

# On the mimicking of geckos and tree frogs for adhering to soft substrates

Master Thesis by

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# On the mimicking of geckos and tree frogs for adhering to soft substrate

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## Preface

After finishing high school and obtaining a bachelor's degree at the Amsterdam University of Applied Sciences, I felt like there was still more knowledge to be obtained before starting a career. In the years after, I have applied and pushed myself more than I thought it was possible, scoring higher than ever. During the bridging program and the theoretical courses at the Delft University of Technology, I grew even more than in most years before. It felt like I started in a whole new world and that there were endless lessons to be learned. By doing an internship in Austria I saw a new side of being abroad. Finally, during my master thesis I have transcended to a whole new level. Everything I studied for in the last seven years had to be applied, and the results have been very promising.

There have been times where everything worked out effortlessly and unfortunately there also have been times which required outside help. During all this a lot of people have helped me immensely to finish this project in something I am proud of and to keep me grounded during the process. Firstly, I want to thank Dimitra Dodou who helped me out more than anyone could ever imagine, both motivating me and teaching valuable lessons. During my thesis she has dedicated many hours to discuss the heading of the project and she has always been genuine in her interest in my project. Next, I would like to thank Peter van Assenbergh for helping me set up my project, giving me new insights and always being happy to discuss the project. Lastly, I would like to thank Eduardo Mendes and Ivan Buijsters for their interest in the project and willingness to be on my committee.

Apart from the university, I have also received lots of support from home. I would like to thank my girlfriend for helping out on almost every front and supporting me enormously mentally. I will be eternally grateful to my parents and sister for always believing in me and supporting me in going the extra mile and obtaining a master's degree. Lastly, I would like to thank all the friends I made during my stay in Delft, and I hope we can keep in touch.

Now it is time for me to finish my school career, but I will never stop learning.

*Tim van Broekhoven*

*Delft, November 2017*



# Abstract

**Background:** Soft-tissue grip is a challenge in minimally invasive surgery. Grasping instruments used in clinical practice require high pinch forces in order to generate sufficient grip for manipulating soft tissue without slipping.

In nature, several animals employ *adhesion* in order to grip on, not only hard, but also soft substrates. Among these animals, geckos and tree frogs are of special interest for engineered gripping systems, because of their high body mass. The toe pads of both animals are soft and characterized by a hierarchical pillar structure ranging from micro to nanoscale. Several research groups have mimicked this structure and demonstrated its potential for adhesive grip. Next to pillars, the toe pads of both animals possess a network of *stiff inner fibers*, which possibly also contributes to (friction) grip.

**Aim:** Inspired by the inner fiber network of geckos and tree frogs, the aim of this work was to investigate whether reinforcing a soft pad with stiff fibers increases friction on soft substrates as compared to a fiber-less pad. Our hypothesis was that provided that a soft exterior of such a pad establishes adhesive contact with the substrate, stiff fibers at a direction parallel to the substrate reduce the compliance of the pad in this direction, thereby preserving the established contact and thus increase the peak friction force.

**Methods:** Three experiments were conducted. In Experiment 1, composites consisting of 3D-printed fibers encapsulated in a polydimethylsiloxane (PDMS) pad were fabricated, and their adhesion and friction forces were measured. In Experiment 2, the friction of composites with stiffer 3D-printed fibers than those in Experiment 1 was measured. Lastly, in Experiment 3, the friction of composites consisting of a carbon fiber fabric encapsulated in PDMS of various stiffness degrees were tested. All experiments were conducted on both hard and soft gelatin substrates of various stiffness degrees, the latter functioning as soft-tissue phantoms.

**Results:** The results showed that, for all substrate types, adding 3D printed fibers with varying degrees of stiffness to a PDMS pad significantly *reduced* peak friction force, whereas adding a carbon fiber fabric significantly *increased* peak friction force compared to a fiber-less PDMS pad. The PDMS stiffness did not have a significant effect on friction force.

**Conclusion:** The results from this research are promising for developing fiber-reinforced composites for gripping to soft substrates, including minimally invasive grasping instruments for soft-tissue grip.

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# 1. Introduction

## 1.1. Grasping in minimally invasive surgery: current challenges

Over the course of the 20<sup>th</sup> century open surgery techniques have been gradually replaced by minimally invasive surgery (MIS) techniques (Lau, Leow, and Li 1997). MIS has benefits over open surgical procedures for both the patient and the hospital, including reduced trauma, faster recovery time and shorter hospital stay (Cuschieri 1995; Keus et al. 2006; Reza et al. 2006; Sauerland, Jaschinski, and Neugebauer 2010). However, the introduction of minimally invasive instrumentation has also introduced new challenges for the surgeon, including a loss of tactile feedback, a reduction in degrees of freedom and suboptimal instrument ergonomics (Breedveld et al. 1999; Tholey, Desai, and Castellanos 2005).

One of the instruments that has been negatively affected by the switch to MIS techniques is the grasping forceps. Grasping forceps are used in virtually every surgical procedure for manipulating soft tissue. The problem with grasping forceps used in clinical practice originates in the fact that they require high normal (i.e., pinch) forces to generate sufficient grip for manipulating soft and wet tissue without slipping. A literature review by Van Broekhoven, Van Assenbergh, and Dodou (2017) showed that the great majority of errors with MIS grasping forceps are made due to the use of either excessive force or insufficient force while manipulating tissue or performing other grasping tasks (e.g., placing a resected tissue in a retrieval bag). Specifically, errors due to insufficient forces were found to occur on average 1.94 (N=198) times per procedure, and errors due to excessive forces were observed on average 0.43 (N=282) times per procedure. The use of excessive force resulted in consequential errors (e.g., tissue tearing) 5.7% of the time (Tang et al. 2004), whereas the most frequent error related to insufficient force was dropping of tissue from the grasper forceps, requiring a re-grasping action and therefore resulting in prolonged procedure time (Eubanks et al. 1999). These findings indicate that surgeons learn to err on the side of patient safety.

The forces that need to be controlled to securely and safely manipulate tissue are the pinch force and the pull force. Pull forces between 0.1 N and 10N exerted on the tissue during in-vivo experiments with MIS graspers have been measured (Rosen et al. 1999; Visser et al. 2002; Picod et al. 2005). Moreover, it has been found that to prevent slipping of the tissue from the grasper pinch forces between 3 N and 22 N are required for a pull force of 5 N (Heijnsdijk et al. 2004). Pinch forces of 7 N and higher have been found to lead to the formation of hemorrhage and hematoma, with forces over 13 N resulting in crushing of liver tissue and bowel perforation (Heijnsdijk et al. 2003; Li et al. 2015).

## 1.2. Existing solutions: mechanical grip & other engineered approaches

Several approaches have been investigated to improve tissue grasping. One solution for reducing grasping errors is to restore the haptic feedback of MIS grasping forceps by using force sensors (Okamura 2009; Rosen et al. 1999; Puangmali et al. 2008; Peirs et al. 2004; Teo et al. 2011). Other researchers have investigated the potential of adjusting the shape of the grasping tip (e.g., by rounding the corners of the grasping tip or by making the tip out of an elastomer instead of stainless steel) to reduce peak pinch forces (Marucci et al. 2002; Shakeshaft et al. 2001; Cartmill et al. 1999; Bos et al. 2013). As yet another solution for reducing pinch forces, prehensile graspers consisting of mechanical “fingers” have been proposed, which grasp tissue by means of shape grip rather than pinching (Frank and Cuschieri 1997).

Next to the aforementioned solutions of mechanical grip, researchers have been investigating the potential of different gripping principles to achieve tissue grip and lift tissue, such as suction vacuum (Gentilli et al. 1998; Vonck et al. 2010), the Bernoulli effect (Trommelen et al. 2011) and ferromagnetism (Ryou and Thompson 2009; Wang et al. 2008, 2013).

A relatively new method for soft-tissue grip is by means of reversible and temporary adhesion (Karagozler et al. 2006; Kwon et al. 2006; Cheung et al. 2005; Glass, Cheung, and Sitti 2008; Dodou, Del Campo, and Arzt 2007). The advantage of this approach as compared to mechanical grip is that adhesion does not require high normal/pinch forces. However, most engineered adhesives that are functional on soft biological tissues are permanent (i.e., glues); reversible and temporary adhesives for soft tissues remain an unresolved challenge in the engineering terrain.

