Graduation Thesis
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Graduation Thesis
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My main motivation to research product development via 3D-Virtual Prototyping (3D-VP) and compression sportswear derived from my specialisation in the minor 3D-Hypercraft. This program introduced me to 3D-VP via self-experimentation with Lectra and Clo3D software. Whilst working on a future-oriented surfing outfit for the brand O’Neill I got to experience the benefits of using these programs.

In the year prior, whilst doing my internship at Delikatessen, I got to see up close how the development of products was done manually. Patterns were created by hand, modelled on a mannequin and afterwards digitized. Seeing the differences between manual product development and the use of 3D-VP highlighted the possibilities and potential of 3D-VP to fashion brands.

As a minor, the Smart Textiles program at AMFI showed me the new innovations on the level of fabrics and the new applications this creates. Properties such as breathability and temperature regulation can be obtained via the manipulation or construction of materials, and used for applications in sportswear. On a bigger scale they can result in better performances for athletes.

I would like to thank my coaches, Lisette Vonk and Ineke Siersema, for supporting and guiding me throughout this process.

Chris Gran
The possible benefits of the use of 3D-Virtual Prototyping software in the development process of compression sportswear is analysed and assessed. Factors such as the used fabrics and their properties, the personalised fit, the exerted pressure and allowing freedom of movement are of great importance for a compression garment. The compression sportswear that is currently being produced by commercial sport brands results in a variety in fit and therefore a variety of exerted pressure. 3D-virtual prototyping software is said to be a cost- and time-efficient alternative to current manual development processes on the longer term. It holds tools that enable for most of the important factors to compression sportswear to be taken into account. Additionally its implementation into the development process works as a solution to the fit issue. Tools including an adjustable avatar/importable 3D-body scan, insertion of custom fabric measurements, fit maps and allow for the fabric and fit to be taken into account in the simulation. Animations that can be added to the simulations allow for the freedom of movement to be taken into account, although the amount of exercise related animations are limited. Due to the fact that the avatar does not have a soft-tissue surface, the exerted pressure cannot be analysed in the garment-specific 3D-VP software. The implementation of 3D-Virtual Prototyping software thus seems like a suitable and logical implementation to the development process of compression sportswear, although it does not dismiss the necessity for the creation of a physical prototype yet because of issues with the avatar.
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The following thesis is a literary review of compression garments (CGs) and 3D Virtual Prototyping (3D-VP). Graduated compression stockings are a common example of CGs. These stockings are a method to treat diseases like Deep Vein Thrombosis and Chronic Inflammatory disorders, and relieve ailments like lymphoedema (Hagan & Lambert, 2008). This is due to its tight fit and the accompanying pressure it therefore applies on the limbs (Davies, Thompson and Cooper, 2009; Bottaro, Martorelli and Vilaça, 2011). Besides its uses in the medical field we have seen an increase in its use by recreational and professional athletes during and after their exercises (Ali et al, 2007; Brothersen, 2015; O'Donnell et al, 1979; Rahulan et al, 2013; Sigel et al, 1975). This is due to its reported benefits on sport performance and recovery (Pruscino, Halsdon and Hargreaves, 2013; Brophy-Williams et al, 2014), which will be addressed in 2.0 Compression. In running the use of lower body CGs is commonly accepted for example, whereas other sports such as cricket and bench-pressing use upper- or full-body CGs since they require extensive exercise of the upper-body (Born, Sperlich and Holmberg, 2013).

3D-Virtual Prototyping is the use of certain Computer Aided Design (CAD) programs which allow one to digitally draw 2D patterns, stitch these together and virtually fit them onto an avatar (Decaudin et al, 2006; Cugini & Rizzi, 2002; Stjepanovic et al, 2010; Volino et al, 2005; Wang & Tang, 2010). It can be used to complement or even replace physical prototyping (Jevsnik et al, 2012; Hoch, 2016). It is frequently used in various industrial sectors and is increasingly targeting the apparel sector as well (Papahristou & Bilalis, 2016). Despite a great focus on the apparel sector we see a rather slow adaption of 3D-VP software by fashion brands. Most of them still depend upon manual labour and physical prototypes to some extend (Fontana, Rizzi and Cugini, 2004).

Introduction

This literary review aims to identify the possible benefits 3D-VP could offer to CG developers. In this way the thesis can answer the research question: “How can 3D-VP be used to develop compression garments for the sportswear market?”. In order to answer this question, Chapter 2.0 Compression will analyse the benefits CGs are said to have and why CGs are so commonly used amongst athletes. This chapter will also look at the current development process of CG’s in order to identify the crucial steps as well as what are the key influencers of the effectiveness of the garment. Next, Chapter 3.0 3D-Virtual Prototyping analyses what exactly 3D-VP software is and what it is used for. The tools it offers are identified as well as the steps that need to be taken for the development process of a garment in 3D-VP. Based upon the previous two chapters, Chapter 4.0 CGs and 3D-VP will align the most important aspects or steps in the making of a CG with the tools and options in 3D-VP and evaluate whether or not the software holds the necessary options for the creation of an effective and accurate CG, and thus if it offers any benefits to the current development process.

Methodology

In order to gather all the necessary information for this literary review, first and foremost literary research will be done. Other methods include interviews, watching tutorials on and experimenting with 3D-VP software programs, and analysing online reviews of CG wearers to get insight into their experience with garment and its effectivity.

The literary research will be done via channels, such as Mens Fitness/ journals.humankinetics/ Google Scholar, to find relevant and accurate research articles. Other sources include manuals and other study material from the 3D-Hypercraft program at the Amsterdam Fashion Institute, which revolves around the use of 3D-Virtual Prototyping. The interviews are executed with various 3D-VP software providers about their software programs. Product developers and pattern makers at sportswear brands, such as Under Armour/ Nike/ Adidas/ O’Neill/ Satisfy/ Skins will be done to obtain insight in their way of working on CGs as well as with 3D-VP software. An example of this is Monique Broeke, a pattern maker at O’Neill that was also involved during the 3D-Hypercraft program. Orthopaedic doctors are also questioned since they have insight into the effects of CGs on the body.
2.0 Compression Garments

As mentioned before, CGs are garments that due to their specific fit exert a certain amount of pressure on the limbs it is applied to. Compression in general can be determined as an external pressure gradient whose force is applied to a surface (a limb for instance) and used to decrease the volume of this surface. Besides compressing, a CG also stabilizes and supports the body (Nakashima et al, 2016; Umar, Hussain and Maqsood, 2015). A survey questioning 65 people, in between the age of 18 and 60, showed that 63% of them actually did not know what CGs were. Of the ones that did know what they were, about half referred to the before mentioned stockings when asked to give an explanation what CGs were. The survey can be found in part 9.4 of the Appendix. Within this chapter the effects of compression garments are described first in 2.1 Mechanisms. In 2.1.1 Performance & Recovery is then explained how these effects relate to performance and recovery, to make clear why athletes make use of CGs. 2.2 Development process of CGs then goes into the development process of CGs and all the steps that need to be taken. 2.2.1 Important Factors specifies which of the related aspects of the garment are of key importance, such as the fabric (MacRae, Cotter and Laing, 2011) of the garment and the fit, as well as the problem that rises with the commonly used standardized measurements by sports brands. Figure 2 on page 14 shows an example of a compression shirt, exerting graduated compression on the upper body.

2.1 Mechanisms

Athletes commonly use CGs because the applied pressure is believed to relieve exercise-induced discomfort which in return can be of advantage for a subsequent exercise performance (MacRae, Cotter and Laing, 2011). In general wearing a compression garment reportedly influences the following mechanisms of the body:
- Haemodynamic;
- Thermoregulation;
- Neuronal;
- Mechanical;
- Metabolism;
- Psychological.
Haemodynamic
The application of a CG reduces the volume of a limbs surface. This further affects the underlying tissue and the arteries/veins/lymphatic vessels located within the tissue. The compression reduces the diameter of the veins located in the limb, which means that the same amount of blood has to push through a smaller tubular space, resulting in a higher speed and thus a higher blood flow. As reported by Litter (1952), the application of 15 mmHg to the deep venous systems reduced its diameter from 2.65cm² to 0.53cm² (Sperlich et al, 2010). In its turn this also affects what we call the capillary filtration. Blood exits the arteries via capillaries¹ into the underlying tissue, to drop off oxygen for example. After dropping off the necessary substances it goes to the vessels via other capillaries to make its way back to the heart. If this process is being enhanced, the oxygenation of the tissues will also be enhanced (Agu et al, 2004; Ali et al, 2007; Bochman et al, 2005; Born et al, 2013; Davies et al, 2009; Ibegbuna et al, 2003; Ido et al, 1995; Kraemer et al, 2001; Lawrence & Kakkar, 1980; Lewis et al, 1976; Sear et al, 2010; Sperlich et al, 2010).

