles became visible after two hours. The gymnasts did not like it that the bar became stiffer due to the extra layer of veneer. The material that fulfilled most requirements from the programme of requirements is the Plasti Dip coating. However, more tests need to be conducted to see if this coating does resist abrasive wear.

5 CONCLUSION

5.1 Literature research

Grip is to hold very tightly and help gymnasts to hold onto the bar and not fall off. Most grip research is performed on friction and less on the perception of grip. Optimal grip according to literature can be achieved by a high coefficient of friction, a large surface contact area and a smaller diameter to make grasping easier. Higher coefficients of friction can be gained by a moist or damped skin, a low surface roughness or extreme high surface roughness, a negative skewness, a high surface energy and low skin temperature.

Magnesium is used on almost all gymnastic apparatuses to prevent gymnasts hands from blisters and to increase torsion with the apparatus. The grip enhancement agent reduces sweat and increases grip. According to Pušnik and Čuk and Amca et al. the coefficient of friction increases when magnesium is used.

During a system analysis different bars were investigated on wear. The dowels of the leather grips cause abrasive wear when the gymnast hangs on the bar. The abrasive wear is visible on the same place of every bar.

A analysis has taken place to find changes over time of the routines, the grip materials and the bar to see were the wear comes from. No changes were found during this analysis.
It is possible that small changes which are not noticed in this research combined caused the bigger problem leading to grip problems. It is possible that the quality of the bars deteriorated and specific craftmanship was replaced by cheaper production processes. Both are speculations made by the author and no direct link could be found between the changes over time and the perceived grip and fast wear.

FIG and NEN have set norms to assure safe uneven bars. The outer layer of the uneven bars should provide the bar with a good slide and turn capability while not being slippery. The surface cannot be too rough, causing any injuries. To improve grip, the bar should absorb water. Last but not least the bar should look like it is made out of wood. However, the bars do not have to be made out of wood. A top gymnastic coach of TON has mentioned that the stiffness of the bar needs to be the same. The surface of the bar should give enough grip but should not lead to blisters. The norms and wishes were taken into account in the design process.

5.2 Experiments

The amount of grip and the amount of friction and bar roughness were experimentally assessed. The gymnast perceived highest grip at bars with little visible wear. All gymnasts gave higher grip marks when they used magnesium then when they did not use magnesium.

The roughness measurement of the bar parts differed significantly for every line measurement. Therefore, only an estimation of the surface typography could be made. The surface of the bar is flat with deep valleys and small curvy peaks.

The coefficient of friction is experimentally determined for skin and the bar parts and for a leather grip and the bar parts. Measurements of the normal and friction force are done for both situations without and with magnesium. For all situations a higher coefficient of friction was calculated when magnesium was used over when no magnesium was used. Skin and bar contact showed higher coefficients of friction than leather and bar contacts. The highest coefficients of friction were calculated for skin and the bar with rubber coating. For leather the highest coefficient of friction was also calculated with the rubber coated bar. The use of magnesium did not change the coefficient of friction.

The coefficients of friction are compared with the grip grades. No similarity could be found. Hence, grip grades are not only depending on the coefficient of friction.

5.3 Results

A programme of requirements has been made with the norms and wishes set by the FIG and NEN and by the trainer of TON. In the search to a new material two possible options are tested. An extra layer of wood veneer is added to a standard bar. During testing different kinds of wear were visible. The durability of the bar was shorter than normal. This is therefor not the ideal solution. Another option that is tested is a bar part which is coated with Plasti Dip. This is a rubber coating which showed high coefficients of friction with both skin as leather. The trainers of TON liked the perceived grip. The gymnasts were in doubt if they would slip off. Due to the positive feedback a whole bar should be tested in the near future the test the durability and grip.

5.4 Overall

The research question for this thesis was: Could grip and durability be improved by changing the surface of uneven bars?
Grip can be improved by adding a couple of layers of Plasti Dip coating. The coefficient of friction increases significantly and less magnesium needs to be used. No durability data is known yet and durability tests should be performed in the near future.

RECOMMENDATIONS

The grip experiments are performed with just 8 gymnasts. The current results differ too much to generalize grip. If the experiment is repeated, more gymnasts need to participate. It has to be considered how to do this time wise, since the gymnasts cannot swing whit magnesium when others are not finished yet without magnesium. This can lead to long waiting times. The questionnaires which are used now are too long to test efficiently. It would be better to shorten the questionnaires to one page and preferably, with little writing.

At this moment the roughness is measured with a confocal microscope. This gives precise measurements, however, it only can scan a small area at the time. A stylus measurement would be preferable. To measure the roughness around the bar, a test rig could be build, similar to the test rig build for the coefficient of friction. The bar can rotate around its own axis, and the stylus is fixed on a certain position in combination with a spring. With this current set up the roughness could also be measured when the bar is still over two meters long.

The measurements to calculate the coefficient of friction are done with only the index fingertip of the researcher. To improve the results multiple female gymnasts should participate to this test. Also different spots of each bar should be measured. In the current leather measurements, the leather was span over a metal block. It is recommended to make a block that has the same properties as a fingertip to replace to metal block. Also the contact area should be taken into account.

In the current material search the norms set by the FIG are taken as guidelines. However, this let to little creative thinking. It would be recommended to think more out of the box and to drop the norms.

The extra layer of veneer on the standard bar was added by a local woodworker. The results were not as good as hoped. It is recommended to redo the extra layer of veneer by someone with more experience. The used wood should also be rougher, so the magnesium sticks to the wood and will be less slippery.

At last it is recommended to test a bar which is prepared with Plasti Dip coating. Not only should the grip be tested, also the durability of the solution. If the durability is good a relatively cheap solution has been found.

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APPENDICES

Appendix A

Description manufacturers

Manufacturer / Distributor	Description
M1	Wood laminated break-resistant fibreglass carbo-flex bar [56]
M2	Glass fibre bar with beech veneer [57]
	Glass fibre bar with laminated birch wood [57]
M3	Glass fibre bar, round model with wood casing [58]
M4	Constructed of a hollow fiberglass core with a wood veneer securely laminated around the outside [59]
M5	Fibreglass rails [60]
	Fibreglass section with timber veneer bonded to the surface [60]
	Thin European Beech veneers are laminated under extreme heat and pressure to produce superwood [60]
M6	New bars consisting of carbon glass fibre covered with birch veneer for better dynamics and a faster reaction time [61]
M7	Made from a fibre glass rod covered with wood [62]

Appendix B

Evaluation of wear problems for different bars

Bar 1

The first bar has several worn patches. There is a piece of tape at the left side. Next to that is a small worn patch. At the right side is a very long worn patch. In the middle is a small one. The core of the bar looks insensitive rough.

Figure 61 - Bar 1: overview

At left side tape is wrapped around the bar. I have not looked underneath the tape to see why it is taped.

Figure 62 - Bar 1: tape around bar

At the left side is a small worn patch. A small piece flew off . This left worn patch is a little bit lower than the right worn patch. As can be seen in the picture below, the worn patch is pretty splintery.

Figure 63 - Bar 1: fatigue

On the right-hand side is a very large worn patch. The entire wood veneer has chipped off. It is like

Figure 64 - Bar 1: fatigue

In between these two worn patches is a small worn patch. This patch is hardly splintery.

Figure 65 - Bar 1: abrasive wear

Bar 2

This bar has one big worn patch over a long length, one big worn patch over the width and a couple of smaller patches. The core is very smooth.

Figure 66 - Bar 2: Overview

In the middle is are two worn patches that are connected to each other. There are different stages of wear visible. The wood veneer is slowly sanded down, there is no difference in height noticeable. Underneath the veneer is a soft fabric-like material visible. A part of this material is sanded down as well. However, the height difference is both visible as noticeable for this material. See the picture below. The shiny white part is the layer beneath the soft material layer. This shiny material is very smooth.

Figure 67 - Bar 2: abrasive wear

At the right side of the bar is also a large worn patch. This patch is over the width of the bar and continues after the seam. The kind of wear is about the same as the worn patch described above.

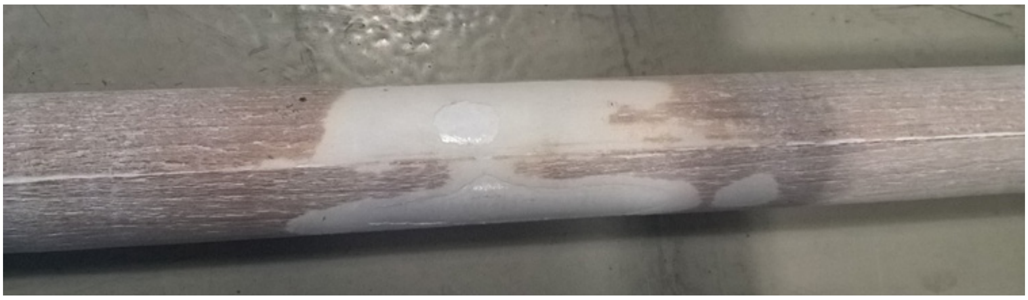

Figure 68 - Bar 2: abrasive wear

At the right-hand side some smaller patches are found.

Figure 69 - Bar 2: abrasive wear

Also at the seam wear is visible.