### 1.3. From mechanical grip to adhesive grip: a biomimetic approach

In nature, a wide variety of animals employ adhesion in order to temporarily and reversibly grip on different types of substrates, including soft and occasionally biotic (e.g., other animals) substrates (Creton and Gorb 2007a). Animals such as flies, spiders, tree frogs and geckos are able to stick to most surfaces, be it at a 90° degree angle, overhanging surfaces and for some animals even upside down (Creton and Gorb 2007b). The tree frog and the gecko are of specific interest for adhesive grip, because of their relatively high body mass (Stanislav N Gorb et al. 2007), which makes them promising paradigms for engineered gripping systems. Geckos are able to stick and release from different surfaces with high speeds, enabling them to climb vertical surfaces (Hansen and Autumn 2005). Tree frogs are able to adhere and release from surfaces ranging from smooth leaves to wet, rough rock structures without damaging these surfaces or their soft body and toe pads (Federle et al. 2006; Endlein, Barnes, et al. 2013; Endlein et al. 2017). These traits are very promising for atraumatic adhering to wet and soft surfaces, which is necessary for safely manipulating tissue. Accordingly, the aim of this work is to develop a gripping method inspired by geckos and tree frogs that is suitable for soft tissue grip and thus holds promise for tissue manipulation in a MIS setting.

#### 1.3.1. Gripping apparatus in geckos

##### *Outer anatomical structure for grip: the role of geometry*

The toes of the Tokay gecko (*Gekko Gecko*) grip on surfaces by means of Van der Waals forces (Autumn et al. 2002; Autumn 2002; Arzt, Gorb, and Spolenak 2003), which require intimate contact with the surface (Autumn et al. 2002; Huber et al. 2005). In order for this so-called dry adhesion to work on surfaces with a variety of roughness degrees (Autumn 2002; Kim and Bhushan 2008), the Tokay gecko employs a hierarchical system with millions of flexible setae which branch off into nanoscale spatulae, as can be seen in figure 1 (Rizzo et al. 2006). The setae are made of stiff  $\beta$ -keratin, but are very flexible due to their high aspect ratio (Persson and Gorb 2003; Autumn 2006). The large number of contact points results in high adhesive forces due to contact splitting (Arzt, Gorb, and Spolenak 2003) and prevention of crack propagation (Glassmaker et al. 2007; McMeeking, Arzt, and Evans 2008; Poulard et al. 2011). Moreover, due to their high aspect ratio, the setae presumably lead to increased elastic energy dissipation at pull-off and thus adhesion compared to low aspect ratio fibrils (Hui et al. 2004; Kamperman et al. 2010).

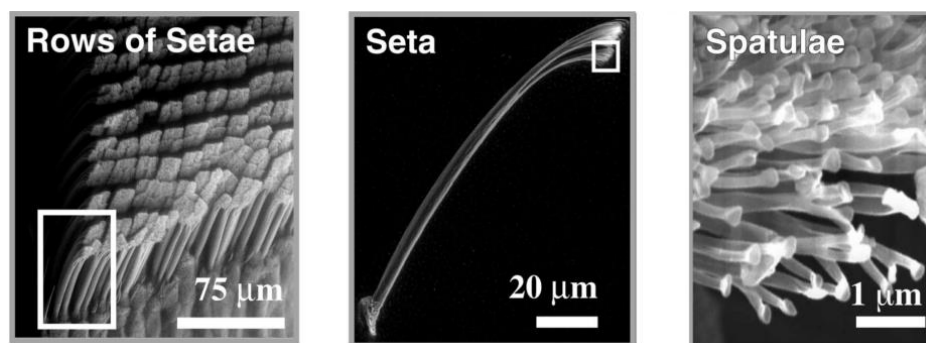


Figure 1 – Scanning Electron Microscopy (SEM) of the setae on the foot surface of Tokay Gecko. Adapted from Autumn et al. (2000).

#### *Inner anatomical structure for grip: the role of tendons*

The inner structure of the gecko toes contains stiff tendons, which have been hypothesized to facilitate adhesion (Russell 1975; Bartlett et al. 2012; King et al. 2014; King and Crosby 2015). As mentioned in the previous paragraph, millions of setae and spatulae on the gecko toe pads reduce the elastic modulus from  $\sim 1\text{-}3\text{GPa}$  of bulk keratin to  $\sim 83\text{ kPa}$  measured for setae (Autumn 2006). This reduction in stiffness makes the setae highly compliant, maximizing contact with the substrate (Persson 2003). However, this high compliance alone does not suffice for a relatively heavy animal to hang upside down, like the gecko does (Peterson and Williams 1981; Labonte and Federle 2015). It has been suggested that when animals become heavier and use larger pad areas, “scansorial plates” become more important (Persson 2003). Russel (1975) has first proposed the idea that the gecko uses stiff flaps called “scansorial plates” with setae to increase contact on surfaces with large scale roughness (figure 2). The stiff scansors are directly connected to the stiff tendons, which in turn are directly connected to the gecko skeleton. This inner hierarchical structure makes the compliance of the complete toe pad very low in the loading (i.e., shearing) direction, while still promoting local rotation freedom (a phenomenon often called “draping”; (Cerda, Mahadevan, and Pasini 2004)) (Russell 1975; Bartlett, Irschick, and Crosby 2013; King 2015).

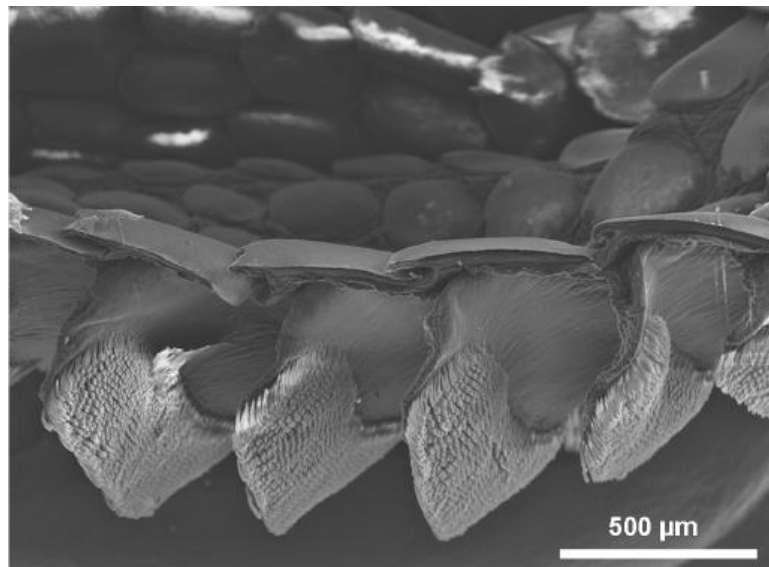


Figure 2 – A graphic representation of the scansorial plates of the gecko. Adapted from Bartlett et al. (2012).

### 1.3.2. Gripping apparatus in tree frogs

#### *Outer anatomical structure for grip: the role of geometry*

Tree frogs have been hypothesized to rely on multiple gripping mechanisms, making the tree frog gripping apparatus a complex system to study (Federle et al. 2006). The term ‘tree frogs’ refers to a range of frogs found in arboreal locations and which feature specific sub-digital toe pads (Smith et al. 2006). These toe pads are mostly found in the frog families Hylidae, Microhylidae, Centrolenidae, Rhacophoridae and Hyperoliidae (Duellman and Trueb 1994; Federle et al. 2006). As can be seen in figure 3, the tree frog toe pad has a hierarchical organization, allowing for contact area maximization at various scales (from macro to nanoscale).

The tree frogs arguably adhere by using a combination of dry and wet adhesion (W. Jon P. Barnes et al. 2011). Wet adhesion is induced by means of mucus that is secreted by glands in the toe (Ernst 1973; Hanna and Barnes 1991; Persson 2007), allowing for adhesion to the different surfaces (Smith et al. 2006). Specifically, the toe pad of the tree frog has an array of large hexagonal cells on a microscopic level with large fluid channels between them (figure 3c). On each hexagonal cell, tiny

blocks with much smaller channels are identified (Persson 2007) (figure 3d). This channel construction and mucous glands allow the tree frog to wet the whole surface of the toe pad with a thin mucus film (Ernst 1973). The watery mucus further fills the thin and deep channels between the hexagonal cells. In this way, the mucus generates grip by means of capillary forces (Hanna and Barnes 1991; Persson 2007; Butt et al. 2010) and Stefan adhesion (Emerson and Diehl 1980; Hanna and Barnes 1991; Barnes et al. 2002).

With respect to dry adhesion on tree frogs, several hypotheses have been formulated, including mechanical interlocking (Gorb 2008; Endlein et al. 2017), suction forces (Gorb 2008) and Van der Waals forces (Endlein, Ji, et al. 2013). However, no conclusive evidence has been found and the actual gripping mechanisms used by the tree frog remains a much debated topic (Hanna and Barnes 1991).