Since the arterial inflow is enhanced, the venous outflow is also enhanced. The amount of blood that enters the blood stream from the heart has to return to the heart in order for it to regain its substances (oxygen, nutrients) for it to return to the blood stream again and again (Ali et al, 2007; Davies et al, 2009; Ibegbuna et al, 2003; Lawrence & Kakkar, 1980; Lewis et al, 1976). On a bigger scale, an increase of arterial inflow and venous outflow increases the stroke volume² and cardiac output³ which results in a lowered heart rate (Sear et al., 2010). On the contrary, Duffield and Portus (2007) reported no changes in any form of blood flow as well as heart rate when a compression garment by manufacturer SKINS was used. However, studies such as Trenell et al (2006) did not report any changes in blood flow/blood flow related issues. Duffield and Porter (2007) reported metabolic changes when compression garments were worn, but no haemodynamic changes.

Thermoregulation
As mentioned before the blood flow in general could be enhanced by the application of CGs. According to Born et al (2013), Doan et al (2003) and Duffield et al (2007), Duffield et al (2010) and Houghton et al (2009) the blood flow through the skin decreases whereas the blood flow through the deeper tissues increases. A lowered blood flow through the skin decreases the evaporation which increases the temperature in the muscles. This is because heat cannot escape the body via evaporation. A higher muscle temperature is beneficial to sports performance, since it accelerates the delivery of nutrients and removal of waste in the muscles (Asmussen & Boje, 1945; Mohr et al, 2004). In turn the overall body temperature is also lifted, confirming the thermoregulatory influence of CGs (Sear et al, 2010).

Mechanical
Exercise usually results in damage to the muscles which we feel as muscle soreness. Eccentric motions are known to cause such damage (Prosk & Morgan, 2001; Prosk & Allen, 2005). An eccentric contraction is an unwilling lengthening motion muscle under pressure (this can be both an internal or external pressure). An example of this occurs when arm wrestling. You contract your biceps in order to withstand the pressure and keep your arm up, whilst the opponent exerts pressure onto your arm to make it go down by unwillingly lengthening your bicep. The contraction of the muscle together with the external pressure results in muscle damage to the motor unit⁴. The muscle tissue is overloaded and therefore stretched out, leaving it inoperable until it has recovered (Prosk & Morgan, 2001). Because of the muscle damage, the amount of functioning motor units decreases, which in turn increases the tensile load⁵ of the functioning motor units which increases their change to get damaged (Davies et al, 2009; Kraemer et al, 2004; Prosk & Allen, 2005).

According to Davies et al (2009) and Trenell et al (2006) the forming of a certain type of bonds within muscles is increased when CGs are worn and so decreases the muscle damage that occurs. The muscle oscillation, or vibration of the muscles, is lowered when compression is applied (Peters, Smith and Lauder, 2015). This decreases the muscles energy consumption and increases its performance, which in turn delays the overall fatigue of the muscle (Bakken, 2011; Doan et al, 2003; Cardinale et al, 2003, Rittweger et al, 2000; Rittweger et al, 2001). A decrease in muscle oscillation and increase in performance of the motor units also means less new functioning motor units need to be activated (Bottaro al, 2011; Bringard et al, 2006; Doan et al, 2003; Hsu et al, 2017; Kraemer et al, 1998; Scanlan et al, 2008).

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¹ Blood vessels that direct oxygen rich blood from the heart to the limbs and organs
² Blood vessels that transport blood with a low oxygen level back to the heart
³ The smallest of blood vessels located in the underlying tissue
⁴ The volume of blood pumped from a ventricle of the heart in one beat
⁵ The volume of blood ejected from the left side of the heart in one minute
⁶ A motoric neuron and the motoric fibers it stimulates
⁷ The load elongating the motor unit
**Metabolism**

Certain proteins can be found in the blood after exercise. Since they occur as a result of muscle damage, they are used as indicators or markers for muscle damage. An example of this is Creatine Kinase (CK). When wearing CGs the levels of CK were significantly lower, as reported by Davies et al. (2009), Duffield & Portus (2007) and Gill et al. (2006). A possible explanation is that the application of CGs reduces the amount of CK that is released (Trenell et al., 2006). Another possibility is the application of CGs enhances the clearance of CK and other proteins from the blood stream (Chatard et al., 2004; Davies et al., 2009; Kraemer et al., 2004). Berry & McMuray (1987), Bottaro et al. (2011), Born et al. (2013), Duffield & Portus (2007) and Sear et al. (2010) used blood lactate as a marker for muscle damage, and also reported decreases in the level of this protein in the blood stream.

**Psychological**

Besides affecting the above mentioned biological factors, studies (Bernhardt and Anderson, 2005; Desharnais et al., 1993; Goh et al., 2010) have shown that wearing CGs also holds certain psychological effects. Bernhardt and Anderson (2005) reported for example that 93% of their subjects believed that the CGs they wore were supportive, regardless of their actual performance. This might have occurred in the studies since the subjects were not blinded to the garment conditions (Desharnais et al., 1993; Goh et al., 2011; McManus et al., 2015). They most likely notice when they are wearing a compression garment and when not. It is likely that it also affected their perceived muscle soreness, since CGs are believed to help an athlete recover.

**Neurological**

Recent studies (Born et al., 2013; Michael et al., 2014; Pearce et al., 2009) have shown that the application of CGs also positively influences the proprioception of athletes. Proprioception is literally the perception or awareness of oneself, ones limbs and where these are positioned (Johnson & Soucacos, 2010). It also registers the movements of the limbs and body. This proprioception helps the nervous system in tracking and controlling the limbs during movements. Usually proprioception decreases when athletes get tired, resulting in a lesser motoric (Torres et al., 2010). When CGs are applied the proprioception is enhanced, which results in a better balance control of the body as well as posture (Born et al., 2013; Michael et al., 2014; Pearce et al., 2009). This is because the compression enhances the tactile sensory feedback that is being send to the nervous system by sensory neurons (Born et al., 2013; Michael et al., 2014; Pearce et al., 2009).

### 2.1.1 Performance & Recovery

Concerning an athletes performance there are various influencers. They include environmental factors as well as the time of the day and ones intrinsic motivation (Traegust, 2014; Traegust, 2016). Other factors, such as your diet, overall health, activity recovery and body proportions are of influence. Length can be an advantage when playing basketball for example (Morrison, 2013; Traegust, 2014). An athletes skillset (are you a professional or recreational athlete) and strength as in how powerful ones muscles are, ones flexibility and endurance is also an influencer. The balance control of an athlete in enhances posture control, which subsequently also influences an athletes performance (Michael et al., 2014). In the study Michael et al. (2014) they reported a significant improvement of balance control and posture control when well-fitted CGs were worn, suggesting further correlation between CGs and performance. In general the influence of CG’s on performance has to do with the affected mechanisms which throughout the exercise can affect for example ones speed and jump hight (Allsop, 2012). Ali et al. (2011) and Doan et al. (2003) reported an increase in sprint performance when CG’s were worn. They believed this was the result of a decrease in muscle oscillation due to the applied pressure (Allsop, 2012). Chatard et al. (2004) and Menetrier et al. (2011) however did not report any significant improvements to athletic performances.

As described before, the application of CGs affects the mechanical mechanisms in the body. By supporting and stabilizing muscles the muscle damage induced by exercise is lowered (Noonan and Garrett, 1999). Less muscle damage means less muscle ache and therefore also less recovery time that is needed to recharge before a subsequent exercise can be done. The psychological affects also relate to the recovery. When less pain is perceived, a subject is more likely to feel recharged and recovered sooner (Kraemer et al., 2001; Sperlich et al., 2010). It has been reported (Duffield and Portus, 2007; Duffield et al., 2008) that compression garments need to be worn, not only throughout the exercise, over the course of 24-48 hours after exercise and even during sleep to be of full effect on the recovery.