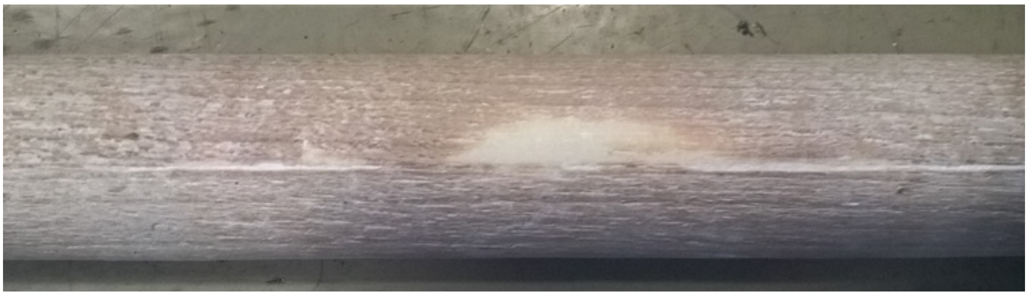

Figure 70 - Bar 2: visible seam

Bar 3

This bar looks different than all the other bars. The woodgrain is twisted along the bar, whereas with other bars this grain is over the length. In spite of the twisting of the woodgrain, the seam is in the length direction of the bar.

Figure 71 - Bar 3: overview

Between the lines of the woodgrains, cracks have developed. Under the crack is still wood visible. See the pictures below. The cracks look like they are very painful for gymnasts to turn around, because the wood sticks out.

Figure 72 - Bar 3: crack

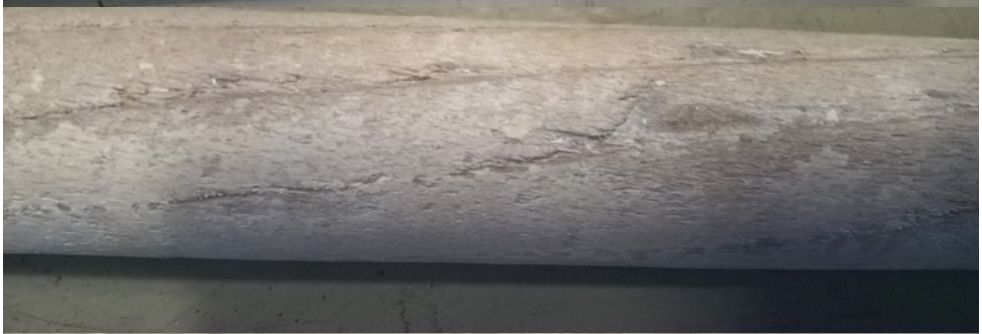

Figure 73 - Bar 3: twisted woodgrain

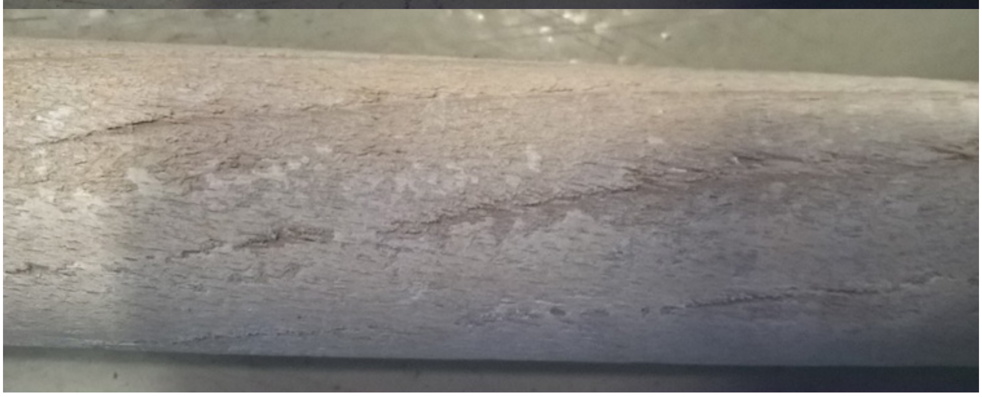

Figure 74 - Bar 3: twisted woodgrain

At some points the woods structure is sanded off. Therefore, the bar looks like wood, without the roughness of wood.

Figure 75 - Bar 3: abrasive wear

Bar 4

This bar has red marking around or at places of wear. It is not clear yet if the users have marked this wear or that it is an inner layer which warns users for wear. There is, in comparison to other bars, small wear. However, the wear looks like sufficient wear to not use it anymore. Underneath the wood is directly a shiny, smooth surface. There is no inner layer.

Figure 76 - Bar 4: overview

At the right side is the largest worn patch, which are actually two patched next to each other. The wear is as well gradually as set backed.

Figure 77 - Bar 4: abrasive wear with red layer

At the left side and the middle, just some little patches are visible. Some are worn off until the underlying layer, others only show some redness.

Figure 78 - Bar 4: abrasive wear with red layer

Bar 5

The veneer of this bar is completely cracked. There are no other worn patches noticeable. There is one main crack which has smaller cracks in length and width directions. The cracks are completely splintered and have delaminated the veneer. The veneer is now set in an angle. Under the horizontal crack is a soft fabric-like material visible.

Figure 79 - Bar 5: Cracked veneer

Figure 80 - Bar 5: Cracked veneer outward angle

Figure 81 - Bar 5: cracked veneer

Figure 82 - Bar 5: cracked veneer

Bar 6

This bar has in total four bigger worn patches. Two at the left side and two at the right side. The patches are at two different heights and are above each other. The layer underneath the wood has a green look and has a certain roughness.

Figure 83 - Bar 6: overview

Left side

Figure 84 - Bar 6: left side abrasive wear

Top left

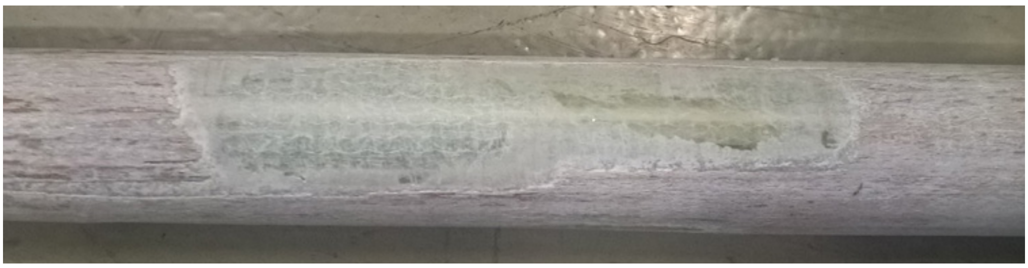

Figure 85 - Bar 6: Abrasive wear top left

Bottom left

Figure 86 - Bar 6: abrasive wear bottom left

Right side

Figure 87 - Bar 6: abrasive wear right side

Top right

Figure 88 - Bar 6: top right abrasive wear

Bottom right

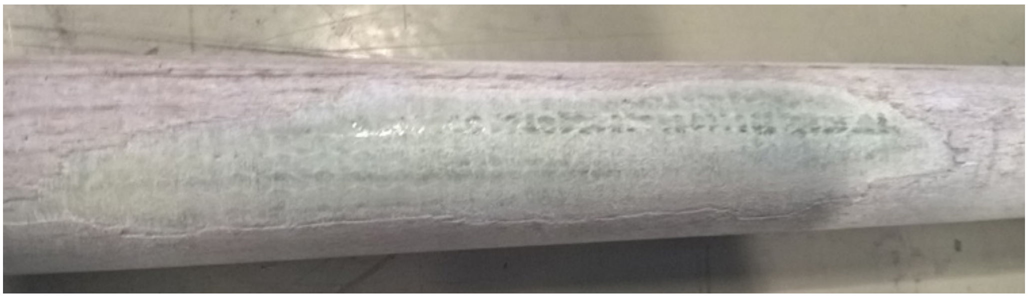

Figure 89 - Bar 6: bottom right abrasive wear

Bar 7

This bar has one enormous worn patch in the middle. The outer sides (length sides) are splintery. There is both wear as chipped of pieces of wood. Below the wood surface is a green looking glass fibre.

Figure 90 - Bar 7: overview

At the left-hand side some pieces of wood have chipped off. Mainly on the most left part of the worn patch pieces have chipped off. More to the middle it is more sanded off.

Figure 91 - Bar 7: fatigue and abrasive wear

In the middle of the worn patch it is clearly visible that the upper side is sanded off, whereas the lower side looks more like it has chipped off. This is mainly visible in the middle of the picture below. At one place, there is no magnesium visible. This has to be chipped of in ones.

Figure 92 - Bar 7: fatigue and abrasive wear

At this right side it is clearly visible that the edges are splintery. The edges on the smaller side of the patch are more smoother and look more like the worn off, whereas the right side of the patch more looks like it has chipped of.

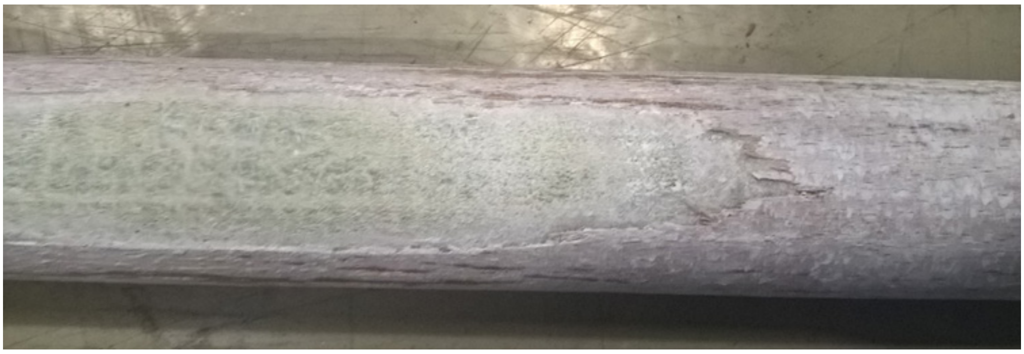

Figure 93 - Bar 7: fatigue

Bar 8

At this bar the worn patches are marked with red. This bar has one big worn patch at the front side. This is worn off until the glass fibre material. The fibreglass is very smooth. At the back is a smaller patch, which has mostly a redness to it and less texture of the wood.