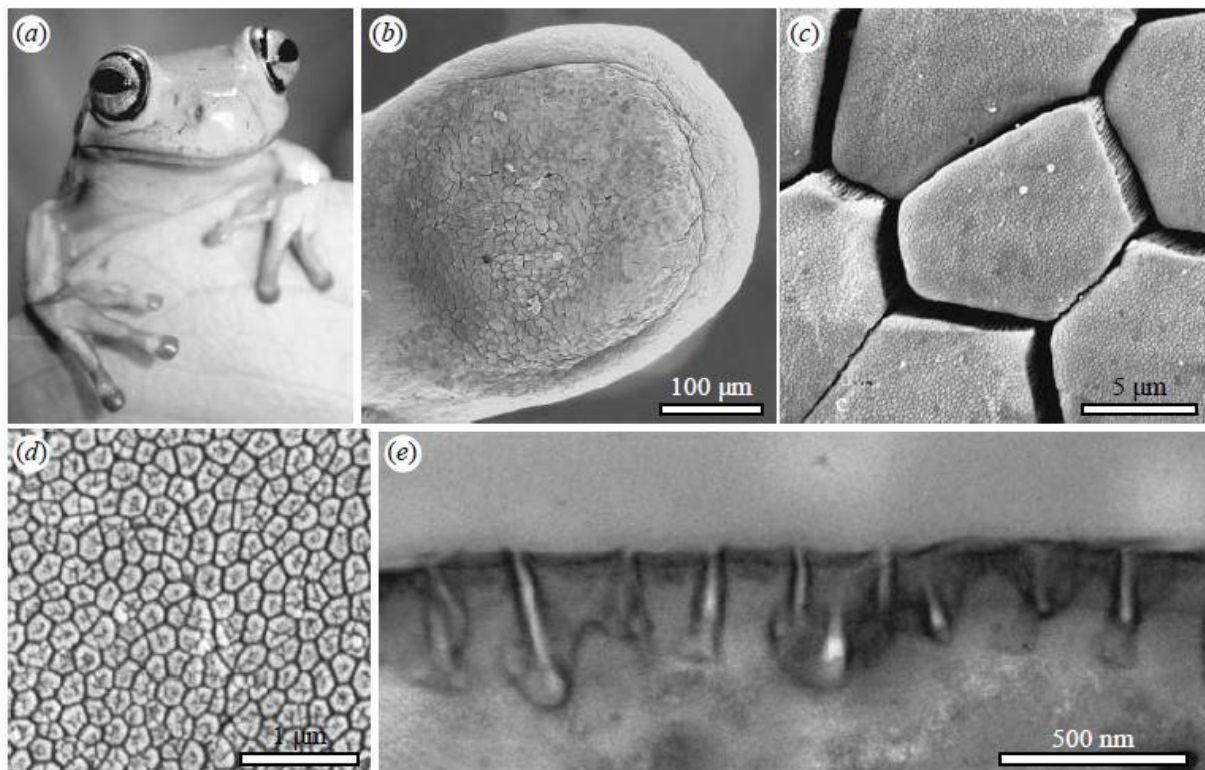


Figure 3 - Morphology of tree frog toe pads. (a) White tree frog (*Litoria caerulea*) (b) Toe pad of a white tree frog (c) Epidermis with hexagonal epithelial cells (d) High power view of the surface of a single hexagonal cell showing peg-like projections (e) Cross-section of the cell surface. Adapted from Federle et al. (2006).

#### *Inner anatomical structure for grip: the role of tendons*

An anatomical characteristic of the tree frog gripping apparatus that has not been extensively investigated yet is the stiff tendons that are present in the toe pad. It has been hypothesized that once the toe pads make close contact with the substrate, these tendons may stiffen the toe pads to control adhesive forces (Endlein, Ji, et al. 2013).

Summarizing, next to their hierarchical adhesive structures, both gecko and tree frog toe pads also possess a network of stiff inner fibers, which possibly contributes to the adhesive performance of these high body mass animals.

## 1.4. From tendons to fiber-reinforced adhesives

### 1.4.1. Crack propagation in fiber-reinforced adhesives: theory & implementation

One of the functions of stiff inner structures in composite materials compared to plain materials is the reduction of crack propagation inside the material (Mori, Saito, and Mura 1988). Bennett, Devries and Williams (1974) showed that the fracture of adhesives mostly depends on the specific adhesive fracture energy, which is defined as the energy released when a crack forms. Maugis and Barquins (1989) suggested that separation of the adhesive from substrate can be seen as crack propagation of mode I (i.e. opening mode) and that the strain energy release rate is thus an important parameter for describing crack propagation at the adhesive interface. This strain energy release rate can be described as the speed at which the strain energy required to form and propagate cracks changes when the crack grows. An important parameter of the strain energy release rate and thus crack propagation is the stress intensity factor, which describes the stress state measured at a crack tip (Irwin 1957). Mori, Saito and Mura (1988) showed that supporting fibers in composite materials significantly reduce the energy release rate and thus effective stress intensity factor of the composites, requiring more work to be used to reach the critical energy release rate and stress intensity factor to form and propagate a crack in, for example, concrete (Beaumont and Harris 1972), aluminum laminates (Lin and Kao 1995), phenolic foams (Shen, Lavoie, and Nutt 2003) and epoxy adhesives (Wernik and Meguid 2014). In other words, introducing fibers to an adhesive requires more work for a crack to propagate at the interface of the adhesive and the substrate, and as a result higher loads can be supported compared to a fiber-less adhesive.

### 1.4.2. Compliance of fiber-reinforced adhesives: theory & implementation

Bartlett et al. (2012) hypothesized that the contribution of the scansor and setae of geckos (see section 1.3.1) to grip, and to resistance against shearing in particular, can be mimicked by combining an elastomer with a stiff fabric as inner core. The working principle of this adhesive relies on an expansion on the theoretical work by Maugis and Barquins (1989), who used Griffith's theory (1921) on the formation of cracks to define the parameters of fracture mechanics in adhesives. In brief, Maugis and Barquins (1989) show that an energy balance exists when an adhesive with surface area ( $A$ ) is loaded with a force ( $F$ ). The total energy ( $U_T$ ) is supposed to be in equilibrium and consists of the surface energy ( $U_S$ ), the potential energy of the load ( $U_W$ ) and the stored elastic energy of the deformed material ( $U_E$ ):

$$\frac{\delta U_T}{\delta A} = \frac{\delta U_E}{\delta A} + \frac{\delta U_W}{\delta A} + \frac{\delta U_S}{\delta A} = 0$$

This energy equilibrium has been rewritten by Bartlett et al. (2012; 2015) for energy conserving systems where the initial energy equals the retained energy (as in gecko toe pads). The energy stored in an energy conserving system due to the deformation is converted to surface energy at a critical loading force ( $F_c$ ), which is the force  $F$  at which an adhesive joint separates in an unstable manner and a crack between the adhesive and substrate is initiated and propagates. Bartlett et al. (2012) determined  $F_c$  as a scaling relationship between the compliance of an adhesive system ( $C$ ), the surface area of the adhesive system that is in contact with the substrate ( $A$ ) and the critical strain energy release rate ( $G_c$ ) of the adhesive system:

$$F_c \sim \sqrt{G_c} \sqrt{\frac{A}{C}} \quad (1)$$

In equation 1, the compliance of the adhesive system is defined by the stiffness of the whole adhesive system in the direction of an applied shear load. The critical strain energy release rate is the energy release rate crossover point at which a crack starts forming between the adhesive and the substrate and can propagate without additional energy input. The critical energy release rate in this equation is

equal to the work of adhesion. The surface area is the theorized contact area between the adhesive and the surface.

In order to maximize the static friction (i.e., resistance to shearing) force generated by the adhesive while preserving adhesive release with low peeling forces, an optimum in geometry and material properties with respect to the compliance, surface area and critical strain energy release rate has to be found. If the function of the adhesive were to maximize the loading of the adhesive, the critical strain energy release rate ( $G_c$ ) should be maximized to prevent crack formation and the loss of contact. However, for a reversible adhesive, the critical energy release rate should be minimized to facilitate easy release. Thus, in order to reach an as high as possible loading force ( $F_c$ ), the ratio  $A/C$  must be maximized. This means that the adhesive pad should be able to generate *an as large as possible contact area with the substrate*, whereas its *compliance in the shearing direction is as low as possible*. The adhesive developed by Bartlett et al. (2012) achieves this apparently contradictory set of properties by combining a soft (i.e., elastomer) pad with a high compliance in the direction normal to the surface and stiff fibers with a low compliance in the direction of the shearing (see also King and Crosby 2015). To ensure that compliance is high in the normal direction, the stiff fiber fabric also needs to be compliant in the normal direction. Moreover, the fibers need to have the ability to drape to keep the rotational freedom, similar to the inner fiber structure found in the gecko.

Under loaded conditions shear stress distribution in adhesives have shown to not be constant across the whole length of the adhesive, but rather to decay with the distance from the point of loading (Kaelble 1960). In order to be able to maximize the loading capacity of the adhesive, the whole contact area has to be used to distribute shear stress, requiring optimization of the adhesive pad geometry and material properties (Bartlett, Irschick, and Crosby 2013).