### 2.2 The development of CGs in sportswear

Sports compression garments are being produced in two different ways. On the one hand we have the more commercial companies that produce them based upon a predetermined size range. On the other hand there are made-to-measure garments. Figure 1 on the following page shows the development processes.

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1. Temperature/ weather conditions/ altitude/ ground surface
2. Driven by ones interest or enjoyment in the activity (Traegust, 2016)
3. Driven by the outcome of the performance in the activity (Traegust, 2014)
4. Height/ weight/ bone structure
5. The ability to continue or last
The garment is designed according to the body parts it needs to support.

In specialised software the necessary size reductions are calculated for the measurements of the basic size range to exert the desired compression.

The garments are fully knitted on a flat or round knitting machine.

First the pattern pieces printed and cut out of the desired fabric.

Sometimes the garments are made via Cut/Sew.

The pattern pieces are then sewn together by means of seams.

Once the garment is done it is fitted on a reference body.

Simultaneously the exerted pressure is tested.

Instead of using the basic size range, each and every customer is measured individually. The size reductions are then also calculated by the specialised software.

The fittings are also done individually and in person for each and every client.
When knitting, multiple yarns are used. The core is a lycra or elastan yarn, that is surrounded by multiple twisted synthetic yarns which are pleasant on the skin. Before the machine can start knitting, the elasticity of the core yarn and yarn tension, which influence the compression and stretch of the fabric. In the factory the climate conditions are daily measured in order to change the settings of the knitting machine whether necessary since the climate conditions can influence the properties of the knitting yarns.

As explained by Marga Koevoets in an interview with her, past research has resulted in various standards for medical compression garments (See the Appendix 9.1 Interview with Marga Aarts-Koevoets: Compression Stockings). However, for sportswear this is not the case. Since the use of compression in sports was influenced by its medical application, the compression strengths mirror this as well. An example of this is CEP sports. CEP sports is a producer of sports compression garments and articles, and is part of Medi\(^1\). They state on their website that the compression strengths they work with are the result of years of research and trials (Medi, 2017).

\(^1\) A producer of medical compression articles
2.2.1 Important factors

Important factors for CGs include the exerted pressure, the fit of the garment and the fabric used for the garment, as well as allowing freedom of movement (Cools, de Raeve and Bossaer, 2011; Liu et al, 2010). Each of these factors will be addressed so that in Chapter 4.0 an evaluation can be made whether or not 3D-VP software offers tools that allow for these factors to be taken into account.

Exerted Pressure

The first and foremost factor that makes a CG is the exerted pressure. Compression garments are adapted by professional and recreational athletes in order to support and aid their exercises. The CGs are not supposed to function just as regular sportswear, what sets them apart is that they are compression exerting clothing. As described at the beginning of this chapter, the fabric and the fit, which will be addressed next, take part in establishing the compression. In order to ensure the exerted pressure is correct, manufacturers check the compression via the use of specialised devices. This can be done on a HATRA Hose Pressure Tester Mk 2 or by using a Kikuhime or Picopress Pressure Monitor whilst the client is wearing the garment (McManus et al, 2015). As described in the appendix part 9.1 development of compression stockings, the HATRA Hose Pressure Tester Mk2 is a device containing a mechanical leg. The stocking is put on the mechanical leg and subsequently the exerted pressure is measured. The Kikuhime and Picopress Pressure Monitor are devices that can be used on a real person. The CG needs to be worn by someone, and by applying sensors on the body and therefore underneath the CG the compression can be measured (Partsch & Mosti, 2010). The exerted pressure also depends upon the position of the wearer, which is why the exerted pressure should be checked throughout various movements and positions in order to ensure that the compression is consistent (Aryal et al, 2002; Brophy-Williams et al, 2013). McLaren et al (2010) has also successfully developed a wearable device that can be used to test the dynamic compression, which refers to the changing exerted pressure depending upon the pose of the wearer. The introduced device showed accurate and comparable results to the Kikuhime and PicoPress devices. Further studies Belbasis & Fuss (2015) and Belbasis, Fuss & Sidhu (2015) have successfully described and developed the working of a smart CG by integrating several pressure sensing nodes to monitor the working of the muscles and the exerted pressure during movement.

Fit

As mentioned before, a CG is a garment with a compression fit. Commonly known fits are for example “loose fit”, “regular fit”, “skinny fit”. As was explained during the coaching for the minor Hypercraft by Sandra Kuijpers and Monique Broeke, compression is an even tighter fit than skinny, with the garments made very close to the measurements of the body (and sometimes even slightly tighter) (See Appendix 9.3 Hypercraft Notes). The fit is usually determined by the comfort1 and appearance2 of the garment. The shape of the wearer, characteristics of the fabric (which will be explained below) as well as the way the garment should be worn need to be taken into account. The fit can be analysed by looking at the following five factors (Boorady, 2011; Chen et al, 2006):

- grain of the fabric;
- construction lines;
- set of the garment3;
- balance4;
- and the ease.

CGs are an example of functional, performance wear which have a purpose they should enable. In this case the purpose is to enhance performance and recovery. The garments therefore need to accommodate the movements of the body, which can be done by adding additional functional ease on top of the wearer ease5 and style ease6 (Huang et al, 2012; Li et al, 2013). Whereas some compression garments are custom made and individually fitted (Marqués-Jiménez et al, 2015), commercially manufactured compression garments are made according to generalized/standardized sizing systems based on generic anthropometric features such as weight, height and circumference. This means that they use average measurements in order to target a broad group of customers. A manufacturer can create a continuous stream of products without having to individually measure a customer and fit a garment. Studies (Aryal et al, 2002; Chowdhury et al, 2012; Dascombe et al, 2013; Davies et al, 2009; MacRae, 2011) have shown that this results in varying sizes due to the variations in body dimensions of the wearers. This in turn, results in varying compressions that are applied to the body which can even differ depending on the posture of the wearer (Aryal et al, 2002; Wertheim et al, 1999). In the study Michael et al (2014) a significant improvement of balance and posture control was reported when wearing well-fitted CGs. Additionally they also studied the effects of loosely fitted CGs, which showed no improvements what so ever, showing the importance of the fit on its possible benefits.

1 Determined by the individual wearing the garment
2 Referring to the look/style/fashion of the garment
3 Referring to the idea that a well-fitted garment should have no wrinkles when the person is standing still
4 Whether a garment is symmetrical and hangs away from the body identically on both sides of the body
5 The ease added to the garment that enables moving and performance in everyday tasks
6 The ease chosen by the designer to create the desired silhouette
Freedom of Movement

Sports CGs are meant to assist athletes throughout their workout. They are meant to be worn during exercise to enable the athlete to experience how application of CGs affects the previously mentioned mechanics. Since it is supposed to be worn during, and after exercise and therefore needs to enable the wearer to execute the exercise (Zwane, 2015). The fabric plays a role in this, by offering enough stretch to allow for movements to happen. Other ways to establish this are the creation of muscle-based panels and the use of dynamic body scanning. Muscle based panels means that during the pattern making process the shape of the panels mimics the shape and location of the muscles. Different movements require different muscles to contract or relax. When a muscle contracts or relaxes it changes shape, meaning that a muscle might need more space in the garment or more elasticity in the fabric. This also requires for dynamic body scanning, where the different poses of a certain movement are identified and analysed (Aryal et al, 2002; Liu et al, 2010). Muscle based patterning might solve this problem since it allows for different fabrics to be used in different parts of the garment. Figure 3 on page 14 is an example of a compression garment with muscle based patterning. The legging in this case contains pattern devisions based upon the shape and placement of the muscles in the upper and lower leg. Figure 4 on the right shows an average percentage of the increase in length of certain body parts when bend or compared to when standing straight.

According to Cools, de Raeve & Bossaer (2011) the issue with fit is a problem for any commercial brand relying on a standardized size range. Only 30-40% of their customers actually fits the clothing well. When targeting a new group of customers this can even be reduced to only 10%. A study by the French fashion institute Institute Francois de la Mode in 2006 (Assouly et al, 2007) reported that 39% of the questioned women and 24% of the questioned men found it hard to find a properly fitting garment. This has to do with the fact that the standardized measurement systems present do not represent the whole customer base of a brand. Globally there is no uniform sizing system, which means that depending on the clothing manufacturer the used sizes might differ from others. This also has to do with the fact that the patterns for a full size range are usually created by grading. This means that the different measurements of a pattern are reduced or increased by an amount that is sometimes based on an educated guess (Li & Lu, 2011). For every company, as well as every style, these steps might be different, resulting in an even bigger inconsistency of size (Cools, de Raeve and Bossaer, 2011; Daanen, 2014; Olaru et al, 2014; Thomassey & Bruniaux, 2013).