Figure 94 - Bar 8: overview

The bigger worn patch is at the front in the middle of the bar. At the left side some more wear is visible in red. The wear is until the fibreglass.

Figure 95 - Bar 8: abrasive wear

The backside only redness is visible. The wood texture is sanded of, but the fibreglass core is not yet reached. There are multiple worn patches at the backside. See the two pictures below. At the left is the biggest patch, in the middle a very small one and at the right side is a bigger patch which is not that deep.

Figure 96 - Bar 8: abrasive wear

Figure 97 - Bar 8: abrasive wear

At the seam is a small piece of wood chipped off.

Figure 98 - Bar 8: fatigue

Bar 9

This bar has three mayor places of wear. Two at the right side, above each other, and one on the left side, at the height of upper right worn patch. Below the wood is a green glass fibre visible.

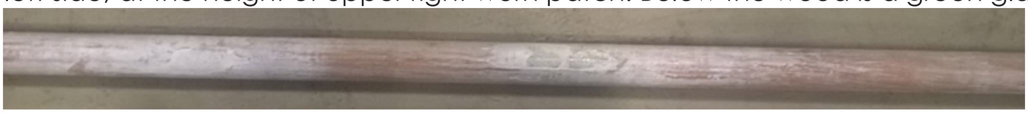

Figure 99 - Bar 9: overview

At the right upper worn patch is still a lot of glue-like material visible. Some places are also clearly chipped off, while others are more worn off.

Figure 100 - Bar 9: glue visible

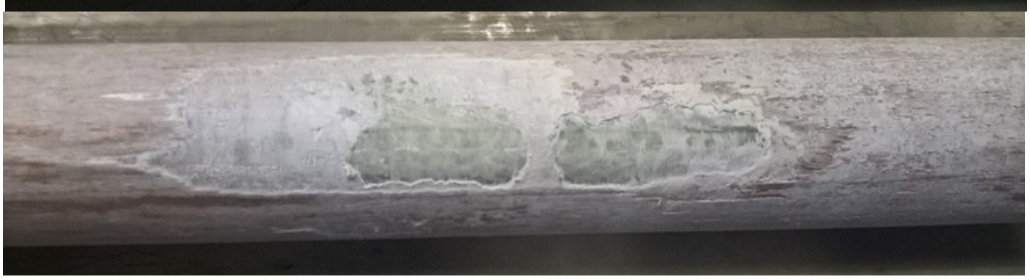

Figure 101 - Bar 9: fatigue and abrasive wear

At the upper left side glue is also clearly visible. The green lower layer is not visible yet, but this is also caused by the magnesium.

Figure 102 - Bar 9: lots of magnesium

At the lower right side the worn patch has some clear places were the wood has chipped off. Besides, it has a very visible and noticeable glue layer between the wood and the fibreglass. This glue is very rough and feels as if the gymnasts would tear open their hands when using this bar.

Figure 103 - Bar 9: fatigue

A the lower left side a small worn patch has been found at the seam. This is chipped off.

Figure 104 - Bar 9: worn patches at seam

Appendix C

FIG Apparatus Norms & Specification

FIG Apparatus Norms WAG 2 Uneven Bars (01.01.2015)

Page	**Alinea**	**Norm**
51	Measurements	Diameter of bars is 4,0 cm *0,1 cm
		Length of bars is 240 cm *1,0 cm
		Distance between the sockets is minimal 200 cm *1,0 cm
52	Functional properties	Both bars must have the same, uniform elasticity. To assure this, their supports must be articulated.
		The bar surface must provide a good glide and turn capability but may not be slippery
		To ensure grip stability, the bars' surface must absorb moisture
		The bars must be secured (reinforced) against breaking through
	Colour	The bars retain the natural colour of wood. They are neither lacquered, nor polished.

FIG Testing Procedures WAG 2 Uneven Bars (11.05.2010)

<table>
<tr><th>Page</th><th>Alinea</th><th>Norm</th></tr>
<tr><td>2
3
4</td><td>14.1.1
Table 1
19.2.1</td><td>When the bar is pulled down vertically, with a tractive force of 1350 N ± 20 N, the maximal deflection is 70 ≤ x ≤ 100 mm.
<table>
<tr><th colspan="2">Test A: Static traction stress</th></tr>
<tr><td colspan="2">Upper bar</td></tr>
<tr><td>Deflection (mm)</td><td>70 ≤ x ≤ 100</td></tr>
<tr><td colspan="2">Lower bar</td></tr>
<tr><td>Deflection (mm)</td><td>70 ≤ x ≤ 100</td></tr>
</table>
</td></tr>
<tr><td>2
3</td><td>14.1.2
Table 2</td><td>When a pendulum from horizontal position is released the maximal force must be 1500 ≤ x ≤ 1800 N</td></tr>
<tr><td></td><td></td><td>When a pendulum from horizontal position is released the maximal positive vertical deflection is 80 ≤ x ≤ 120 mm</td></tr>
<tr><td></td><td></td><td>When a pendulum from horizontal position is released the maximal negative horizontal deflection is -41 ≤ x ≤ -26 mm</td></tr>
</table>

		When a pendulum from horizontal position is released the maximal positive horizontal deflection is 46 ≤ x ≤ 71 mm

Test B: Stress by pendulum swing	
Upper bar	
F_{max} (N)	1500 ≤ x ≤ 1800
Positive vertical deflection (mm)	80 ≤ x ≤ 120
Negative horizontal deflection (mm)	-41 ≤ x ≤ -26
Positive horizontal deflection (mm)	46 ≤ x ≤ 71
Lower bar	
F_{max} (N)	1500 ≤ x ≤ 1800
Positive vertical deflection (mm)	80 ≤ x ≤ 120
Negative horizontal deflection (mm)	-41 ≤ x ≤ -26
Positive horizontal deflection (mm)	46 ≤ x ≤ 71

2 **3** **4**	14.1.3 Table 3 19.4.2	When a pendulum is pulled vertically downwards with an initial tension of 1000 N ± 30 N the maximum frequency of oscillation is 2.50 ≤ x ≤ 3.50 Hz
		When a pendulum is pulled vertically downwards with an initial tension of 1000 N ± 30 N the half amplitude interval is 350 ≤ x ≤ 5700 ms

Test C: Oscillation damping	
Upper bar	
Frequency of oscillation (Hz)	2.50 ≤ x ≤ 3.50
Half amplitude interval (ms)	350 ≤ x ≤ 5700
Lower bar	
Frequency of oscillation (Hz)	2.50 ≤ x ≤ 3.50
Half amplitude interval (ms)	350 ≤ x ≤ 5700

NEN-EN norms

NEN-EN 913-2008 (en)

Page	**Alinea**	**Norm**
5	5.1	Rough surfaces should not present any risk of injury
7	5.3.1	Unless specified elsewhere in individual equipment standards verification of the stability and strength of equipment shall be achieved by engineering calculation or by testing in accordance with the procedures specified in Annex B.

	5.3.3	When tested in accordance with Annex B, equipment shall not collapse or fracture, or show any permanent deformation that would result in an additional safety hazard as described in the standard.
13	B 1.1	A test force is determined by combining a body load, a static load and a variable load and applying appropriate dynamic and safety factors $F_t = m_b * a * C_d * S + F_s + L_v$
	B 1.3	The human body mas to be used is based on the 95th percentile of the distribution of body masses expected to be encountered.
14		For use by adults or by adults and children this shall be taken as 94 kg
	B 1.4	Preferably, the dynamic factor should be determined from the average of factors measured experimentally in tests with a typical range of persons carrying out the movement in question. In the absence of such data the factors given in Table B.2 shall be assumed. **Dynamic factor** / **Horizontal acceleration** **Bar & exercise**: 2.5 / 20 m/s_2
	B 1.5	For the purposes of this standard the safety factor shall be taken as 1.2 unless the product standard specifies a higher figure for high risk equipment.
16	B 3.1	Unless otherwise specified in the product specification the load shall be applied over the area and/or the time given below.
	B 3.2	Loading area bars: strap (100 ± 1) mm wide
	B 3.3	Loading time: Apply the load for (65 + 5) s Measure residual deflection (45 ± 15) s after removal of load

NEN-EN 915-2008 (en)		
Page	**Alinea**	**Norm**
4	3.2	The diameter of the bar profile shall be circular (40 ± 1) mm
5	Fig. 1	Length of the bar is 2400 ± 10 mm
6	4.4	When each bar is tested in accordance with 5.3 using a force of 1350 N ± 50 N, the deflection of each bar shall be a minimum of 40 mm and a maximum of 100 mm. The residual deflection shall be no greater than 1 mm.
	4.6	When tested in accordance with 5.2, the bar at the supporting cup point shall not deflect by more than 20 mm in the longitudinal or the transverse direction when subjected to horizontal forces of 570 N ± 20 N in each of these directions. Transverse forces shall be applied to the middle of the bar and perpendicular to its length. Longitudinal forces shall be applied along the axis of the bar.