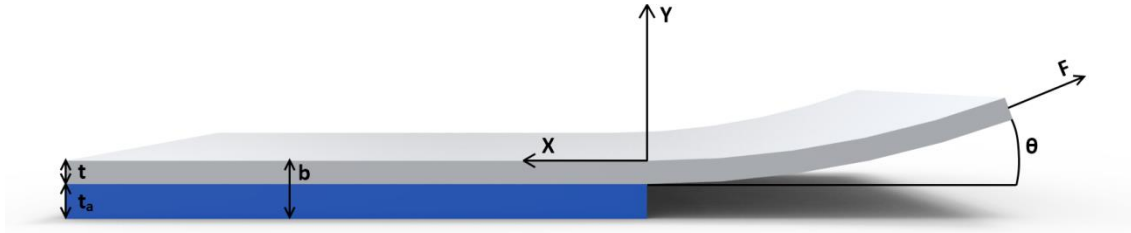


Figure 4 – A graphical representation of the adhesive surface (blue) and the stiff fabric (white) used by Bartlett and coworkers with the geometrical parameters effecting the shear stress decay length.

When the adhesive pad lies on the substrate and is loaded in the shearing direction, a shear stress is generated on the adhesive pad. The shear stress ( $\tau_{xy}$ ) at any point in the adhesive is dependent on the distance from the point of loading ( $x$ ), the load force ( $F$ ), the angle of the load ( $\theta$ ) the total width of the adhesive ( $b$ ) and the decay rate ( $\lambda$ ):

$$\tau_{xy} = -\frac{F \cos \theta}{b} \lambda e^{-\lambda x} \quad (2)$$

In order to minimize the decay of shear stress in the adhesive pad further away from the point of loading ( $x=0$ ), the decay rate of the shear stress needs to be as low as possible. The decay rate of the shear stress is dependent on the layer thickness of the adhesive ( $t_a$ ), the thickness of the fabric ( $t$ ), the shear modulus of the adhesive ( $\mu_a$ ) and the elastic modulus of the fabric ( $E$ ).

$$\lambda = \left( \frac{\mu_a}{E t_a t} \right)^{1/2} \quad (3)$$

Equation 2 and 3 show that in order to optimize the distribution of the shear stress in the adhesive pad the elastic modulus of the fabric, the thickness of the fabric and the thickness of the adhesive need to be as large as possible, while the shear modulus of the adhesive and the total width of the adhesive needs to be minimized.



Additionally, Bartlett, Croll and Crosby (2012) showed that a low aspect ratio between the thickness ( $t$ ) and the length ( $h$ ) of the adhesive has a positive effect on the deformation of the adhesive pad under loading. Bartlett, Croll and Crosby (2012) found that for adhesives with high aspect ratios, the adhesive deforms through bending rather than shearing.

### 1.4.3. Gecko inspired fiber-reinforced adhesives

Based on the theoretical considerations presented in the previous section, over the last five years Crosby and coworkers (Bartlett et al. 2012; King 2015; Bartlett and Crosby 2014; King et al. 2017; King and Crosby 2015) have designed and optimized a gecko-inspired adhesive consisting of a stiff fiber fabric partially embedded in a soft elastomer pad (figure 5). The fabrics that were used were selected to be stiff in the plane of the fiber while maintaining rotational freedom out of plane to guarantee the draping ability of the fibers. Additionally, the soft elastomers used ensure intimate contact with the substrate.

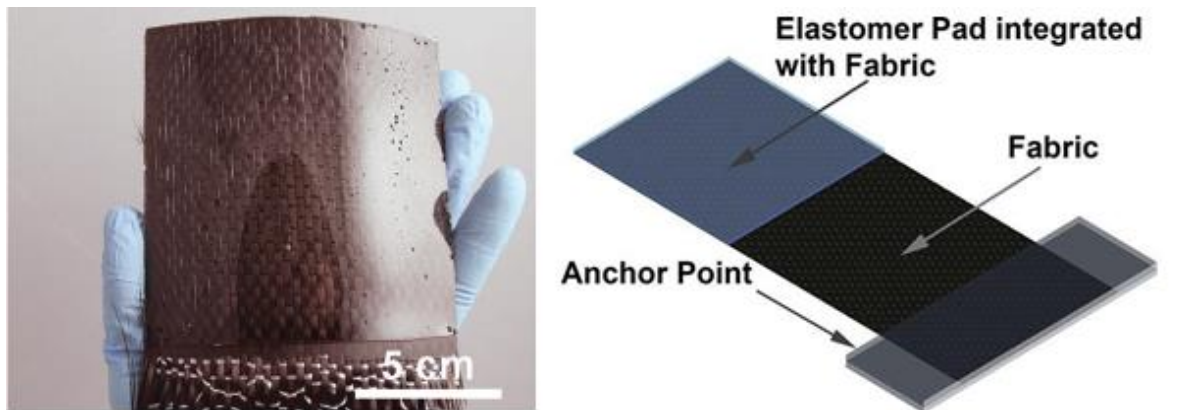


Figure 5 – (left) Photograph of gecko inspired adhesive. Adapted from Bartlett et al. (2012). (right) 3D render of gecko inspired adhesive. Note that in all experiments reported by Crosby and coworkers, the adhesive pad was loaded directly on the fibers via an anchor point outside the elastomer pad, as shown on the picture. Adapted from King et al. (2014).

Crosby and coworkers have experimented with several types of elastomers (e.g., polydimethylsiloxane [PDMS], polyurethane), fiber fabrics (e.g., carbon, nylon) and combinations thereof to maximize the aforementioned A/C ratio. An overview of the material combinations and resulted peak shearing forces (force capacity) tested by Crosby and coworkers are shown in table 1. For more details on the material properties of these structures, the reader is referred to Appendix I. The forces shown in table 1 were measured on glass; these adhesives have been also tested on various other hard substrates, including aluminum and painted drywall.

Table 1 – Overview of fibers and elastomers tested by Crosby, Bartlett and King and their maximum force capacity on glass.

Fibers	Elastomer	Force capacity	Reference
Stiff unidirectional 12k 11oz fabric	Polyurethane (PU) - ST1060	2950 N	(Bartlett et al. 2012)
Carbon fiber/Kevlar plain weave 3k 4.8oz fabric	1:10 (curing agent:base) polydimethylsiloxane (PDMS)		
Plain weave polyester	1:10 PDMS		
Plain weave nylon fabric	1:10 PDMS		
-	1:10 PDMS		
24K unidirectional carbon fiber tape	PU - ST1060 PU - F15 PU - ST3040	±2700N ±930N ±1390N	(King and Crosby 2015)

	PU - ST1075 PU - ST1085	±1810N ±1740N	
24K unidirectional carbon fiber tape	PU - ST1060 PU - ST3040 PU - F15	±2600N ±580N ±1700N	(King et al. 2014)
3K plain weave carbon fiber fabric	PU - ST1060 PU - ST3040 PU - F15		
Satin weave S-glass fabric	PU - ST1060 PU - ST3040 PU - F15		
24K unidirectional carbon fiber tape	PU - ST1060 PU - F15 PU - ST3040	1750N	(King et al. 2017)
3K carbon fiber/Kevlar composite fabric	PU - ST1060 PU - F15 PU - ST3040	875N	
glass fiber fabric	PU - ST1060 PU - F15 PU - ST3040	1250N	
plain weave nylon fabric	PU - ST1060 PU - F15 PU - ST3040	700N	
1K plain weave carbon fiber fabric	1:10 PDMS		(Bartlett, Croll, and Crosby 2012)
Fine Hemp Linen 5.3 oz 100% Jute cotton fabrics	natural rubber latex natural rubber latex natural rubber latex	720N 420N 810N	(Bartlett and Crosby 2014)

As it can be seen in table 1, the highest shearing forces are achieved with stiff unidirectional carbon fiber fabrics (effective stiffness modulus about 33 GPa) and medium stiffness polyurethane elastomer (about 3.1 MPa). King (2015) further showed that for adhesives consisting of 24K unidirectional carbon fiber fabric and polyurethane polymer, a maximum in force capacity can be achieved for polyurethane with a elastomer modulus of 3.1 MPa (figure 6), with both softer and stiffer polyurethanes leading to lower force capacities.