Fabric

The fabric of the garment is also of great importance to the exerted compression of a CG (Troynikov et al, 2013). The construction, physical parameters, performance attributes and tensile characteristics of the fabric all play a role in this (Troynikov et al, 2010; Macrae, 2011). Most commonly knitted fabrics are used because of their stretch and recovery properties. As reported by Wardiningsih et al (2013) the exerted compression increases when the extension of a fabric increases. They allow the wearer freedom of movement and make sure the garment maintains its intended shape, which is of great importance since fabric fatigue is a well-known problem that occurs after wearing (Kozar et al, 2014; Troynikov et al, 2010; Senthilkumar and Anbumani, 2011). During a movement the body skin can extend by up to 50%, which the fabric will need to allow in order for the wearer not to be restricted (Senthilkumar et al, 2010). Extensive fabric testing is necessary in order for the characteristics and properties of the fabric to be determined.
Figure 4: an average percentage of length increase of certain body parts when muscles contract (Allsop, 2012; Voyce et al, 2005)
3.0 3-D Virtual Prototyping

3.1 The software programs

As mentioned in the introduction, 3D-Virtual Prototyping (3D-VP) can simply be described as the use of specialised computer software in the prototyping stage of a clothing brand. Within this thesis only the pattern based applications specialised in garment construction and simulation are looked at. Providers of the software include Browzwear, Clo3D, Gerber, Lectra Modaris, Optitex and TukaTech. The software used for 3D-VP is called Computer Aided Design (CAD) and consists out of a 2D and 3D part (Decaudin et al, 2006; Cugini & Rizzi, 2002; Stjepanovic et al, 2010; Volino et al, 2005; Wang & Tang, 2010). Its use is a recent trend in many industries, and is said to have various advantages to apparel companies that lower their sampling costs and increase their efficiency (Olaru et al, 2014; Siersema & Klijpers, 2011; Wang et al, 2005). It is for example very easy and quick to make changes to a design. It is only a matter of a few mouse clicks and responses from the software. The sampling time, that can take up to 70% of the development stage (Power et al, 2011), can be reduced by 20%-50% (Chowdhury et al, 2012; Papahrístou et al, 2016; Stjepanović et al, 2010; Volino et al, 2005; Wu et al, 2011). Another advantage is that fittings can be done virtually and do not require the physical presence of a customer (Chowdhury et al, 2012).

There are also reasons why companies might hesitate looking into 3D-VP. Due to the size and complexity of the software, obtaining a subscription as a company can be quite the investment. Nevertheless the prospect of adding 3D-VP to your company is believed to be cost-efficient over time (Papahrístou et al, 2016). The complexity of the software also means one needs training to be able to work with it. This means another time-, and possibly money-, investment before the software can be effectively introduced (Siersema, 2015; Thomassey & Brunieux, 2013).
Due to the adaptation to 3D-VP of innovative and influential sports brands, such as Nike and Adidas, the popularity of 3D-VP has expanded beyond the fashion market into fashion education (Dabolina & Vilumsone, 2012; Siersema, 2013; Lectra Modaris, 2011; Siersema & Kuijpers, 2011). The software is celebrated because the garments are easily adaptable to quick changes (Jevsnik et al., 2012), allowing for a lot of experimentation. Since we see a rise in adaptation of 3D-VP amongst brands, the incorporation of 3D-VP within education is also a great way to prepare students for their future career (Taylor et al, 2005).

3D-VP offers the ability to build a virtual model based on a real product, without the necessity to physically produce this product. Within the 2D part one can create a network of points, which are accurately connected by straight or curving lines to create the shape of a 2D pattern (similar to a paper pattern). When a perfect pattern is created, the patterns need to be arranged and the stitching needs to be assigned. After this the pattern pieces can be exported and imported into the 3D part. Within this part an avatar needs to be chosen, on which the imported pattern pieces need to be placed and draped around. Once this has been done successfully the garment can be fitted and whether necessary adjusted. Subsequently the appearance of the garment can be designed. Via different tools, colours can be assigned to the pattern pieces and prints can be placed upon the garment. Fabrics, which the according characteristics, can be linked to certain pattern pieces to enhance the realistic appearance. In part 3.2 Tools of the Software the most important tools will be highlighted. Part 3.3 will describe the necessary steps to create a 3D-VP prototype will be described.

### 3.2 Tools of the software

#### Fabric Testing and Parameters

The simulation of the fabrics is another key element to the 3D part of the software (Volino et al, 2004). For the fitting to be effective, the characteristics of the actual fabric need to be applied to the garment (Chowdhury et al, 2012). Depending on the type of fabric the fit and outlook of the garment differs. Because of this the software programs contain special simulation models which can be altered. Via specialised fabric tests, such as FAST-testing and the KES-FB measuring system, fabric properties like the extension, bending rigidity, shear rigidity, surface thickness, mass per unit area, compression, and tensile are measured. These can subsequently be inserted into the software and applied onto the fabric used for the virtual prototype. Whereas FAST only tests the linearity, KES-FB also tests the nonlinearity of the fabric. This allows for the deformability and nonlinearities (such as folds and wrinkles) of the fabric to be taken into account as well (Volino et al, 2007; Magnic-Naglic et al, 2016; Volino et al, 2005). Sometimes programs such as Fabric Converter are used before the measurements can be inserted into the 3D CAD-software.

The main fabric properties that are important for virtual simulation applications are tensile, bending, compression and shear characteristics (Ancutiene et al, 2010; Ghosh & Zhou, 2003; Kozar et al, 2014). These characteristics are important since they influence the drape and handle of the fabric, and thus the appearance of it. Another important fabric property is for instance the friction of the fabric against the body, since this greatly affects how comfortable the eventual garment is to wear (Ancutiene & Sinkeviciute, 2011; Lectra Modaris, 2011).

#### Dynamic Movement

Some of the software, like Lectra Modaris, only offers the option to fit your garment on an avatar in static T-position, with the sole option to lower the arms for a more “relaxed” pose. Others like Clo3D and Browzwear offer the option to add animations to your avatar in simulation mode (Volino et al, 2004). This means that the avatar can move in certain directions and in different ways. Browzwear even has the option to have your avatar do sports related manoeuvres. This offers the option to look at the fit and strain maps during one of these animations, which enhances the assessment of the fit (Browzwear, 2017).

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1 A pattern with the correct measurements and necessary reference points and marks, ready to be printed and subsequently used to cut patterns
The Avatar & 3D Body Scanning

The avatar, or 3D body model, is one of the key elements in the 3D part of the software (Volino et al., 2004). In order for the fitting to be accurate and precise, the measurements need to be as realistic as possible and resemble the targeted customer. Commonly the software programs offer a variety of avatars based on so called parametric models. This means that the avatar is based upon various parameters, each parameter corresponds with an anthropometric measurement, such as the length and waist circumference (Dong et al., 2014). These parameters can be modified within a certain value range (Dong et al., 2014; Stjepanovic et al., 2010). Parameter based avatars are known to be symmetrical, since the parameters are not divided per body side or limb. The measurement for the length of the leg and circumference of the thigh are linked to both legs. Many brands prefer symmetrical avatars since they allow for an easier pattern making process. A pattern has to be created for one side of the body and can then simply be mirrored, since the body is symmetrical. A downside from the used models is not a flexible surface. Human bodies are made up out of soft tissue, which means that the surface is flexible. It responds to pressure by reducing its surface and becoming more compact, and expands when the pressure is removed. Two decades ago Nebel (2001) already described a method of soft-tissue modelling based on 3D-body scans, however these models have yet to be implemented into the apparel-specific 3D-VP programs. The non-garment-specific program Abaqus however has implemented forms of such soft-tissue models, allowing one to create a compression garment and use a contact-pressure tool to calculate the exerted pressure on the body in the commonly used unit for compression mmHg (Tarrier, 2010). Park & Hodgins (2008) also successfully simulated avatars based on these soft-tissue models. More recently Pons-Moll et al. (2015) and Kim et al. (2017) worked out a method to successfully animate such soft-tissue model-based avatars.