7	5.3.1	A vertical force is applied to the centre of each bar and any deflection is measured. The force is then removed and any residual deflection is measured.
8	5.4.1	The equipment is loaded with a vertical force and examined for fracture or other damage.

Conflicting and related norms

FIG	NEN-EN	Conflicting or related?
Diameter of bars is 4,0 cm *0,1 cm	The diameter of the bar profile shall be circular (40 ± 1) mm	✓
Length of bars is 240 cm *1,0 cm	Length of the bar is 2400 ± 10 mm	✓
Distance between the sockets is minimal 200 cm *1,0 cm		
Both bars must have the same, uniform elasticity. To assure this, their supports must be articulated.		
The bar surface must provide a good glide and turn capability but may not be slippery	Rough surfaces should not present any risk of injury	× The roughness of the bars should not be too high, leading to injuries. The NEN norm is a general norm to prevent injuries. The FIG norm is to provide the best possible bar.
To ensure grip stability, the bars' surface must absorb moisture		
The bars must be secured (reinforced) against breaking through		
The bars retain the natural colour of wood. They are neither lacquered, nor polished.		
When the bar is pulled down vertically, with a tractive force of 1350 N ± 20 N, the maximal deflection is 70 ≤ x ≤ 100 mm.	When each bar is tested in accordance with 5.3 using a force of 1350 N ± 50 N, the deflection of each bar shall be a minimum of 40 mm and a maximum of 100 mm. The	× The FIG norms do not show a minimum deflection. The maximum deflection is the same. Both norms show that a deflection is mandatory.

	residual deflection shall be no greater than 1 mm.	
When a pendulum from horizontal position is released the maximal force must be 1500 ≤ x ≤ 1800 N		
When a pendulum from horizontal position is released the maximal positive vertical deflection is 80 ≤ x ≤ 120 mm		
When a pendulum from horizontal position is released the maximal negative horizontal deflection is -41 ≤ x ≤ -26 mm		
When a pendulum from horizontal position is released the maximal positive horizontal deflection is 46 ≤ x ≤ 71 mm		
When a pendulum is pulled vertically downwards with an initial tension of 1000N ± 30 N the maximum frequency of oscillation is 2.50 ≤ x ≤ 3.50 Hz		
When a pendulum is pulled vertically downwards with an initial tension of 1000N ± 30 N the half amplitude interval is 350 ≤ x ≤ 5700 ms		
	When tested in accordance with 5.2, the bar at the supporting cup point shall not deflect by more than 20 mm in the longitudinal or the transverse direction when subjected to horizontal forces of 570 N ± 20 N in each of these directions. Transverse forces shall be applied to the middle of the bar and perpendicular to its length. Longitudinal forces shall be applied along the axis of the bar.	

Appendix D
Questionnaire after every serie (in Dutch)

Naam: ______________________

Serie: 1 ○ 2 ○ 3 ○ Magnesium: Ja ○ Nee ○

1. Hoe voelde de ligger aan?

Hard	○	○	○	○	○	Zacht
Warm	○	○	○	○	○	Koud
Effen	○	○	○	○	○	Oneffen
Ruw	○	○	○	○	○	Glad

2. Had je voldoende grip om deze vijf reuzezwaaien te maken?

○ Ja

○ Nee, omdat ______________________

____

2.1. Waar in de zwaai verloor je (bijna) je grip en waarom had je geen grip meer?

____

____

____

3. Heb je het gevoel dat je voldoende grip had om hier een hele oefening op te turnen?

○ Ja

○ Nee, omdat ______________________

____

4. Als je in het algemeen de grip die je had moet uitdrukken in een cijfer, waarbij 1 helemaal geen grip is en 5 de maximale grip. Welk cijfer zou je grip dan geven voor deze ligger?

Geen grip 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ Maximale grip

5. Ik vind deze ligger fijner/minder fijn/even fijn* als een net nieuwe ligger. Waarom?

____

____

____

*Doorhalen wat niet van toepassing is

6. Zat er verschil tussen links en rechts? Zo ja, wat was er anders?

○ Nee

○ Ja, ______________________

____

____

7. Doet de ligger pijn aan je handen?

○ Nee

○ Ja, namelijk blaren / splinters / te veel wrijving / anders ______________________

8. Voelde de ligger comfortabel aan?

○ Ja

○ Nee, omdat ______________________________

9. Als jij zou mogen bepalen, zou je dan blijven turnen op deze ligger of zou je deze ligger afschrijven? Waarom?

9.1. Maakt het uit hoe versleten de ligger eruit ziet bij deze keuze?

Questionnaire after all series (in Dutch)

Naam: ______________________________

1. Wil je bij een ligger liever meer grip of meer snelheid kunnen maken? En waarom?

1.1. Zit hierbij verschil tussen trainingen en wedstrijden?

2. Geven magnesium en rekleertjes je meer vertrouwen op de brug?

3. Geven rekleertjes en magnesium je meer comfort?

4. Wat bepaalt grip voor jou? Denk aan grootte ligger, ruwheid, rekleertjes, rolletjes van leertje, warm/koud gevoel, zweet/droog, hard/zacht, effen/oneffen, etc.

5. Als je zou mogen kiezen, wat vind je dan fijner? Een herenrekstok van metaal of een damesligger van glasvezel met hout. Waarom? Denk aan diameter, grip, snelheid maken, wrijving, doorbuiging, etc.

6. Hoe zou jij je ideale ligger beschrijven? Denk aan diameter, materiaal, doorbuiging.

7. De liggers zijn op dit moment gelijk afgeschuurd. Normaal zijn ze op een punt veel verder versleten dan op andere plekken. Merk je een verschil tussen de liggers die je vandaag hebt getest en waar je normaal op traint?

7.1. Welk soort slijtage vind je prettiger om nog op te trainen, volledig afgeschuurd of op een punt afgeschuurd?

7.2. Wat vind je prettiger turnen, een ligger waarbij de fineer weggeschuurd is of een ligger waarbij het fineer afgeknapt is? Waarom?

Appendix E

Combined results grip data

Gezamenlijk

Serie	1NM	1M	2NM	2M	3NM	3M	GEM Z	GEM M	GEM 1	GEM 2	GEM 3	GEM TOT
1. Hoe voelde de ligger aan?	(1t/m5)	(1t/m5)	(1t/m5)	(1t/m5)	(1t/m5)	(1t/m5)	(1t/m5)	(1t/m5)	(1t/m5)	(1t/m5)	(1t/m5)	(1t/m5)
Hard/zacht												
G1 (grips)	3	3	3	3	3	3	3,00	3,00	3,00	3,00	3,00	3,00
G2 (grips)	3	3	4	3	2	3	3,00	3,00	3,00	3,50	2,50	3,00
G3 (grips)	2	2	2	2	2	2	2,00	2,00	2,00	2,00	2,00	2,00
G4 (no grips)	2	2	2	2	2	2	2,00	2,00	2,00	2,00	2,00	2,00
G5 (grips)	1	1	1	1	1	1	1,00	1,00	1,00	1,00	1,00	1,00
G6 (grips)	2	4	4	4	4	3	3,33	3,67	3,00	4,00	3,50	3,50
G7 (grips)	3	3	3	3	3	3	3,00	3,00	3,00	3,00	3,00	3,00
G8 (no grips)	2	2	4	3	5	3	3,67	2,67	2,00	3,50	4,00	3,17
Average	***2,25***	***2,5***	***2,875***	***2,625***	***2,75***	***2,5***	***2,63***	***2,54***	***2,38***	***2,75***	***2,63***	***2,58***
Warm/koud												
G1 (grips)	3	3	3	3	3	2	3,00	2,67	3,00	3,00	2,50	2,83
G2 (grips)	2	3	3	2	2	2	2,33	2,33	2,50	2,50	2,00	2,33
G3 (grips)	2	2	2	2	2	2	2,00	2,00	2,00	2,00	2,00	2,00
G4 (no grips)	2	2	2	2	2	2	2,00	2,00	2,00	2,00	2,00	2,00
G5 (grips)	3	3	3	3	2	2	2,67	2,67	3,00	3,00	2,00	2,67
G6 (grips)	3	3	4	3	2	3	3,00	3,00	3,00	3,50	2,50	3,00
G7 (grips)	3	3	3	3,5	3	3	3,00	3,17	3,00	3,25	3,00	3,08
G8 (no grips)	2	2	3	3	3	3	2,67	2,67	2,00	3,00	3,00	2,67
Average	***2,5***	***2,625***	***2,875***	***2,6875***	***2,375***	***2,375***	***2,58***	***2,56***	***2,56***	***2,78***	***2,38***	***2,57***
Effen/Oneffen												
G1 (grips)	2	1	3	1	3	2	2,67	1,33	1,50	2,00	2,50	2,00
G2 (grips)	1	1	1	3	3	2	1,67	2,00	1,00	2,00	2,50	1,83
G3 (grips)	2	2	2	2	3	3	2,33	2,33	2,00	2,00	3,00	2,33
G4 (no grips)	2	3	3	3	3	3	2,67	3,00	2,50	3,00	3,00	2,83
G5 (grips)	2	2	1	3	4	4	2,33	3,00	2,00	2,00	4,00	2,67
G6 (grips)	1	3	3	2	4	3	2,67	2,67	2,00	2,50	3,50	2,67
G7 (grips)	2	3	3	2	5	2	3,33	2,33	2,50	2,50	3,50	2,83
G8 (no grips)	4	5	2	2	1	1	2,33	2,67	4,50	2,00	1,00	2,50
Average	***2***	***2,5***	***2,25***	***2,25***	***3,25***	***2,5***	***2,50***	***2,42***	***2,25***	***2,25***	***2,88***	***2,46***
Ruw/Glad												
G1 (grips)	4	2	5	3	5	3	4,67	2,67	3,00	4,00	4,00	3,67
G2 (grips)	4	1	5	4	2	2	3,67	2,33	2,50	4,50	2,00	3,00
G3 (grips)	2	2	1	2	4	5	2,33	3,00	2,00	1,50	4,50	2,67
G4 (no grips)	5	3	3	2	3		3,67	2,50	4,00	2,50	3,00	3,20
G5 (grips)	4	3	4	2	4	4	4,00	3,00	3,50	3,00	4,00	3,50
G6 (grips)	1	5	5	1	4	3	3,33	3,00	3,00	3,00	3,50	3,17
G7 (grips)	2	3	4	4	5	5	3,67	4,00	2,50	4,00	5,00	3,83
G8 (no grips)	2	2	4	4	4	5	3,33	3,67	2,00	4,00	4,50	3,50
Average	***3***	***2,625***	***3,875***	***2,75***	***3,875***	***3,85714***	***3,58***	***3,08***	***2,81***	***3,31***	***3,87***	***3,33***