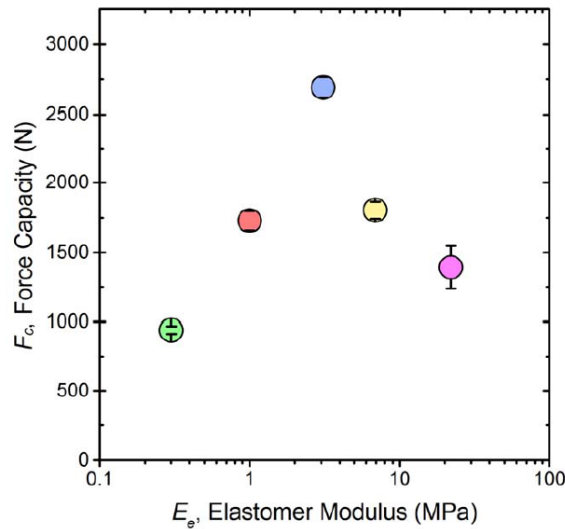


Figure 6 – Plot of the force capacity as a function of the elastomer modulus of different polyurethane adhesive pads with 24K unidirectional carbon fiber fabric tested on glass. Adapted from King (2015).

#### 1.4.4. Tree frog inspired fiber-reinforced adhesives

Xue et al. (2017) developed fiber-reinforced adhesive patterns inspired by the internal rigid structure located in the tree frog toe pads. Composites of soft (Young’s modulus = 2 MPa) polydimethylsiloxane (PDMS) micropillars arranged in a hexagonal pattern and an internal system of rigid (Young’s modulus = 3 GPa) polystyrene (PS) nanopillars (Figure 7, left) exhibited significantly higher adhesive force than micropillars without rigid nanopillar internal structure (Figure 7, right). Adding a vinyl group to the nanopillars surface to increase the covalent link between the PDMS and the PS led to a further increase in adhesive force as compared to a composite without vinyl group (Figure 7, right).

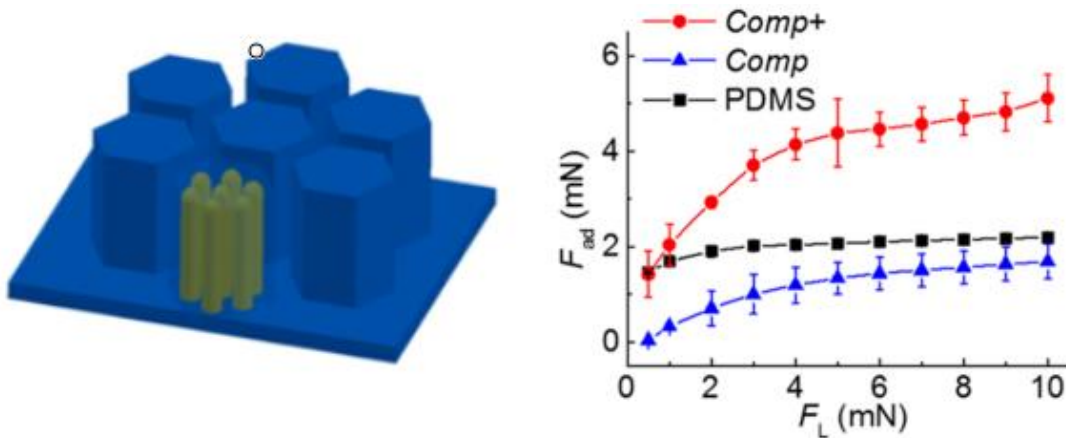


Figure 7 - (left) Composite made of PS nanopillars (yellow) casted in a PDMS layer of micropillars (blue) (right). Adhesive force for PDMS without nanopillars (PDMS), composite of PS and PDMS without a vinyl interface (Comp) and composite of PS and PDMS with vinyl groups at the PS-PDMS interface (Comp+), as a function of the normal load on the structure. Adapted from Xue et al. (2017).

#### 1.5. Goal of the research

In this paper we investigate whether the positive contribution of internal fibers to grip and particularly static friction on hard substrates as found in geckos, tree frogs and their mimics also holds for soft substrates emulating soft biological tissue. We hypothesize that:

- Provided that a good contact between an adhesive and a soft substrate is made, adding stiff fibers to the adhesive at a direction parallel to the substrate reduces the compliance of the composite in this direction, thereby preserving the established contact and thus increasing peak friction forces.
- An adhesive composite with stiff fibers and soft pad generates higher peak friction forces on a hard (i.e. glass) substrate compared to soft substrate.

## 1.6. Outline of the report

This report is subdivided into three separate experiments. Before each experiment multiple series of pilot tests have been performed to investigate whether the selected materials hold promise, to examine the degradation of the samples and substrates over use and to be able to reduce the number of conditions to be included in the successive experiments.

Experiment 1 was performed with adhesive composites consisting of fibers printed with a PolyJet printer and encapsulated in a polydimethylsiloxane (PDMS) pad. In Experiment 1, both adhesion and friction on both soft and hard substrates were measured. Experiment 2 was conducted with stiffer fibers printed with a direct light projection (DLP) printer and casted in a PDMS pad. These samples were tested on the friction generated on soft and hard substrates. Lastly, Experiment 3 was performed with samples similar to these described in the works by Crosby and coworkers (see section 1.4.3). These samples featured various carbon fiber fabrics and PDMS adhesive pads of various stiffness degrees. These samples were again only tested on the friction force generated on hard and soft substrates.

## 2. Methods

### 2.1. Experiment 1

#### 2.1.1. Fabrication of adhesive samples

##### *Fabrication of inner fiber structure*

Internal stiff fiber structures with various numbers of fiber layers, fiber spacing, and fiber orientation (see sections 2.1.3 & 2.1.4) were manufactured by printing fibers with a height and width of 300  $\mu\text{m}$  and a length of 20 mm (Appendix H). The pilot tests were performed with samples using fibers structures 3D printed with a Perfactory 4 mini XL printer (Envisiontec, Dearborn, USA) using ABS-tuff filament (Appendix C). The experiment was performed with samples using fiber structures 3D printed with a Connex3 Objet350 PolyJet printer (Stratasys, Eden Prairie, USA) using VeroCyan (RGD841) filament (Appendix B).

A rectangular mold with dimensions 20x20x4.5 mm was printed with an Ultimaker Extended 2+ (Ultimaker, Geldermalsen, The Netherlands) and sanded for a smooth finish (Figure 8). During fabrication of the samples, the fibers were stacked on top of each other into the mold, making direct contact with each other or spaced with spacers (see section 2.1.3 & Figure 8). Four rods held the fibers straight and into place. The fibers were stacked with the fibers layers oriented in the same direction to make it possible to observe the effects on the friction force when testing the samples perpendicular or parallel to the fibers. The fibers were spaced from the bottom of the mold with spacers of 400  $\mu\text{m}$  to ensure a layer of PDMS is coating the fibers on the contact surface.

##### *Elastomer encapsulation*

The base component and the curing agent of SYLGARD® 184 (Dow Corning, Midland, USA) silicone elastomer (PDMS) were mixed for two minutes in a plastic cup (Appendix A). The silicone elastomer was then degassed in a vacuum chamber until all air bubbles had been removed.

Next, directly after degassing in the vacuum chamber, the PDMS was poured into the molds with the fibers (Appendix G). The mold featured an inner vessel with overflow buffer to guarantee a constant sample height of 4.5 mm. The samples without fiber structure were manufactured by pouring the PDMS in an empty mold. To guarantee that no curing inhibiting chemicals were released from the mold during curing of the PDMS, and to facilitate easy release of the samples, a Vaseline petroleum jelly coating (Unilever, London, UK) was applied to the molds and fiber structures.

The samples in the molds were degassed for 15 minutes and then cured for 4 hours in an oven at 40 °C to minimize the release of curing inhibiting chemicals and reduce warping/degradation of the 3D printed parts. Then the samples were removed from the molds and got rested overnight. Next, the samples were cured for an additional 4 hours at 40 °C in the oven, after which they were cut to size with a single blade applied perpendicular to the contact surface, removing all excess material.