With the introduction of commercially used 3D body scanners, a new type of avatars has arisen. Via a single camera, or multiple cameras, the shape of the body is captured in a so called point cloud, containing up to 600,000 points, which is then transformed into a surface mesh (Dong et al., 2014; Feng et al., 2015; Han & Nam, 2011; Jevsnik et al., 2012; Liu et al., 2010; Luo & Yuen, 2003; Power et al., 2011; Stjepanovic et al., 2010; Tarrier et al., 2010; Taylor et al., 2005; Wang et al., 2003). Contrary to avatars based on parametric models, avatars based on 3D body scans are not symmetrical. This is because they accurately scan the actual shape of the body, and our bodies are not completely symmetrical by nature. Some scanners are not able to generate enough information which leads to defect avatars. In this case the 3D body models need to be reconstructed via the use of specialised software programs¹ (Tarrier et al., 2010; Zhang et al., 2016).

¹ Such as Anthoscan 3.0.4, Atos, Blender, Rhino 4.0, Netfabb, Meshlab (Stjepanovic et al., 2010)
In other cases the generated scans might be too complex. The mesh will then have to be reduced which deforms the realistic body shape (Magnic-Naglic et al, 2016).

**Fit tools**

As mentioned before, the fit of the garment is of great importance. This is especially important for performance wear, since an incorrect fit could withhold the wearer from moving (Gregorcic et al, 2011; Yu, 2004). Within the 3D-VP software, specific tools have been created to assess the fit of the garment, which are the so called fit, strain and stress maps (Ancutiene & Sinkeviciute, 2011; Lee et al, 2007; Lee et al, 2013; Olaru et al, 2014; Surville, 2010; Wang & Tang, 2010). The stress map shows the stress per unit on a fabric. It will show the different tensions in different colours and numbers (gf/cm², kPa, mmHg) and takes the stretch of the fabric into account. Figure 7 on the right shows the stress map in Marvelous Designer. The strain map is a geometrical measure of garment deformation (Ancutiene & Sinkeviciute, 2011). It takes the extension and elasticity properties of the fabric into account and analyses how the actual pattern deforms while worn (Milne, 2016) and is therefore a good indication whether more fabric needs to be added or taken out at certain spots (Tarrier et al, 2010). The fit map shows the distance to the body and thus how tight the garment is when draped around the body. This can be easily used to determine whether a garment actually has the desired amount of ease (Ancutiene & Sinkeviciute, 2011). Additionally pressure points show where the garment comes into contact with the body of the avatar, due to a lack of ease. The pressure points cannot measure the actual pressure since the avatar does not have a soft-tissue surface like human bodies do. In contrary, Tarrier et al. (2010) worked with the Abaqus software (which is not garment-specific) to create a compression garment and fit it on an avatar. They reported that the program offers a contact pressure tool that calculates the applied pressure in mmHg. The software is able to do this since a soft-tissue model was applied on the avatar to imitate the soft-tissue of human bodies (Tarrier et al, 2010).

![Figure 7: the stress map shown in Marvelous Designer (Marvelous Designer, 2017)](image)

![Figure 8: Desk of stitches in Lectra Modaris: where information concerning seams and seamtotypes is inserted (picture of own work during the Hypercraft minor)](image)
3.3 The development process in 3D-VP

As described by Salman (2011) the (partial) implementation of 3D-VP by fashion brands resulted in changes to their pre-existing design and development processes (Siersema, 2015). As mentioned before, 3D-VP consists of a 2D and 3D part. Depending on the company it might differ whether they work with both parts or just one of them. Since I am looking at the whole of 3D-VP, the development process in both parts will be described. They are used by companies in addition to/instead of parts of their traditional development process (Chowdhury et al, 2012; Thomassey & Bruniaux, 2013).

In 2D you either start from scratch or use a basic block. A basic block is a template pattern (Huang et al, 2012; Lectra Modaris, 2011; ) of a rather basic design, containing proper fit. This design will be changed to look like the desired design and completed until it is a perfect pattern. Otherwise a new pattern will be created from scratch. Similar to drawing a paper pattern, a digital pattern is created by connecting reference points with lines. These eventually form a closed shape (Lectra Modaris, 2011; Luo & Yuen, 2003; Rizzi & Cugini, 2002). Afterwards information can be added to the pattern document. Seams need to be defined as well as the according stitching (Dabolina & Vilumsone, 2012; Cichocka et al, 2014; Rizzi & Cugini, 2002; Tisserand & Magnenat-Thalmann, 2015). Figure 8 on page 21 shows the Desk of Stitches in Lectra Modaris, which is the menu where information regarding the seams and seamtypes needs to be inserted. After this the garment can be imported into the 3d part. Figure 9 on the right shows the 3d process 3D-VP.

Different from regular patterning, seam allowance does not have to be added to the patterns in order for the software to simulate the stitched garment. The fabric necessary for the seam or stitching is not taken into account, and not necessary since the two lines of the two corresponding lines from the pattern pieces are simply connected. The simulation of the actual seams is, partially due to the absense of seam allowance, not accurate. Lectra Modaris for instance offers the option to add stitching to the garment as a type of trimming, which is more visual than functional (See Notes on Hypercraft, 2017). There is in 3d the option to simulate two layers on top of each other. The simulation does not go as smoothly as the baselayer however, the second layer does not drape as nicely and is being pulled towards the baselayer. Figure 6 on page 20 shows the insertion of a second layer, with the subsequent deformation since the garment is being pulled towards the baselayer.

Some 3D-VP programs, such as Lotta and YDT (Papahristou et al, 2016), offer the ability to construct patterns in 3D (Bartle et al, 2016; Huang et al, 2012; Li & Lu, 2014; Magnic-Naglic, 2016). Within a 3d environment the contours of the garment are defined by placing anthropometric points around the body. They are placed at a certain distance from the body which corresponds with the eventual ease of the garment. After the points are connected, the shapes are flattened and turned into a pattern surface. These so called 3D-2D programs are however not always usable. Garments created via this way are not always usable since flattening the patterns sometimes reshapens them (Decaudin et al, 2006; Li & Lu, 2011).

3D-VP software can also be used in different ways. In 2D, once the perfect pattern is created, there is in some programs also the option to prepare the patterns for actual production. They can be proportionally graded according to the full size range (Lectra Modaris, 2011). Next a marker or inlay can be made of all of the pattern pieces. This can either be done manually or automatically by the software to get the most efficient marker that is possible. Once the marker is made, it can be plotted and printed, after which the print can be applied onto fabric and the pieces can be cut out. Within its simulation 3D-VP is not only suitable for use in the development process, but goes beyond this phase. It is also often used by companies as a communication tool or selling tool. With the increasingly realistic simulation and animation options imagery of the digital garment is suitable to use as a selling tool because it gives such an accurate and beautiful view of the product.

3.4 Related Work

In previous years there have been reports that were focussing on product development related methods that incorporate the use of 3D-VP. Some are related to the designing of a method to fully design a garment in the 3D part of 3D-VP (Au & Ma, 2010; Durupinar & Gudukbay, 2007; You et al, 2002). Others focus on the automatic pattern generation for a whole sizerange based on a single size pattern (Meng et al, 2012), or the development of basic blocks in 3D that can be flattened into accurate 2D patterns (Huang et al, 2012). Brouet et al (2012) designed a method to automatically transfer garments from one avatar to the other. This does however alter the fit of the garment, since the measurements of the avatar change whilst the garment measurements do not. This method is also pose-dependent, avatars need to be placed in T-position. Lee et al (2013) Li et al (2010) designed a method to automatically transfer the garments from one avatar to another that is pose-independent. Olaru et al (2015) described an effective method to work with basic block patterns for atypical bodies.
Either a basic avatar is chosen and edited, or a 3d-body scan is imported.

The pattern pieces need to be imported and applied around the avatar and draped.

The pattern pieces need to be virtually stitched together according to 2D information and the garment can be simulated.

Fabrics can be applied onto the garment by using the existing database.

Custom measurements can also be inserted after specific fabric testing.

Next the garment can be styled: colours can be added and prints applied, as well as trimings like taping and stitching can be added.

Some programs offer the option to add animations to rendered simulations.

If the fit is incorrect the 2d pattern can be adjusted and the 3d file updated afterwards.

When the fit, drape and look are correct the garment can be rendered to show perfect texture and to add light and shadows.