2. Had je voldoende grip om deze vijf reuzezwaaien te maken?

G1 (grips)	N	J	N	J	N	J
G2 (grips)	N	J	N	=	N	=
G3 (grips)	J	J	J	J	J	N
G4 (no grips)	N	N	N	N	N	N
G5 (grips)	J	J	J	J	J	N
G6 (grips)	J	J	N	J	N	J
G7 (grips)	J	J	N	J	N	N
G8 (no grips)	N	N	J	J	J	J
Aantal Ja	*4*	*6*	*3*	*6*	*3*	*3*

3. Heb je het gevoel dat je voldoende grip had om hier een hele oefening op te turnen?

G1 (grips)	N	J	N	=	N	N
G2 (grips)	N	J	N	=	N	=
G3 (grips)	J	J	J	J	N	N
G4 (no grips)	N	J	J	J	J	N
G5 (grips)	J	J	J	J	N	N
G6 (grips)	J	J	N	J	J	J
G7 (grips)	N	J	N	N	N	N
G8 (no grips)	J	N	J	J	J	J
Aantal Ja	*4*	*7*	*4*	*5*	*3*	*2*

4. Algemeen cijfer voor grip	1Z (1t/m5)	1M (1t/m5)	2Z (1t/m5)	2M (1t/m5)	3Z (1t/m5)	3M (1t/m5)	GEM Z (1t/m5)	GEM M (1t/m5)	GEM 1 (1t/m5)	GEM 2 (1t/m5)	GEM 3 (1t/m5)	GEM TOT (1t/m5)
G1 (grips)	2	4	1	3	1	3	1,333333	3,333333	3	2	2	2,333333
G2 (grips)	2	5	1	3	2	3	1,666667	3,666667	3,5	2	2,5	2,666667
G3 (grips)	4	4	3	4	2	2	3	3,333333	4	3,5	2	3,166667
G4 (no grips)	1	3	3	4	4	2	2,666667	3	2	3,5	3	2,833333
G5 (grips)	3	3	3	3	2	2	2,666667	2,666667	3	3	2	2,666667
G6 (grips)	5	4	2	5	2	5	3	4,666667	4,5	3,5	3,5	3,833333
G7 (grips)	3	4	2	3	1	2	2	3	3,5	2,5	1,5	2,5
G8 (no grips)	3	2	4	4	4	4	3,666667	3,333333	2,5	4	4	3,5
Average	*2,875*	*3,625*	*2,375*	*3,625*	*2,25*	*2,875*	*2,5*	*3,375*	*3,25*	*3*	*2,5625*	*2,9375*

5. Deze ligger is fijner/minder fijn/even fijn als een nieuwe ligger.						
G1 (grips)	>	>	=	>	<	>
G2 (grips)	=	>	<	<	<	<
G3 (grips)	=	<	<	<	<	<
G4 (no grips)	=	=	=	=	=	=
G5 (grips)	=	<	=	=	<	<
G6 (grips)	<	<	<	>	<	>
G7 (grips)	=	=	<	<	<	<
G8 (no grips)	0	<	0	=	=	=

	1Z	1M	2Z	2M	3Z	3M	
G1 (grips)	1	1	0	1	-1	1	
G2 (grips)	0	1	-1	-1	-1	-1	
G3 (grips)	0	-1	-1	-1	-1	-1	
G4 (no grips)	0	0	0	0	0	0	
G5 (grips)	0	-1	0	0	-1	-1	
G6 (grips)	-1	-1	-1	1	-1	1	
G7 (grips)	0	0	-1	-1	-1	-1	
G8 (no grips)	0	-1	0	0	0	0	
Opgeteld	*0*	*-2*	*-4*	*-1*	*-6*	*-2*	
Gemiddeld	*0*	*-0,25*	*-0,5*	*-0,125*	*-0,75*	*-0,25*	>0 is goed

6. Zat er verschil tussen links en rechts?	J/N	J/N	J/N	J/N	J/N	J/N
G1 (grips)	N	N	N	N	N	N
G2 (grips)	N	N	N	N	N	N
G3 (grips)	N	N	J	N	N	N
G4 (no grips)	N	N	J	N	J	J
G5 (grips)	J	N	N	N	N	N
G6 (grips)	N	N	N	N	J	N
G7 (grips)	N	N	J	N	N	N
G8 (no grips)	J	J	N	N	N	N
Aantal Ja	*2*	*1*	*3*	*0*	*2*	*1*

7. Doet de ligger pijn aan je handen?	J/N	J/N	J/N	J/N	J/N	J/N
G1 (grips)	N	N	N	J	N	J
G2 (grips)	N	N	N	N	N	N
G3 (grips)	N	N	J	N	N	N
G4 (no grips)	J	J	J	J	J	J
G5 (grips)	N	J	J	J	J	J
G6 (grips)	N	N	N	N	N	N
G7 (grips)	N	N	N	N	N	N
G8 (no grips)	J	J	J	J	J	J
Aantal Ja	*2*	*3*	*4*	*4*	*3*	*4*

8. Voelde de ligger comfortabel aan?	J/N	J/N	J/N	J/N	J/N	J/N
G1 (grips)	J	J	N	J	N	=
G2 (grips)	J	J	J	J	N	J
G3 (grips)	J	J	N	J	N	N
G4 (no grips)	N	N	J	N	J	N
G5 (grips)	N	N	N	N	N	N
G6 (grips)	J	J	J	J	J	J
G7 (grips)	J	J	N	J	N	N
G8 (no grips)	N	N	J	J	J	J
Aantal Ja	*5*	*5*	*4*	*6*	*3*	*3*

9. zou je blijven turnen op deze ligger of	T/A	T/A	T/A	T/A	T/A	T/A
G1 (grips)	A	T	A	T	A	T
G2 (grips)	A	T	A	A	A	A
G3 (grips)	T	A	A	A	A	A
G4 (no grips)	A	T	T/A	T	A	A
G5 (grips)	T	A	T	T	A	A
G6 (grips)	T	T	A	T	A	T
G7 (grips)	T	T	A	T	A	A
G8 (no grips)	T	A	T	T	T	T
Aantal Afschrijven	*3*	*3*	*5*	*2*	*7*	*5*

T=turnen
A=afschrijven

Maakt het uit hoe de ligger eruit ziet in c	J/N	J/N	J/N	J/N	J/N	J/N
G1 (grips)	=	N	J	N	J	N
G2 (grips)	N	N	J	N	J	N
G3 (grips)	J	N	J	N	N	N
G4 (no grips)	N	N	N	N	N	N
G5 (grips)	J	J	J	J	J	J
G6 (grips)	N	N	J	J	J	J
G7 (grips)	N	N	N	N	J	J
G8 (no grips)	N	N	N	N	N	N

Appendix F

Answers additional questionnaire (in Dutch)

1. Wil je bij een ligger liever meer grip of meer snelheid kunnen maken? En waarom?

G1	Meer grip, want als je dat hebt kun je ook voluit turnen
G2	Meer grip, want als ik geen grip heb kan ik ook geen snelheid maken
G3	Meer grip, dan heb ik meer zekerheid dat ik er niet afglijd en durf ik meer
G4	Veel grip, veiliger gevoel. Veiligheid & durf zijn de belangrijkste punten bij turnen naar mijn mening
G5	Grip geeft een veilig gevoel maar zonder snelheid kan je niet fijn een oefening uit turnen. Dus beiden in goede balans. Niet het een meer dan de ander. Snelheid creëer je vooral door je techniek.
G6	Zo veel mogelijk grip tot een moment dat dit ervoor zorgt dat het snelheid in de weg zit, grip vind ik dus belangrijker, dit is veilig.
G7	Meer grip. Geeft meer vertrouwen dat je niet valt
G8	Een combinatie van beide, bij meer snelheid kost het minder kracht maar meer grip voelt veiliger.

Conclusie: Meer grip. Grip geeft (gevoel van) zekerheid en geeft meer vertrouwen en veiligheid.