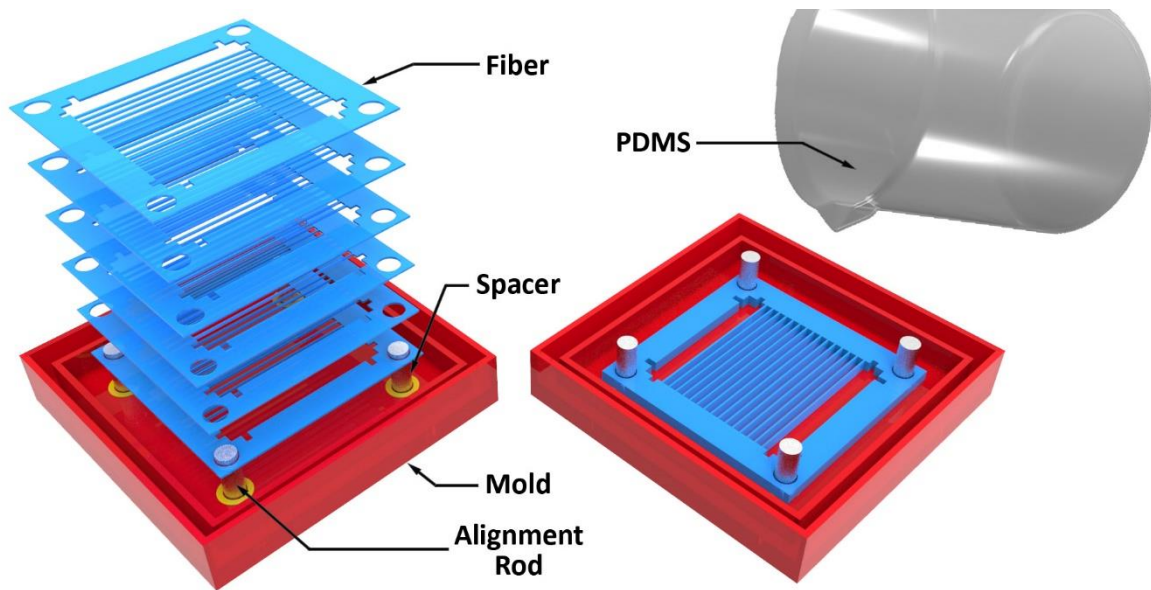


Figure 8 – (left) Exploded view of the manufacturing setup for the samples of the pilot test, Experiment 1 and Experiment 2. The setup consists of a mold, alignment rods, spacers and fibers. (right) Manufacturing setup of the samples with the fibers making direct contact with each other and degassed PDMS being poured into the mold with the fibers at place.

#### Fabrication of the substrates

Gelatin substrates were manufactured by pouring gelatin solution into a mold (Appendix F) and refrigerating until cured. Gelatin solutions with varying weight percentage of gelatin powder (Dr. Oetker, Bielefeld, Germany) were made by mixing gelatin powder into a beaker with 60 °C tap water. The solution was kept at a constant 60 °C and stirred with a IKA RCT basic magnetic hotplate stirrer until the gelatin powder was dissolved. The mold was manufactured with an Ultimaker Extended 2+ printer and lined with Parafilm M (Bemis, Neenah, USA) for easy release of the substrates. After pouring the gelatin in the mold, the gelatin solution was cooled down to room temperature and kept in the fridge at a temperature of 6.5°C. Before use the gelatin substrates were taken out of the fridge to warm to room temperature for a minimum of 30 minutes. All gelatin substrates were tested within 24h from production.

#### 2.1.2. Measurement setup

The measurement setup for the friction tests consisted of a force sensor, a pulley system, a linear motion stage, a sample attached to a sample holder and a substrate and a substrate holder (Figure 9). For the adhesion tests the setup consisted of the same components as the friction test setup, but without the pulley system (figure 10).

### *Linear motion equipment*

An Aerotech ACT115 linear motion stage (Aerotech Inco, Pittsburgh, USA) was used to move the sample over the substrate. The linear motion stage was controlled via an Aerotech Soloist CP controller with a custom build GUI in Matlab R2016a (Mathworks, Natick, USA) connected to the computer via a LabJack UE9 (LabJack, Lakewood, USA) data acquisition device. The vertical linear motion of the motion stage was translated to a horizontal motion with a Silkam 2/0 (B. Braun Medical, Pennsylvania, USA) surgical wire run through a single pulley aligned with the substrate. The interface cables were shielded from magnetic noise and additional noise filters were built in.

### *Measurement equipment*

For both the friction and adhesion force measurements, two FUTEK s-beam load cells (FUTEK advanced sensor technology, Irvine, USA) with varying capacities were used. Specifically, for the measurements on gelatin substrates, a 5lb LSB200 load cell was used, whereas for the measurements on glass substrate, a 10lb LSB200 load cell was used. The signal measured by the 5lb load cell was amplified by the FUTEK amplifier module and converted from an analog to a digital signal by the LabJack UE9 DAQ device. The signal from the 10lb load cell was amplified and converted with a CPJ2S (Scaime, Juvigny, France) signal conditioner.

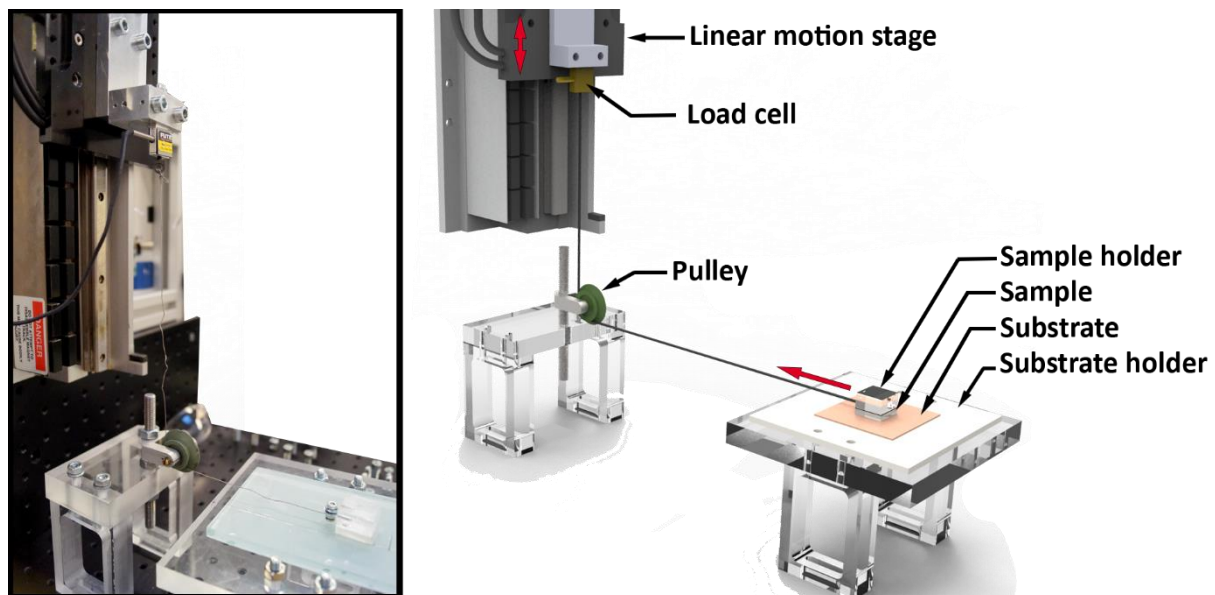


Figure 9 – Picture and 3D render of the experimental setup for measuring friction force. In this picture the load cell, linear motion stage, pulley system, sample on sample holder and substrate on substrate holder are shown.

### *Sample clamping*

In order to slide the samples over the substrate, the top of the samples was taped at the bottom of a Perspex sample holder with double sided tape. For the friction experiments, the actuation wire was tied to a bolt aligned with the middle of the sample and connected to the sample holder. For the adhesion experiments, the actuation wire was connected to a centered hook on top of the sample holder.

### *Substrate clamping*

The substrates were clamped via a form fit substrate holder pressing down on the sides of the substrate, leaving part of the substrate surface open for testing. The glass substrate was taped directly to the substrate support.

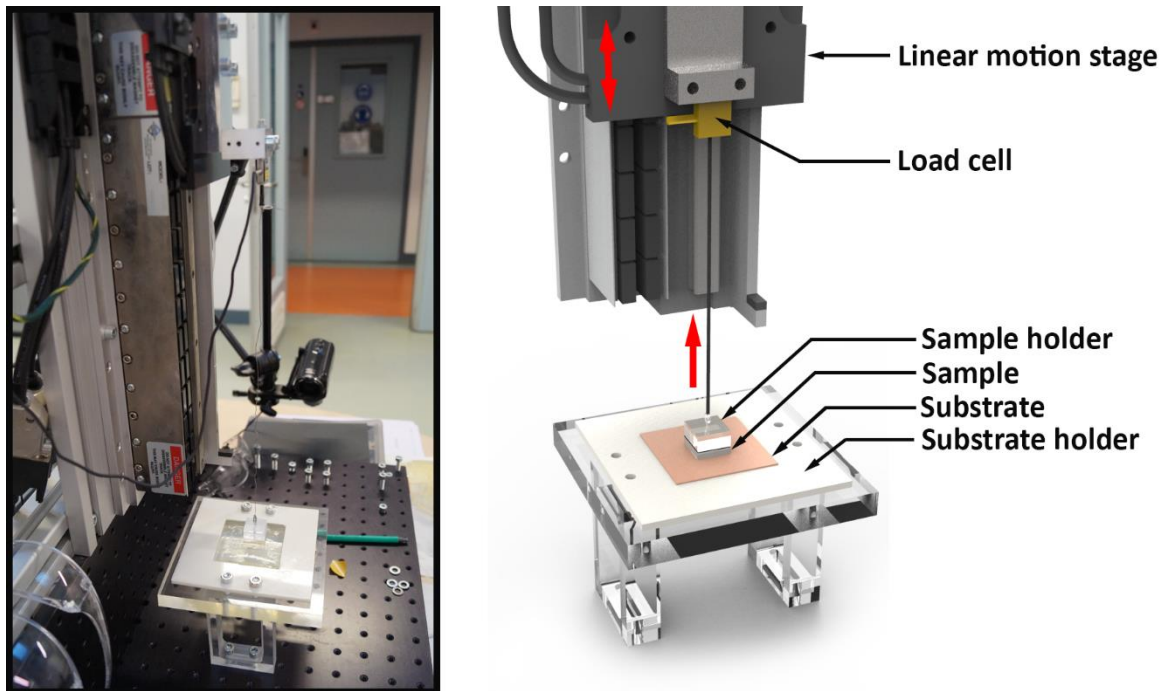


Figure 10 – Picture and 3D render of the experimental setup for measuring the adhesion forces. In this picture the load cell, linear motion stage, sample on sample holder and substrate on substrate holder are shown.