Other examples include Thomassey & Bruniaux (2013) whom described a method to calculate suitable ease allowance for designs. Also Lee et al (2013), whom described a method to automatically apply a garment on an avatar that is placed in various positions and subsequently fit the garment. Kim & Kang (2002) developed a method to automatically generate garment patterns based upon body scan data. Cordier et al (2003) even turned such a fit method into a web application for webshops to fit and resize garments. These studies show how the possibilities of 3D-VP software have successfully been expanded.

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Compression Sportswear & 3D-Virtual Prototyping

The aim of this thesis is to research the working of compression garments and 3D-VP software in order to assess whether the software could be used in the development process of CGs and if it holds any beneficial tools. In Chapter 2.0: Compression the use and creation of CGs was thoroughly analysed in order to find out what a garment requires to be a proper CG. Chapter 3.0: 3D-Virtual Prototyping next analysed the virtual prototyping applications and its possibilities, to find out what tools the software has that could be suitable for CGs. In this chapter the requirements of a CG will be aligned with the tools of the software, to evaluate whether or not the software holds all of the necessary components to be implemented in the development of compression garments.

Based upon Chapter 2.0: Compression we can identify a number of requirements, such as a proper, individual fit, a fabric with high elasticity and recovery properties, the garment needs to actually exert a pre-determined amount of pressure, and lastly the garment needs to allow freedom of movement for the wearer.
The modelling of fabrics is one of the founding principles of 3D-Virtual Prototyping software. Complex models allow for the various properties of fabrics, beyond the weight and the thickness, to be applied onto the garment to simulate various different fabrics. With this comes also the option to insert custom values for the various properties in order to simulate a specific fabric or experiment with the settings. After rendering accurate surface textures are simulated which enhance the visualisation of the garment.

Exerted Pressure/Compression
One of the most important, and obvious, factors for a CG is the compression it applies to the body. As mentioned by Ronald van Oers (see Appendix 9.2 for the full interview with Ronald van Oers) a CG needs to exert pressure. Manufacturers use specialised software that calculates the correct dimensions the garment should have so it exerts the right amount of compression. Next they use specialised machines, such as the Kikuhime or Picopress Pressure monitor (McManus et al, 2015) which are used to measure the exerted pressure whilst the garment is being worn. Although 3D-VP holds different fit tools, these do not measure the actual compression. The tools can be used to find out whether the garment is touching the avatar but does not allow to visualise the exerted pressure. This is also due to the fact that the commonly used avatars are not made up of soft-tissue like our bodies. Tarrier et al. (2010) showed that it would be possible to successfully calculate pressure when using a soft-tissue model-based avatar.

Freedom of Movement
CGs that are targeting athletes need to function as regular sportswear, with the addition of exerting pressure. This means that the garment needs to support and assist the wearer throughout its efforts. The activity cannot be obstructed but needs to be enabled by the outfit, meaning that it is of great importance that the compression outfit allows the wearer to execute all the necessary movements and positions. One way to ensure this is to fit the garment whilst the body varies in posture and position. In 3D-VP applications, such as Browzwear and Clo3D, we see that it is possible to fit a garment on an avatar and have the avatar perform various animated poses and walks in simulation mode. This comes with the option to use the fit tools in some of these different poses. However the animations include very little exercise-related options. On top of that, the avatar, as described earlier, does not have a soft-tissue surface like we do. It therefore also does not reflect or take the changes in muscular shape into account.

Individualised Fit
As mentioned before, the fit is of great influence when it comes to CGs. This has to do with the compression that depends on the tightness of the garment around the body. The use of standardized sizes by commercial sports brands result in a fit that is not coherent. Since each and every customer in their target group has different dimensions to their body, they will all fit the garment differently (Chowdhury et al, 2012) which eventually results in a varying compression level exerted on the different customers. It is therefore of great importance that CGs are individually fitted and developed since this results in a correct fit and therefore appropriate support and compression.

For commercial sports brands to develop individual patterns manually, would be a very cost-intensive process since each pattern will have to be drawn from scratch (Cools, de Raeve & Bossaer, 2011). Via the use of 3D-VP this would be different however. Not only is it faster to construct a pattern from scratch, it holds the option to alter a pre-made basic block. This shortens the time to create a fitting pattern even more (Lectra Modaris, 2011). It is also believed that the use of 3D Body Scanning is suitable to resolve the issue with fit is resolved and to secure a consistent fit. It is a relatively quick technique to gain all anthropometric measurements that can be inserted into the 3D-VP software to create a custom avatar. So not only does it give you instantly all of the anthropometric measurements to construct a pattern, there is the option to create a custom avatar to fit the garment on. The ease maps can be used to check the fit and see whether or not the garment is big enough for the body to wear.

Fabric with specialised properties
The fabric is another key component of a CG. Not only does the elasticity and stretch properties of the fabric allow for wearers to be able to put the extremely tight fit on, properties such as the recovery are important since they play a role in the durability of the garment. This has to do with the fact that the recovery allows for the garment to return to its original fit after it has been worn instead of getting out of shape (Ancutiene et al, 2010; Ancutiene & Sinkevičiute, 2011; Macrae, 2011; Power et al, 2011; Senthilkumar et al, 2010; Senthilkumar & Anbumani, 2011; Troynikov et al, 2010; Umar et al, 2015).
Discussion & Feedforward
As stated in Chapter 4.0, we can identify a number of requirements, such as a proper, individual fit, a fabric with high elasticity and recovery properties, the garment needs to actually exert a pre-determined amount of pressure, and lastly the garment needs to allow freedom of movement for the wearer. Commercial sport brands work with average/standardized size ranges and the corresponding measurements, which leads to an inconsistency in compression. For sports brands the size of Nike or Adidas, it is simply not manageable to produce made to measure garments for all of their consumers. Smaller companies that do work on a made-to-measure base, usually incorporate multiple fittings into their development process to find out whether or not compression garments fit properly and exert the appropriate compression. By incorporating 3D-VP into their development process, they can individually adapt their avatar to the customers measurements and subsequently use the fitting tools of the software to figure out whether the garment fits properly. Since fabric characteristics can be applied onto the garment for a very realistic and accurate visualization, experimentation with various fabrics can be done without necessarily having to develop multiple CGs in various fabrics. On top of that you can animate the avatar in some software programs. This offers the ability to analyse the fit of the garment throughout movements. For this moment it is very likely that 3D-VP can be used for a large part of the development process of CGs, however the creation of a physical sample will still be necessary in order to measure and check the exerted pressure.

We see however that due to the fact the avatars do not have a soft-tissue surface like real humans, it would not be possible to analyse the exerted pressure on the body. However, as described in Chapter 3.0, we see an increase in studies that successfully expand the possibilities of 3D-VP (Au & Ma, 2010; Brouet et al, 2012; Cordier et al, 2003; Durupinar & Gudukbay, 2007; Kim & Kang, 2002; Lee et al, 2013; Li et al, 2010; Meng et al, 2012; Olaru et al, 2015; Thomasset & Bruniaux, 2013; You et al, 2002). It is therefore reasonable to assume this is an issue that could be resolved in future studies. Currently manufacturers of CGs work with specialized software programs that calculate the size reductions that are necessary for the garment to exert a certain amount of compression. With the previously mentioned studies, that worked out methods expanding the possibilities of 3D-VP, in mind, there might be a possibility to expand the software specifically for the creation of CGs. As mentioned before there are already fit tools present. The fit map measures the tightness of the garment around the avatar. This tool could be further worked into a similar tool as the contact pressure tool in Abaqus (Tarrier et al, 2010). With recent studies in mind it is also very likely that the integration of soft-tissue models will be introduced for apparel-specific 3D-VP programs. Additionally a new tool could be introduced that incorporates the calculation of necessary size reductions of a garment in order to get to exert a specific compression.