1.1. Zit hierbij verschil tussen trainingen en wedstrijden?

G1	Ja elke ligger is anders maar wel fijn.
G2	Nee, want in de training train je eigenlijk voor een goede wedstrijd.
G3	Sommige wedstrijden hebben de liggers enorm veel magnesium aan de stok, dit is pijnlijker
G4	Nee, hoewel ik dan wel meer adrenaline heb en daardoor meer durf
G5	Nee
G6	Nee
G7	Nee
G8	Ik heb geen wedstrijd ervaring

Conclusie: Deze vraag is niet duidelijk genoeg gesteld. Echter willen de meeste turnsters wel trainen op een zelfde ligger als die gebruikt wordt tijdens de wedstrijden.

2. Geven magnesium en rekleertjes je meer vertrouwen op de brug?

G1	Ja
G2	Ja, want dan heb ik veel meer grip
G3	Magnesium ja, leertjes zodra je eraan gewend bent
G4	[heeft geen rekleertjes] magnesium ja
G5	Leertjes sowieso, magnesium voorkomt het schuren tussen hand en leertje. Voelt fijner door gewenning.
G6	Nee
G7	Ja > ik heb last van zweethanden dus zonder leertjes is de brug te glad voor mij en vind ik alles veel te eng.
G8	Ik train zonder leertjes. Magnesium geeft me niet meer vertrouwen, het is vooral het comfort

Conclusie: Over het algemeen geven magnesium en leertjes meer vertrouwen op de brug.

3. Geven rekleertjes en magnesium je meer comfort?

G1	Ja
G2	Ja, want ik krijg minder snel blaren, en heb meer grip
G3	Ja
G4	[heeft geen rekleertjes] magnesium ja
G5	Ja, zie vraag 2 [Leertjes sowieso, magnesium voorkomt het schuren tussen hand en leertje. Voelt fijner door gewenning.]
G6	Ja
G7	Ja, vooral meer grip en vertrouwen
G8	Ja magnesium geeft me meer comfort

Conclusie: Rekleertjes en magnesium zorgen voor meer comfort.

4. Wat bepaalt grip voor jou? Denk aan grootte ligger, ruwheid, rekleertjes, rolletjes van leertje, warm/koud gevoel, zweet/droog, hard/zacht, effen/oneffen, etc.

G1	Wel grip = ruwheid, rekleertjes, rolletjes van leertje, droog, hard & zacht, effen, normale dikte van de ligger Geen grip = een dikke ligger, zweet, glad, oneffen
G2	Als mijn rolletje over de ligger zit heb ik meer grip. De ligger moet niet te glad zijn. Ik heb wel magnesium en leertjes nodig en ik vind het ook fijn om iets water te gebruiken.
G3	Ik heb het liefst een wat ruwere stok, leertjes, koude, droge handen
G4	Ruwheid zeker meer grip, maar ook veel meer pijn. Zweet beter dan helemaal droog. Liever oneffen, meer grip.
G5	Dikte van de ligger bepaald hoe goed je hand er omheen kan en je knijpkracht vormt ook heel groot deel van je grip.
G6	Grip is een ligger die goed in de hand ligt (niet te dik). Een ruwe ligger waar leertjes goed op vast grijpen, hierbij zijn de rolletjes erg belangrijk. Ik heb graag een warme/droge/harde/effen ligger.
G7	Grootte ligger> gewenning, als het anders is ervaar ik minder grip. Leertjes > zonder durf ik niks Zweet/droog > zweet maakt glad en door magnesium wordt dit droger.
G8	De ruwheid, zweethanden en de effenheid bepalen voor mij het grip. Bij zweethanden heb ik minder grip.

Conclusie: Droge handen, dikte van de ligger zodat de hand erom heen kan maar nog wel in geknepen kan worden, ruwe ligger zodat de leertjes hier meer aan vast blijven hangen als het ware, gebruik van magnesium.

5. Als je zou mogen kiezen, wat vind je dan fijner? Een herenrekstok van metaal of een damesligger van glasvezel met hout. Waarom? Denk aan diameter, grip, snelheid maken, wrijving, doorbuiging, etc.

G1	Damesligger, want die is iets dikker en bij metaal lijkt het mij heel vervelend voelen en niet fijn zwaaien
G2	Ik zou nu kiezen voor een houten ligger, omdat ik dat gewend ben, en als ik bijvoorbeeld een zolendraai moet maken glijden mijn voeten er minder snel af.

G3	Metaal vind ik vervelend, vaak is de diameter van de herenrekstok ook kleiner, dat vind ik ook minder fijn. Damesligger heeft meer doorbuiging vind ik ook fijner
G4	Damesligger met glasvezel en hout. Dat ben ik nu gewend. Herenrekstok te dun
G5	Dameslegger. Metaal is veel dunner, gladder en ander diameter, maar dit is vooral gewenning.
G6	Glasvezel: minder zweterig. Je hoeft minder hard te knijpen om te blijven hangen. Het is ruwer en heeft dus meer grip. En dus meer controle.
G7	Dames, de herenrekstok is heel dun, is kouder en je maakt meer snelheid waardoor controle soms lastiger is.
G8	Ik heb allen op de brug van Linea Recta geturnd, ik heb geen andere ervaring.

Conclusie: Damesligger, omdat ze deze gewend zijn. Daarnaast geeft deze meer grip en kan deze iets meer doorbuigen dan een herenrekstok. Grip gaat voor op snelheid.

6. Hoe zou jij je ideale ligger beschrijven? Denk aan diameter, materiaal, doorbuiging.

G1	Van hout en van de voorbeelden wel serie 1, die was het fijnst
G2	Goede vering van de ligger. Niet te glad. Niet te dik, want je handen moeten er wel goed omheen kunnen.
G3	Standaard houten damesligger, maar niet té veel doorbuiging
G4	Diameter van 39 mm, ben ik gewend. Doorbuiging iets los, niet te vast. Materiaal glasvezel met hout
G5	39 mm hout, flexibel, vering maar niet te veel
G6	Diameter gelijk of iets dunner dan conventioneel (absoluut niet dikker). Redelijk stijf en van glasvezel/hout
G7	Damesligger, niet te ruw en zonder slijtageplekken
G8	Ik denk dat het veel gewenning is, ik ben nu gewend aan deze ligger en die vind ik fijn.

Conclusie: Zoals deze nu ook is, waarbij er niet te veel doorbuiging is. Daarnaast ook niet versleten.

7. De liggers zijn op dit moment gelijk afgeschuurd. Normaal zijn ze op een punt veel verder versleten dan op andere plekken. Merk je een verschil tussen de liggers die je vandaag hebt getest en waar je normaal op traint?

G1	Ja, want onze eigen ligger wordt vanzelf heel fijn en deze ligger was soms heel glad
G2	Bij serie 2 en 3 gleed ik er echt af, maar serie 1 vond ik wel net zo fijn als de normale ligger.
G3	Normaal zie je in het midden plekken waar meestal geturnd wordt. Op leggers die al erg versleten zijn vermijdt ik die plekken door iets ernaast te gaan
G4	Ja! Delen zijn veel gladder dan onze brug
G5	Ja, normaal meer magnesium laagje dit voelt fijner dan het pure hout
G6	Ja
G7	Ja, komt door meer magnesium op de ligger waar ik normaal op train

G8	Ja bij de liggers waar op getraind wordt zit al magnesium en geeft meer grip.

Conclusie: Geen eenduidig antwoord op de gestelde vraag.

7.1 Welk soort slijtage vind je prettiger om nog op te trainen, volledig afgeschuurd of op een punt afgeschuurd?

G1	Punt afgeschuurd, anders is het heel glad
G2	Ik den k als die helemaal is afgeschuurd
G3	Gelijkmatig
G4	Geen slijtage, bij afbreken, dan moet de brug vervangen worden
G5	Volledig. Nooit ergens tot op een punt zonder hout dat voelt niet fijn
G6	Volledig afgeschuurd
G7	Volledig
G8	Ik denk volledig zodat je druk gelijk verdeeld wordt

Conclusie: Volledig afgeschuurd.

7.2 Wat vind je prettiger turnen, een ligger waarbij de fineer weggeschuurd is of een ligger waarbij het fineer afgeknapt is? Waarom?

G1	Afgeschuurd, want ander doet het zeer aan je handen en er ontstaan splinters
G2	Als de ligger afgeschuurd is, want anders krijg je snel splinters.
G3	Weggeschuurd, dat is gelijkmatiger en merk je dus minder
G4	Weggeschuurd, dan is het in ieder geval glad.
G5	Afgeschuurd
G6	Weggeschuurd
G7	Weggeschuurd, dan voelt het gelijkmatiger. Bij afgeknapt fineer is het meer een ‘gat’.
G8	Hier heb ik geen ervaring mee

Conclusie: Weggeschuurd.