### 2.1.3. Pilot experiment

#### *Independent variables*

The following variables were tested in the pilot experiment:

- Fiber density [0, 2, 4, 6]: the number of fiber layers in the samples was varied between 0, 2, 4 and 6
- Fiber layer spacing [0  $\mu\text{m}$ , 300  $\mu\text{m}$ ]: the spacing between layers in the samples was varied between 0  $\mu\text{m}$  and 300  $\mu\text{m}$
- Fiber orientation [X, Y]: the orientation of the fibers in the samples was varied between parallel to the shear loading (X) and perpendicular to the shear loading (Y)
- Substrate stiffness [5 w%, 10 w%, 15 w%, 20 w%]: the stiffness of the substrates was varied with 5 w%, 10 w%, 15 w%, and 20 w% gelatin substrate
- Substrate surface [dry, wet]: the experiments were performed on dry and wet substrates. Wet substrates were wet with three drops of water administered with a 1-mm syringe before each measurement
- Preload [0 gram, 250 grams]: the preload (i.e., load before the measurement) of the samples was varied between 0 gram and 250 grams
- Load [0 gram, 50 grams]: the load (i.e., load during the measurement) of the samples was varied between 0 gram and 50 grams

#### *Dependent variables*

The following variables were measured in the pilot experiment:

- Adhesion force: The peak adhesion force is the maximum adhesive force that is measured before the sample loses contact with the substrate and detaches
- Friction force: The peak friction force is the maximum friction force that is measured before the sample loses contact with the substrate and detaches

#### *Constant*

The following parameters were kept constant in the pilot experiment:

- Adhesion measurement stroke: the sample was lifted from the substrate by 10 mm
- Friction measurement stroke: the sample was moved 35 mm along the substrate
- Movement speed: the sample was moved with a speed of 5 mm/s
- PDMS stiffness [1:20]: the stiffness of the PDMS adhesive pad was kept constant by using a ratio of curing agent to base of 1:20

#### *Experimental procedure*

The fiber layer spacing was 0  $\mu\text{m}$  for 0, 2 and 6 fiber layer samples, the 4 fiber layer sample was tested with both 0  $\mu\text{m}$  and 300  $\mu\text{m}$  spacing.

The dry friction and adhesion experiments were performed with all previously described samples in both fiber orientations on all substrates.

The wet friction and adhesion experiments were performed on 15 w% and 20 w% gelatin substrate with all previously described samples in both fiber orientations.

Experiments with varying preload and load combinations were performed with all previously described samples with the fibers parallel to the shear loading (X) on all gelatin substrates.

Per condition five repetitions were performed with one sample. No randomization was applied.

### 2.1.4. Experimental conditions

#### *Independent variables*

- Fiber density: 0, 4, 6
- PDMS stiffness: 1:10, 1:20
- Substrate stiffness: 10 w% gelatin, 15 w% gelatin, 20 w% gelatin, glass

#### *Dependent variables*

- Adhesion force
- Friction force

#### *Constants*

- Preload: 250 grams
- Fiber direction: Parallel to the shear load direction (X)
- Adhesion measurement stroke: 10 mm
- Friction measurement stroke: 35 mm
- Movement speed: 5 mm/s

#### *Experimental procedure*

For Experiment 1, 24 conditions (3 fiber densities x 2 PDMS stiffness degrees x 4 substrates) were tested. For each of the six adhesive structures (3 fiber densities x 2 PDMS stiffness degrees), five samples were fabricated. For each of the 24 conditions, five repetitions were performed, with one repetition per sample. To control for substrate surface deterioration, blocks of ten randomized conditions were made per substrate, with fresh substrate being loaded after each block of ten randomized repetitions. Next, the order of the previously described blocks was randomized. Randomization of the conditions was done with Excel (Microsoft, Washington, USA). The friction and adhesive experiments were performed in succession.

### 2.1.5. Data processing

All force data was processed in MATLAB 2017b, and prior to analysis, filtered with a zero-phase unweighted moving average filter function with a window of 20 samples, to reduce noise in the signal. An example of raw data measured during a friction test is shown in Figure 11. The peak forces in the measured data were extracted and used to compare performance of the samples between conditions. The MATLAB scripts used for the filtering and data extraction can be found in Appendix J.



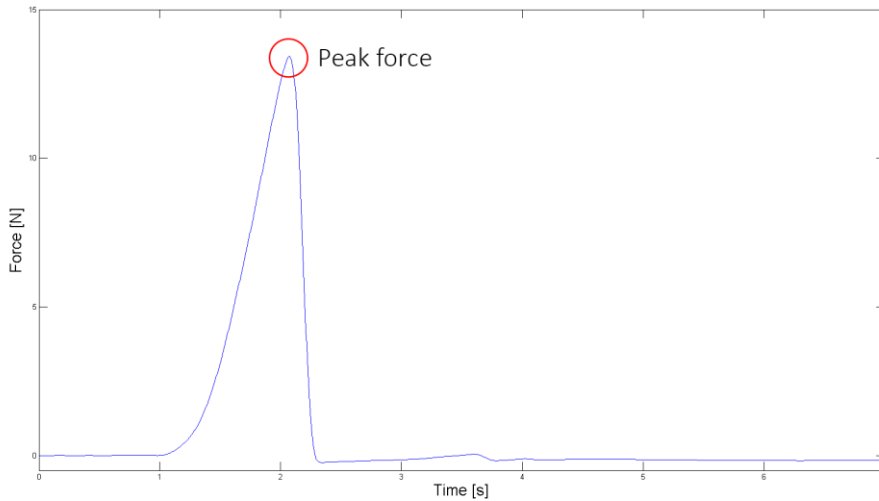


Figure 11 – Example of raw data measurement

### 2.1.6. Data analysis

Data analysis was performed with MATLAB 2017b. A three-way analysis of variance (ANOVA) with a post-hoc Tukey-Kramer test was conducted to test the effect of the independent variables and their interactions on friction and adhesion. Because the force data may have unequal variances and/or be non-normally distributed, the data were ranked-transformed prior to performing the statistical analysis. The significance level ( $\alpha$ ) used for the ANOVA was set to 0.05 for the main analysis and to 0.001 post-hoc analysis. The MATLAB scripts used for the data analysis can be found in Appendix J.

## 2.2. Experiment 2

### 2.2.1. Fabrication of adhesive samples

The fabrication of the samples for Experiment 2 were identical as described in Experiment 1. The sole difference was that the fibers used for Experiment 2 were printed with a Perfactory 4 mini XL printer using ABS-tuff filament.

### 2.2.2. Measurement setup

The friction force measurement setup was identical as described in Experiment 1.

### 2.2.3. Experimental conditions

#### *Independent variables*

- Fiber density: 0, 4, 6
- PDMS stiffness: 1:10, 1:20
- Substrate stiffness: 10 w% gelatin, 15 w% gelatin, 20 w% gelatin, glass

#### *Dependent variables*

- Friction testing

#### *Constants*

- Preload: 250 grams
- Fiber direction: Parallel to the shear load direction (X)
- Friction measurement stroke: 15 mm
- Linear movement speed: 1 mm/s

### *Experimental procedure*

For Experiment 2, 36 conditions (3 fiber densities x 2 PDMS stiffness degrees x 4 substrates) were tested. For each of the six adhesive structures (3 fiber densities x 2 PDMS stiffness degrees), three samples were fabricated. Each condition with 1:20 PDMS was repeated five times, with two samples being tested twice each and one sample being tested once. Every condition with a PDMS stiffness of 1:10 was repeated ten times, with two samples being tested three times each and one sample being tested four times. The randomization of the conditions was performed in the same way as described in Experiment 1.

#### 2.2.4. Data processing

Data processing was performed identical as described in Experiment 1.