Feedforward
Concerning the initial research for Chapter 2: Compression there are a lot of studies and reviews to be found related to both medical as well as sport compression garments. However, what became evident was that there is a lack of coherency amongst these studies. Most of the studies report at some point that there is still not enough significant evidence to support all of the benefits of CGs on sport activity and recovery. On top of that, not all of the studies confirm the same hypothesis. In literary reviews, such as Marqués-Jiménez (2015), one can clearly see that the studies do not form a united front when it comes down to their results. The studies suggest that the differences in test results have to do with differences in the structure of the tests. The test procedures (such as the type of activity, duration of the activity, duration the CG is worn) and products used (type of compression garment, applied compressive pressure, area the compression is applied to) are all factors that differ per study (Born et al, 2013; Bottaro, Martorelli and Vilaça, 2011; Duffield et al, 2008; Brophy-Williams et al, 2015; Goh et al, 2010; MacRae et al, 2011; Marqués-Jiménez et al, 2015; McManus, Murray & Morgan, 2015; Sear et al, 2010; Sperlich et al, 2010; Sperlich et al, 2013). Marqués-Jiménez et al (2015) even executed a meta-analysis of current literature at that time, and came to the conclusion that a lot of method and subject related factors were inconsequent. Sperlich et al (2010) also mentions that some of the studies are bias, since they are initiated and/or sponsored by companies producing compression garments. Another suggested explanation is the use of incorrect control situations. Some of the garments used in these control situations still exert some sort of compression, and are therefore not reliable to use as a neutral garment.

Since there is currently not a uniform standard for CGs, it is my advice for future studies to focus on generating such a standard. The first step in doing so is to generate standardized test results that are suitable for comparison. In the past tests were based on recommendations of manufacturers of CGs (Driller & Halson, 2013; Ménétrier et al, 2011; Rugg & Sternlicht, 2013). Instead future studies should be based upon different compression profiles in order to find out clearly what level of compression affects the body in which way.
Limitations
Initially, as part of the methodology, there were interviews planned with some of the commercial developers of compression sportswear, such as Adidas / O’Neill / Nike / Satisfy / Skins / Under Armour. In the end however I was not able to contact these companies. The planned interviews with Monique Broeke – Pattern Maker at O’Neill – and Esther Greveling – orthopaedic therapist – were also not conducted in time. Instead interviews with Marga Aarts-Koevoets – self-employed measurer for compression stockings and salesperson of orthopaedic products – and Ronald van Oers – Osteopath – were conducted to shine light on the development process of medical compression products. This was later used as a foundation to assume what the development process of sports CGs looks like. It would be my advice to future studies to reach out to commercial sports brands to find out how they actually go about developing their CGs and what they base their compression strengths on. On top of that I would suggest they reach out to manufacturers, such as Medi, since they have been producing compression garments for multiple decades and have a lot of expertise about this topic. In order to find out the development process of compression garments in sportswear, various sportswear brands have been reached out to. Due to a lack of responses and time, this however did not result in proper insight into their development processes. Therefore the development process of support stockings, as can be found in the appendix part 9.1, is used as a base to assume what the development process of sport compression garments looks like.
Conclusion
In recent years we have seen an increase in 3D-VP software that has been targeting the apparel market. Simultaneously we see an increase in CGs offered by sports brands for both professional and recreational athletes. The aim of this thesis was to identify the possible benefits 3D-VP could offer to the development of CGs. In this way the thesis can answer the research question: “How can 3D-VP be used to develop compression garments for the sportswear market?”. It was my hypothesis that 3D-VP holds useful tools that could contribute to and even improve the development of CGs. Chapter 2.0 Compression found that important for CGs are various aspects. These include the exerted pressure, the used fabric with high stretch and recovery properties, the skin-tight fit of the garment and the fact that the CG needs to allow freedom of movement. As stated in Chapter 4.0, we can identify a number of requirements, such as a proper, individual fit, a fabric with high elasticity and recovery properties, the garment needs to actually exert a pre-determined amount of pressure, and lastly the garment needs to allow freedom of movement for the wearer throughout the sport activity. On top of that an issue with the fit was identified, since commercial companies work with standardized sizes that result in varying compression levels. Chapter 3.0 3D-Virtual Prototyping analysed the possibilities of the software, highlighting tools such as the customization of avatars, the adaptation of fabric properties, the various fit tools and the ability to add animations in simulation mode. To a fair extend do the tools of 3D-VP give an answer to the necessities of CGs, however since most avatars are not based on a soft-tissue model yet the software is withheld from replacing all physical prototyping stages. Nevertheless 3D-VP software is considered a good and suitable investment for companies expanding into CGs, since it allows for relatively time- and cost-efficient experimenting as well as the individual development of CGs.
8.0 Sources


Appendix
4. The garments are usually fully knitted on a flat or round knitting machine. When knitting, multiple yarns are used. The core is a lycra or elastan yarn, that is surrounded by multiple twisted synthetic yarns which are pleasant on the skin. Before the machine can start knitting, the elasticity of the core yarn and yarn tension, which influence the compression and stretch of the fabric. The manufacturer also takes the climate conditions into account on a daily base. The temperature and humidity are moderated and controlled daily, since they might affect the behaviour of the yarns. Whether necessary the settings of the knitting machine are adjusted.

5. During knitting, the amount of working needles can be adapted to shape the garment according to its destined form.

6. After knitting, if the garment was knitted on a flat knitting machine, the garment needs to be finished via sewing. Seams need to be closed and hems need to be stitched on the edges.

7. When the garment is done, the exerted pressure needs to be measured and checked. This can for example be done via a HATRA Hose Pressure Tester Mk 2 (McManus et al, 2015). These devices will be explained later on.

8. After roughly five workdays the garment is finished. The garment then needs to be fitted on the patient. This means that it will be send to the person in charge of taking the measurements. This person will also execute the fitting and evaluate whether the garment is correct.

9. In case the fit or compression of the garment is incorrect, the design needs to be adjusted if this is possible. Otherwise a new sample needs to be produced and fitted again.

9.1 Interview with Marga Aarts-Koevoets:
Compression Stockings

In order to sketch an overview of the development of sports CGs, the development of medical compression stockings was described during the interview with Marga Aarts-Koevoets.

The figure shown below was based upon the following step by step description of the development of compression stockings, sketched by Marga Aarts-Koevoets.

The made-to-measure production:
1. The manufacturer already has basic designs for its various compression articles. Depending on the patient’s needs the appropriate article is chosen.
2. Next the measurements of the applicable body part are taken in person according to the form that can be seen in figure 15 on page 44. On this form the specifics of the shape and finishing of the garment are indicated and faxed to the manufacturer.
3. These measurements are then inserted into a custom measurement chart and imported into a specialised software program by the manufacturer to calculate the size reductions. A basic design for the garment is altered according to the custom measurements (Istook, 2002).

Figure 10: Flow chart of the development process of Compression Stockings based on the interview with Marga Aarts-Koevoets

1. The garment is designed according to the body parts it needs to support
2. In specialised software the necessary size reductions are calculated for the measurements of the basic size range to exert the desired compression
3. The garments are fully knitted on a flat or round knitting machine.
4. Once the garment is done it is fitted on a reference body Sometimes the garments are made via Cut/Sew

First the pattern piece printed and cut out of the desired fabric
The pattern pieces are then sewn together by means of seams

1. Instead of using the basic size range, each and every customer is measured individually. The size reductions are then also calculated by the specialised software
3a. The fittings are also done individually and in person for each and every client
4a. Simultaneously the exerted pressure is tested
In general medical compression garments have a lifespan of at least a year, due to the fact that insurances only reimburse one garment a year.

There are no uniform standards for the use and creation of compression. In the medical field however, standards exist for various countries. The United Kingdom has three British Standards, as shown in figure 11 below.

At the bottom figure 11 shows the values corresponding to the British Standards. It shows that a garment is developed based on a range of graduated compression values. At the ankle the compression is 100%, and further upwards the compression decreases up to a certain percentage of its total value. In this way the return of the blood to the heart is stimulated the most.

What has also been taken into account is the proportion of original compression after 30 washes in percentages. This means that for two of the British Standards the CG must at least contain 85% of its original compression after the amount of washes.

As mentioned before, compression can be applied graduated, uniform or progressive. There has however not been significant research into which of these types is most efficient, especially not performance and recovery related (Born et al., 2013; Davies et al., 2009). Commonly the compression is gradually divided over a limb (in this case a leg) as it would be done for graduated compression stockings. The highest amount of compression is applied at the ankle (100%). This is then reduced to 80 or even 50% at the height of the calf, and even further reduced to 40 or 20% at the thigh (Morrison, unknown date).