Appendix G

Results roughness data of all bar parts

Magnesium		Ra ⊥ to grain		Ra ǀǀ to grain		Rz ⊥ to grain		Rz ǀǀ to grain		Skewness ⊥ to grain		Skewness ǀǀ to grain		Kurtosis ⊥ to grain		Kurtosis ǀǀ to grain		Rp ⊥ to grain		Rp ǀǀ to grain		Rv ⊥ to grain		Rv ǀǀ to grain	
# sample	# test	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
1	1	15,507	9,066	5,665	2,499	122,320	88,106	46,393	23,984	1,2426	-0,5438	-0,3053	0,6188	4,9301	3,5250	3,1315	4,2214	79,886	45,539	20,474	15,269	42,442	42,567	25,919	8,715
	2	16,531	9,541	7,769	5,227	201,500	85,905	67,629	48,572	2,6058	-0,4808	1,2103	-0,4555	11,8142	3,4623	5,3470	3,3158	127,370	44,406	48,535	20,735	74,128	41,500	19,094	27,837
	3	12,196	9,844	6,072	5,268	134,460	81,206	90,729	36,773	-2,2678	-0,5501	1,9547	0,2213	9,7152	3,0709	10,4401	2,6940	38,130	43,531	78,839	20,956	96,336	37,676	16,890	15,817
	4	8,229	10,110	4,531	10,917	78,585	104,520	44,296	72,105	-0,8120	-1,4697	0,4751	0,2653	3,9108	6,2068	3,7160	2,5292	34,171	31,533	20,901	39,081	44,414	72,991	23,395	33,024
	5	8,853	8,544	4,055	3,668	94,286	99,847	42,163	45,652	-0,4704	-0,1767	0,6431	0,8929	3,7872	4,1011	4,7766	5,8276	51,892	64,955	27,067	26,435	42,392	34,892	15,096	19,217
	6	7,525	8,266	4,480	5,437	67,389	77,466	49,070	55,835	-0,6576	0,3328	0,1976	0,9574	3,3304	3,5140	3,9927	5,6096	30,495	44,883	25,941	33,356	36,894	32,584	23,128	22,479
	7	4,725	8,216	3,492	3,211	70,464	64,812	40,240	38,000	0,0309	-0,2560	0,0692	0,0911	5,8402	3,0356	4,0776	4,9244	32,130	31,514	18,726	21,907	38,334	33,298	21,513	16,093
	8	4,995	6,998	3,086	6,866	85,129	52,362	37,752	78,483	0,7658	-0,5011	0,0673	-0,0243	6,9846	2,6735	5,5766	4,4190	51,293	21,754	20,324	41,598	33,386	30,608	17,428	36,885
	9	4,358	10,417	3,354	10,293	46,225	99,799	51,070	59,580	0,1651	1,0595	0,1376	0,6103	3,7145	5,4376	6,2736	2,3481	24,270	66,992	23,287	35,710	21,955	32,808	27,783	23,870
	10																								
	Average	9,213	9,000	4,723	5,932	100,040	83,780	52,149	50,998	0,067	-0,287	0,494	0,353	6,003	3,892	5,259	3,988	52,182	43,901	31,566	28,339	47,809	39,880	21,138	22,660
		9,107		5,327		91,910		51,574		-0,110		0,424		4,947		4,623		48,041		29,352		43,845		21,899	
	Average - MIN&MAX	8,861	9,084	4,521	5,710	93,233	85,306	48,694	50,931	0,038	-0,311	0,400	0,382	5,555	3,735	4,823	3,959	45,428	43,766	26,647	28,311	44,570	36,475	21,052	22,620
		8,940		5,155		87,916		50,851		-0,145		0,383		4,660		4,402		44,726		27,815		41,932		21,786	
	Median	8,229	9,066	4,480	5,268	85,129	85,905	46,393	48,572	0,031	-0,481	0,198	0,265	4,930	3,514	4,777	4,221	38,130	44,406	23,287	26,435	42,392	34,892	21,513	22,479
	sd	4,576	1,097	1,525	2,963	46,808	17,181	16,890	17,441	1,386	0,692	0,697	0,459	2,987	1,180	2,183	1,326	32,778	14,906	19,910	9,346	22,920	13,079	4,311	8,905
	Median	8,699		4,879		85,517		47,483		-0,363		0,243		3,849		4,320		43,969		24,514		38,005		21,996	
	sd	3,230		2,369		35,213		16,666		1,078		0,577		2,456		1,870		25,066		15,179		18,557		6,832	
2	1	11,789	5,491	11,601	4,552	115,830	64,298	77,937	101,590	0,4694	-0,6777	-0,0717	2,1217	4,2318	4,9633	2,5612	24,4494	68,300	32,007	42,502	82,960	47,529	32,292	35,435	18,637
	2	8,413	8,105	9,818	8,385	123,510	99,736	86,889	77,287	0,5098	0,6311	0,0816	0,4592	5,0377	6,7246	2,9438	4,0844	47,932	67,932	43,363	52,602	75,580	31,804	43,526	24,685
	3	8,131	7,119	10,676	8,864	65,552	69,336	101,060	64,639	0,5117	-0,2296	0,3599	-0,6735	3,9085	3,7183	3,4419	3,1227	36,500	31,073	65,199	33,519	29,052	38,263	35,865	31,120
	4	5,520	6,193	3,399	8,900	76,168	73,922	31,832	57,582	-1,0598	-1,5346	-0,1675	-0,7934	6,3412	7,7550	3,7868	2,8561	33,861	31,840	13,857	28,736	42,307	42,082	17,975	28,845
	5	5,737	9,102	4,696	5,506	81,636	131,370	45,554	88,050	-1,0513	2,8032	0,1079	3,1283	7,1944	13,9092	4,1509	20,7045	28,722	97,346	23,003	68,569	52,914	34,029	22,551	19,481
	6	4,545	9,480	10,089	7,722	61,175	107,260	73,990	99,443	-0,9486	-0,3899	0,5981	0,6939	5,8668	4,0569	3,1322	6,2837	21,373	49,976	52,832	60,757	39,802	57,293	21,158	38,686
	7	8,228	8,144	3,186	8,046	71,780	121,570	42,987	85,665	-1,7977	-1,4339	-0,2447	-1,0646	6,5169	7,5851	5,2680	5,4958	21,324	31,234	21,352	33,035	50,455	90,341	21,635	52,630
	8	7,450	8,186	3,689	6,122	59,516	81,173	40,945	60,831	-1,0847	0,1642	-0,2302	-0,2553	4,0464	3,4308	4,2619	3,5843	23,697	45,897	18,687	28,047	35,818	35,276	22,257	32,784
	9	7,863	13,848	7,318	8,055	68,888	72,884	59,250	78,605	-1,8764	-0,1092	-0,8092	-0,5344	6,6508	2,0950	3,6903	3,9011	20,531	36,392	25,187	37,596	48,357	36,492	34,063	41,008
	10																								
	Average	7,520	8,408	7,164	7,350	80,451	91,283	62,272	79,299	-0,703	-0,086	-0,042	0,342	5,533	6,026	3,693	8,276	33,582	47,077	33,998	47,313	46,868	44,208	28,274	31,986
		7,964		7,257		85,867		70,785		-0,395		0,150		5,780		5,984		40,330		40,556		45,538		30,130	
	Average - MIN&MAX	7,335	8,047	7,098	7,529	77,290	89,412	61,079	79,217	-0,709	-0,292	-0,024	0,145	5,527	5,462	3,630	6,740	30,487	42,183	32,418	44,973	45,312	39,390	27,566	30,944
		7,809		7,240		84,670		71,295		-0,502		0,040		5,502		5,044		38,004		39,687		43,768		29,484	
	Median	7,863	8,144	7,318	8,046	71,780	81,173	59,250	78,605	-1,051	-0,230	-0,072	-0,255	5,867	4,963	3,690	4,084	28,722	36,392	25,187	37,596	47,529	36,492	22,551	31,120
	sd	2,123	2,411	3,461	1,566	23,362	24,503	23,810	16,015	0,959	1,290	0,402	1,436	1,251	3,546	0,810	8,234	15,854	22,506	17,631	19,799	13,166	18,967	8,978	10,906
	Median	8,118		7,884		75,045		75,639		-0,534		-0,120		5,452		3,844		32,934		35,558		40,942		29,983	
	sd	2,251		2,608		23,884		21,546		1,147		1,042		2,592		6,146		20,121		19,434		15,898		9,877	
3	1	9,341	10,406	5,966	6,112	65,843	147,540	50,678	59,906	-0,5978	-0,7830	-0,3287	-0,2255	3,2849	5,3178	3,5160	3,8398	26,469	44,224	23,225	24,598	39,374	103,310	35,639	35,308
	2	12,837	10,917	5,514	5,870	97,748	87,770	87,151	61,693	-1,0764	0,2883	2,3698	-0,0133	4,2867	2,5056	17,3181	4,5397	44,346	48,378	59,433	38,937	53,403	39,392	27,718	23,026
	3	13,709	12,595	4,991	6,945	85,281	100,490	50,513	42,523	-1,3935	-0,2888	0,3389	0,2384	4,386	3,1413	3,6120	2,3564	28,166	40,251	24,981	22,369	57,116	60,248	25,532	20,154
	4	3,705	9,311	5,011	5,781	52,051	130,830	63,546	37,741	0,2717	2,2589	0,6875	0,2663	5,0953	13,8607	8,5023	3,1612	23,799	103,330	39,840	18,643	28,252	27,496	23,706	19,098
	5	3,200	12,203	3,970	4,495	34,305	176,210	29,955	47,121	-0,0460	1,7432	-0,0456	0,3005	3,8452	10,6480	2,9696	3,9566	17,687	134,360	15,303	27,285	16,619	41,847	14,652	19,386
	6	4,059	9,621	3,750	5,754	58,758	70,180	27,903	50,167	0,2827	-0,5952	0,3877	-0,5248	5,1041	2,6515	3,1479	3,5178	31,889	30,559	16,333	23,086	26,869	39,621	11,570	27,081
	7	5,841	21,288	4,019	19,079	47,332	129,660	36,307	97,338	0,1519	-0,7816	0,5406	-0,7299	3,6046	2,7782	4,9724	2,3248	23,215	55,939	21,778	39,892	24,117	73,724	14,529	57,446
	8	8,988	27,623	5,241	9,459	97,083	192,980	35,963	94,603	-1,0241	-0,7087	-0,5409	-0,2707	4,3890	2,8768	4,5999	3,9370	54,506	85,784	28,526	50,462	42,577	107,190	35,963	44,141
	9	8,489	22,749	4,762	6,993	90,948	116,580	20,073	45,770	-1,0332	-0,8640	-0,4297	0,6204	4,7297	2,6184	2,8540	3,2658	43,327	45,079	16,011	27,648	47,621	71,501	20,073	18,122
	10	8,351		11,893		89,033		38,234		-0,6920		-0,2394		4,5626		2,3797		52,639		33,412		36,393		38,234	
	Average	7,852	15,190	5,512	7,832	71,838	128,027	44,032	59,651	-0,516	0,030	0,274	-0,038	4,329	5,155	5,387	3,433	34,604	65,323	27,884	30,324	37,234	62,703	24,762	29,307
		11,521		6,672		99,932		51,842		-0,243		0,118		4,742		4,410		49,963		29,104		49,969		27,034	
	Average - MIN&MAX	7,701	14,254	4,934	6,702	73,291	127,011	41,637	57,398	-0,506	-0,161	0,114	-0,033	4,362	4,290	4,272	3,434	34,231	60,426	25,513	29,116	37,326	61,378	24,727	26,885
		10,848		6,046		96,667		50,575		-0,338		0,045		4,313		3,831		45,994		28,060		47,815		26,021	
	Median	8,420	12,203	5,001	6,112	75,562	129,660	37,271	50,167	-0,645	-0,595	0,147	-0,013	4,388	2,877	3,564	3,518	30,028	48,378	24,103	27,285	37,884	60,248	24,619	23,026
	sd	3,660	6,813	2,352	4,431	22,993	39,981	19,768	21,964	0,630	1,179	0,852	0,436	0,602	4,192	4,544	0,743	13,081	34,815	13,619	10,444	13,265	28,687	9,653	13,710
	Median	9,621		5,754		90,948		47,121		-0,598		-0,013		4,287		3,518		44,224		24,981		41,847		23,706	
	sd	6,442		3,593		42,492		21,771		0,946		0,688		2,859		3,402		29,539		11,349		24,989		11,644	
Not used part	1	10,056	10,056	8,680	8,680	106,000	106,000	61,014	61,014	-0,8208	-0,8208	-0,4151	-0,4151	5,4403	5,4403	2,9338	2,9338	35,782	35,782	29,302	29,302	70,218	70,218	31,712	31,712
	2	10,659	10,659	8,710	8,710	97,104	97,104	62,133	62,133	-0,4525	-0,4525	-0,5858	-0,5858	3,4928	3,4928	2,9588	2,9588	44,999	44,999	28,627	28,627	52,105	52,105	33,506	33,506
	3	10,472	10,472	12,151	12,151	79,711	79,711	71,807	71,807	-0,4892	-0,4892	-0,5769	-0,5769	3,4841	3,4841	2,2335	2,2335	33,181	33,181	36,526	36,526	46,530	46,530	35,281	35,281
	4	9,709	9,709	6,038	6,038	88,445	88,445	44,978	44,978	-0,8350	-0,8350	-0,5842	-0,5842	4,5429	4,5429	3,2333	3,2333	29,856	29,856	19,775	19,775	58,589	58,589	25,203	25,203
	Average	10,224	10,224	8,895	8,895	92,815	92,815	59,983	59,983	-0,649	-0,649	-0,541	-0,541	4,240	4,240	2,840	2,840	35,955	35,955	28,558	28,558	56,861	56,861	31,426	31,426
		10,224		8,895		92,815		59,983		-0,649		-0,541		4,240		2,840		35,955		28,558		56,861		31,426	
	Average - MIN&MAX	10,264	10,264	8,695	8,695	92,775	92,775	61,574	61,574	-0,655	-0,655	-0,581	-0,581	4,018	4,018	2,946	2,946	34,482	34,482	28,965	28,965	55,347	55,347	32,609	32,609
		10,264		8,695		92,775		61,574		-0,655		-0,581		4,018		2,946		34,482		28,965		55,347		32,609	
	Median	10,264	10,264	8,695	8,695	92,775	92,775	61,574	61,574	-0,655	-0,655	-0,581	-0,581	4,018	4,018	2,946	2,946	34,482	34,482	28,965	28,965	55,347	55,347	32,609	32,609
	sd	0,426	0,426	2,506	2,506	11,300	11,300	11,115	11,115	0,207	0,207	0,084	0,084	0,942	0,942	0,426	0,426	6,499	6,499	6,860	6,860	10,178	10,178	4,397	4,397
	Median	10,264		8,695		92,775		61,574		-0,655		-0,581		4,018		2,946		34,482		28,965		55,347		32,609	
	sd	0,394		2,320		10,462		10,291		0,191		0,077		0,872		0,395		6,017		[illegible]		9,423		4,071	

Appendix H

Programme of requirements

Requirements	PEBA	Plasti Dip	Extra veneer layer
Measurements			
The diameter of the bar is 40 mm ± 1 mm. (According to FIG & NEN-EN 915 norms)	✓[5]	✓[5]	✓[5]
The length of the bar is 2400 mm ± 10 mm. (According to FIG & NEN-EN 915 norms)	✓[5]	✓[5]	✓[5]
The distance between the sockets must be at least 200 cm ± 1,0 cm. (According to FIG norms)	✓[5]	✓[5]	✓[5]
Appearance			
The bars retain the natural colour of wood. They are neither lacquered, nor polished. (According to FIG norms)	✓[6]	✓[6]	✓
The bar has a core of fibreglass.	✓	✓	✓
Grip			
The bar surface must provide a good glide and turn capability but may not be slippery. (According to FIG norms)	[7]	✓	✓
The surface cannot be too rough, leading to injuries. (According to NEN-EN 913 norms)	[7]	✓	✓
The bars' surface must absorb moisture, to ensure grip stability. (According to FIG norms)	✗	[7]	✓
[Wish] No magnesium powder or grips are needed to have enough grip.	[7]	✓[8]	✗
Surface roughness			
The surface should be flat with deep steep valleys.	[9]	✓	✓
The valleys should be deeper than that the peaks are high	[9]	✓	✓
Wear			
The bars can be used twice as long as now.	[7]	[7]	✗
[Wish] The bars can be used for at least a couple of years of extreme use, before wear is too large.	[7]	[7]	✗
The outer layer does not splinter off while using the bar for gymnastics.	✓[7]	[7]	✗
Within 6 months, the core should not become visible, due to wear.	[7]	[7]	[10]
Safety			
The bars must be secured (reinforced) against breaking through. (According to FIG norms)	✓[5]	✓[5]	✓[5]
The bar will not break, during normal use.	✓[5]	✓[5]	✓[5]
Mechanical properties			

[5] Not depending on top layer

[6] If brown colour is available, the top layer could be made to look like wood.

[7] Needs to be tested first.

[8] The coefficient of friction tests show high frictions without magnesium and grips. However, grip and coefficient of friction are not comparable.

[9] Should be tested if this is possible to make.

[10] The core did not become visible, but other problems occurred faster.

When the bar is pulled down vertically, with a tractive force of 1350 N ± 20 N, the minimal deflection is 40 mm and the maximal deflection is 70 ≤ x ≤ 100 mm. (According to FIG & NEN-EN 915 norms)	✓[5]	✓[5]	✓[5]
When a pendulum from horizontal position is released the maximal positive vertical deflection is 80 ≤ x ≤ 120 mm. (According to FIG norms)	✓[5]	✓[5]	✓[5]
When a pendulum from horizontal position is released the maximal negative horizontal deflection is -41 ≤ x ≤ -26 mm. (According to FIG norms)	✓[5]	✓[5]	✓[5]
When a pendulum from horizontal position is released the maximal positive horizontal deflection is 46 ≤ x ≤ 71 mm. (According to FIG norms)	✓[5]	✓[5]	✓[5]
When a pendulum from horizontal position is released the maximal force must be 1500 ≤ x ≤ 1800 N. (According to FIG norms)	✓[5]	✓[5]	✓[5]
The bar should withstand a maximum force of 4 times body weight or 4205 N. **[43] [46]**	✓[5]	✓[5]	✓[5]
When a pendulum is pulled vertically downwards with an initial tension of 1000N ± 30 N the maximum frequency of oscillation is 2.50 ≤ x ≤ 3.50 Hz. (According to FIG norms)	✓[5]	✓[5]	✓[5]
When a pendulum is pulled vertically downwards with an initial tension of 1000N ± 30 N the half amplitude interval is 350 ≤ x ≤ 5700 ms. (According to FIG norms)	✓[5]	✓[5]	✓[5]
Norms			
The bar fulfils all norms and specifications set by NEN-EN.	[5]	✓	✓
[Wish] The bar fulfils all norms and specifications set by NEN-EN and FIG.	✗	✓	✓
Bar is usable for trainings, with about the same specifications as the competition bars.	✗	✗	✓
[Wish] The bar can be used for competitions at high level. (Related to fulfilling FIG requirements)	✗	✓	✓
Costs			
[Wish] The selling price should be in the same price range as the current model.	[11]	✓	✗

[11] Unknown