<table>
<thead>
<tr>
<th>British Standard</th>
<th>Garment compression range (mmHg)</th>
<th>Compression value at ankle (mmHg)</th>
<th>Compression profile: proportion of ankle compression at calf (%)</th>
<th>Compression profile: proportion of calf compression at thigh (%)</th>
<th>Stiffness: variation in compression for normal former size ++ 1 for each girth (%)</th>
<th>Durability: proportion of original compression after 30 washes for each girth (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS 6612</td>
<td>6 to 10</td>
<td>Stated value +9% + 1</td>
<td>Less than 100</td>
<td>Less than 100</td>
<td>25 max.</td>
<td>85 min.</td>
</tr>
<tr>
<td></td>
<td>11 to 16</td>
<td>Stated value +9% + 1</td>
<td>80 max.</td>
<td>85 max.</td>
<td>25 max.</td>
<td>85 min.</td>
</tr>
<tr>
<td></td>
<td>19 and over</td>
<td>Stated value +9% + 1</td>
<td>70 max.</td>
<td>70 max.</td>
<td>25 max.</td>
<td>85 min.</td>
</tr>
<tr>
<td>BS 7672</td>
<td>10 to 18</td>
<td>10 to 18; stated value +9% + 1</td>
<td>80 max.; 8 to 14 mmHg</td>
<td>80 max.</td>
<td>25 max.</td>
<td>85 min.</td>
</tr>
<tr>
<td>BS 7563</td>
<td>6 to 12</td>
<td>6 to 12</td>
<td>100 max.</td>
<td>100 max.</td>
<td>25 max.</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Figure 12: British Compression Standard with its corresponding values (Segar Technology, 2017)
As figure 13 below shows, compression comes in various strengths. They belong to different classes, as portrayed in figure 14 on the right (Morrison, unknown date; Lim and Davies, 2014). The different classes correspond to the strengths of the compression.

Each class is used in different scenarios and are therefore also to be used in a different way. Compression garments used in the recovery period after a surgery are designed to be worn for long periods of time. They are designed specifically to the measurements of the patient and two items are usually created. In this way the patient can wear one of them whilst the other one is being washed. Patients are recommended to wash their garments by hand, at about 40°C (NHS, 2013). This all to avoid any damages that could occur when the garment is being machine washed, as well as to avoid possible shrinkage or loss of stretch/elasticity.

<table>
<thead>
<tr>
<th>Table IV. Medical compression stockings versus bandages, with high stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Medical compression stockings</strong></td>
</tr>
<tr>
<td>&quot;Moderate* pressure (mm Hg)&quot;</td>
</tr>
<tr>
<td>&quot;Strong&quot; pressure</td>
</tr>
<tr>
<td>Main indications</td>
</tr>
<tr>
<td>Worn</td>
</tr>
<tr>
<td>Changed</td>
</tr>
<tr>
<td>Practicability</td>
</tr>
<tr>
<td>Action during walking</td>
</tr>
<tr>
<td>Main effects</td>
</tr>
</tbody>
</table>

Figure 14: Different levels of compression in compression stockings (Morrison, 2013)
Figure 15: Overview of the information that needs to be filled in and the reference points of the measurements that need to be identified (Juzo, 2014)
9.2 Interview with Ronald van Oers

Osteopathy

Could you briefly describe osteopathy and what problems your patients deal with?

Osteopathy is a form of manual therapy which has a holistic philosophy. In osteopathy 3 systems are important:
- Musculoskeletal system
- Visceral system
- Neurological system

Those systems work together in our daily life and are therefore connected. In order to examine patients, there has to be taken into account that the problem is often the symptom of a bigger picture. Each complaint has to be evaluated in a number of qualities:
- biomechanical
- neurological
- vascular
- metabolic state

The main problems an osteopath sees in his daily practice are problems in the musculoskeletal system such as low back pain, shoulder complaints and so on. Also irritable bowel syndrome, stomach problems and other problems in the digestion are not uncommon.

Do you use compression garments (CGs) within your own treatments?

During treatments I never use this. When I have patients who are trying to be more active in sports but have a bad fascial system which has a negative effect on the vascular system I do recommend compression socks for example. Also after breast surgery after cancer compression can also be applied to an arm in order to eliminate the lymphatic fluids.

What are CGs traditionally used for?

Compression is used to stimulate fluid motion in the body. When blood vessels have a dysfunction in valves, the blood cannot reach the heart properly. However every vessel has valves, this means that muscular and fascial pressure is needed to get the blood flow back to the heart.

Reflection

Ronald interviewed since there is in my opinion a lot of overlap in mechanics of the body that compression garments influence and Ronald treats as an Osteopath. On top of that he collaborates with a lot of other medical disciplines for his treatments. Therefore I thought it to be very likely he would be using CGs as treatment. Sadly however, this was not the case. He did know what they were and therefore contribute to the survey. Remarkable about his answers however was that he was not aware of any details of the development of compression garments. With the rise in popularity of CGs used in the sport world, I would have expected him to be aware of at least some details since he works together with the discipline of medical fitness. On top of that he also collaborates with the discipline of lymph-oedema therapy. He did mention that he thought there were no other requirements for CGs to be considered as one but to exert compression.

Product Development

Are there certain steps you take when creating a CG? (think of measuring, calculating the necessary width of the garment for the compression)

How do you decide what amount of compression the CG should have?

I never calculate this, I thrust sportswear companies to have trustworthy products

How do you check what the actual amount of compression is the CG has?

I don’t, specialised care in hospitals has to be done for this when you want to know this.

Are there specific requirements for a garment to be acknowledged as a CG?

Not to my knowledge. It just has to be compressive

What types of fabric do you use for your CGs? (think of the construction, special properties)

Why is the fit and the fabric important for an effective CG?

If the compression isn’t tight, the effect is less efficient.

Application

Why are CGs used amongst athletes?

To recover faster after sports activities. A healthy blood flow is needed to get lactate out of the muscular system. Again, compression helps to get the blood flow return to the heart and therefor the drainage of lactate.
9.3 Hypercraft Notes

For my specialisation 3D Hypercraft, I had to design and create a future-oriënted surf outfit for the brand O'Neill. In my case I came up with a capsule collection of compression garments. My approach however was fictive since I was not aware of the actual development process of CGs.

From O'Neill we received their standardized measurements for their size range. I then based my avatar in Lectra Modaris and Clo3D on their male sample size ‘M’. Throughout Hypercraft I started with basic pattern drawing according to an AMFI reader. I already knew how to work with Lectra Modaris, but was not familiar with the actual pattern drawing before. For my designs I started with basic block patterns for a t-shirt and pants, which I changed and adapted. Via subsequent discussions with Sandra Kuijpers and Monique Broeke, I found out that if I would reduce the measurements of the patterns so that they would be close to the body measurements, or even smaller, I would “kind off” end up with compression garments.

By using the various fit tools in the two software programs I was able to fit the garment properly on the avatar and make the garment fit so tightly that it would fit due to the elasticity and stretch of the fabric. Within my research I was further inspired by the muscle anatomy of the body, which resulted in the designs to be inspired by and based on the actual human muscle anatomy. The patterns were divided in such a way that the various muscles each had their own pattern part, allowing some of them to have more stretch were necessary and others more support.

For the actual prototyping I did FAST-testing to get measurements of a custom fabric I found to be suitable for compression wear. It was elastic and stretchy, but had a very high recovery and tight construction. These were later inserted into the programs and applied to my garments to enhance the simulation.

Other things that became evident whilst working with Lectra Modaris and Clo3D were some issues with layering, seams and seam allowance. Different from regular patterning, seam allowance does not have to be added to the patterns in order for the software to simulate the stitched garment. The fabric necessary for the seam or stitching is not taken into account, and not necessary since the two lines of the two corresponding lines from the pattern pieces are simply connected. The simulation of the actual seams is, partially due to the absense of seam allowance, not accurate. Lectra Modaris for instance offers the option to add stitching to the garment as a type of trimming, which is more visual than functional. There is in 3d the option to simulate two layers on top of each other. The simulation does not go as smoothly as the baselayer however, the second layer does not drape as nicely and is being pulled towards the baselayer. Figure 6 on page 20 shows the insertion of a second layer, with the subsequent deformation since the garment is being pulled towards the baselayer.
9.4 Questionnaire on Compression Clothing

Weet je wat compressie kleding is? / Do you know what Compression Clothing is?

<table>
<thead>
<tr>
<th>Antwoorden</th>
<th>Ja / Yes</th>
<th>Nee / No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reacties</td>
<td>36,36%</td>
<td>63,64%</td>
</tr>
<tr>
<td>Total</td>
<td>24</td>
<td>42</td>
</tr>
</tbody>
</table>

Total: 66