#### 2.2.5. Data analysis

Data analysis was performed identical as described in Experiment 1.

### 2.3. Experiment 3

#### 2.3.1. Fabrication of adhesive samples

The samples in Experiment 3 were manufactured according to the fabrication method present in Bartlett (2012; 2014). and King et al. (2014; 2015; 2017). The fabrics (ECC-fabrics, Heek, Germany) used were 3K plain weave 200g/m<sup>2</sup> carbon fiber fabric (Appendix E) and 12K plain weave 400g/m<sup>2</sup> carbon fiber fabric (Appendix D) (ECC-fabrics, Heek, Germany). The carbon fiber fabric was stretched and taped on a plastic substrate to guarantee that no folds in the fabric were created. Next, a spacer made of polyurethane with 20x20-mm square holes was taped down on top of the fabric. Then, degassed PDMS was poured into the polyurethane mold, and the PDMS was smoothed with a razor blade to remove excess. The PDMS was allowed to seep into the fabric for 10 minutes. Next, a rigid plate with a 2 kilogram weight was placed on top of the polyurethane spacer and the complete setup was placed in an 70°C oven for 4 hours. The samples without fiber structure were manufactured by pouring degassed PDMS in a Petri dish and placed in an 70° oven for 4 hours. Next, the samples were cut to size with a single blade applied perpendicular to the contact surface, and the edges of the fabric were taped with office tape to prevent the fibers from unraveling. Lastly, a liquid super glue-3 (Loctite, Düsseldorf, Duitland) was applied to the top 3 mm of the fabric of the fiber samples with in the middle a G-line fishing wire (Gamakatsu, Nishiwaki, Japan) to facilitate the attachment of the samples to the measurement setup (figure 12). On the samples without fibers fishing wire was glued on the top of the sample starting from the center (figure 12).

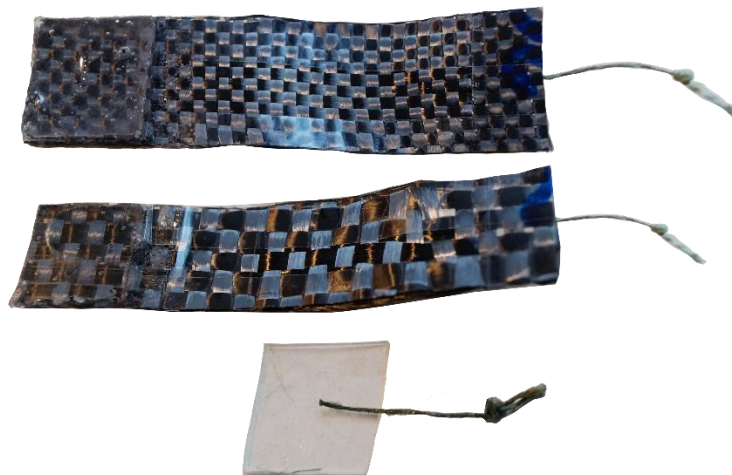


Figure 12 – (top) 3K plain weave 200g/m<sup>2</sup> carbon fiber fabric sample. (middle) 12K plain weave 400g/m<sup>2</sup> carbon fiber fabric. (bottom) sample without fibers.

### 2.3.2. Measurement setup

For Experiment 3, instead of using the sample holder used in Experiments 1 and 2, the actuation wire was connected directly to the sample via a small hook. The rest of the force measurement setup was identical as described in Experiment 1.

### 2.3.3. Experimental conditions

#### *Independent variables*

- Fiber density: 0, 3K plain weave carbon fiber fabric, 12K plain weave carbon fiber fabric
- PDMS stiffness: 1:10, 1:20, 1:30
- Substrate stiffness: 15 w% gelatin, glass

#### *Dependent variables*

- Friction testing

#### *Constants*

- Preload: 2475 grams
- Fiber direction: Parallel to the shear load direction (X)
- Friction measurement stroke: 15 mm
- Linear movement speed: 1 mm/s

#### *Experimental procedure*

For Experiment 3, 36 conditions (3 different fiber densities x 3 PDMS stiffness degrees x 2 substrates) were tested. For each of the nine adhesive structures (3 different fiber densities x 3 PDMS stiffness degrees), two samples were fabricated. Per condition ten repetitions were performed with five repetitions per sample. The randomization of the conditions was performed in the same way as described in Experiment 1.

### 2.3.4. Data processing

Data processing was performed in the same way as described in Experiment 1.

### 2.3.5. Data analysis

Data analysis was performed in the same way as described in Experiment 1.

## 3. Results

### 3.1. Experiment 1

#### 3.1.1. Pilot test

The 5 w% gelatin substrates tended to tear during the friction experiments, both when using samples with and without load, and for each type of sample. The 10 w% gelatin substrates exhibited tearing when a load was applied to the sample, and for each type of sample. Neither the 15 w% or 20 w% gelatin substrates showed signs of degradation, either with or without load. When testing on wet substrates, both adhesion and friction forces were too low to be recorded. When no preload was used on dry substrates, also the friction force was too low to be recorded. Therefore, subsequent measurements in this pilot test were performed with a setup using a preload vs. no load on dry 10 w%, 15 w%, and 20 w% gelatin substrates and a glass substrate.

The results of the pilot tests are shown in figure 13. It can be seen that samples with fibers parallel to the shear loading direction generated significantly higher friction forces as compared to samples with fibers perpendicular to the shear loading direction for all substrate types ( $F(1, 50) = 55.56$   $P < 0.001$ ). For the 15 w% gelatin substrate and fibers parallel to the shear loading direction, the 4- and 6-fiber

samples generated friction forces significantly higher than the 2-fiber sample ( $F(2, 14) = 12.18$   $P < 0.001$ ). For the 20 w% gelatin substrate, an outlier of the 6-fiber sample apparently affected the results, and no significance difference in the friction force was observed as a function of the number of fibers in that case ( $F(2, 14) = 1.36$   $P = 0.295$ ).

Figure 14 shows that for all gelatin substrates, significantly higher friction forces were measured when no spacing between the fibers was used compared to using 300 micrometer spacing ( $F(1, 26) = 299.23$   $P < 0.001$ ).

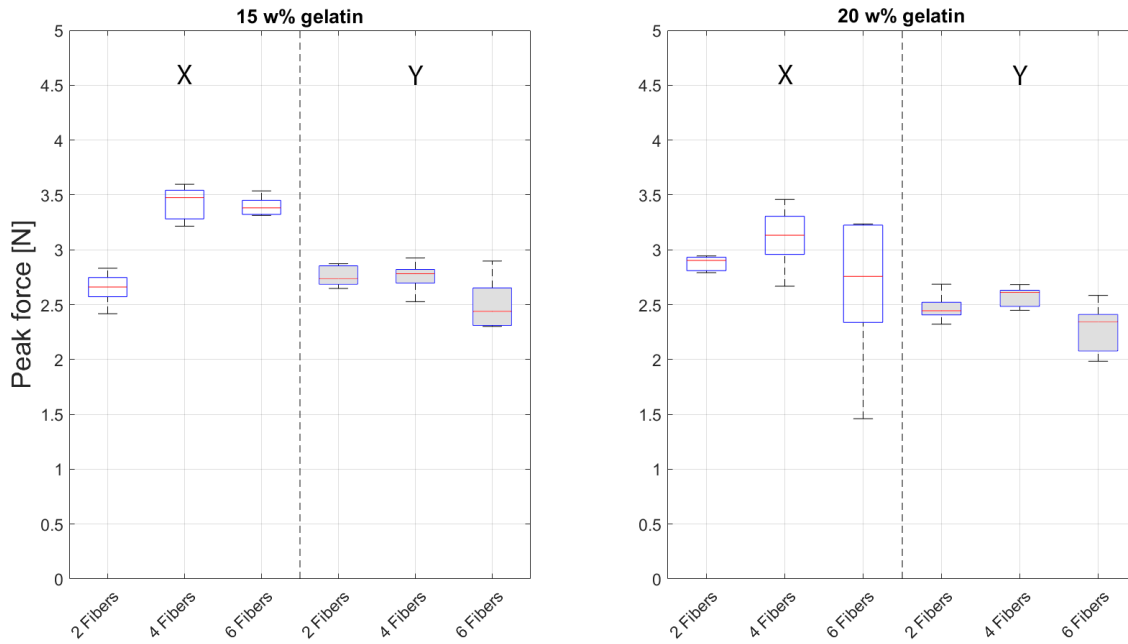


Figure 13 – Friction forces measured with samples with 2, 4, and 6 fibers on 15 w% and 20 w% gelatin substrates. ‘X’ and ‘Y’ annotate fibers parallel and perpendicular to the motion direction, respectively. A load of 50 gram and a preload of 250 gram were used for all the measurement.

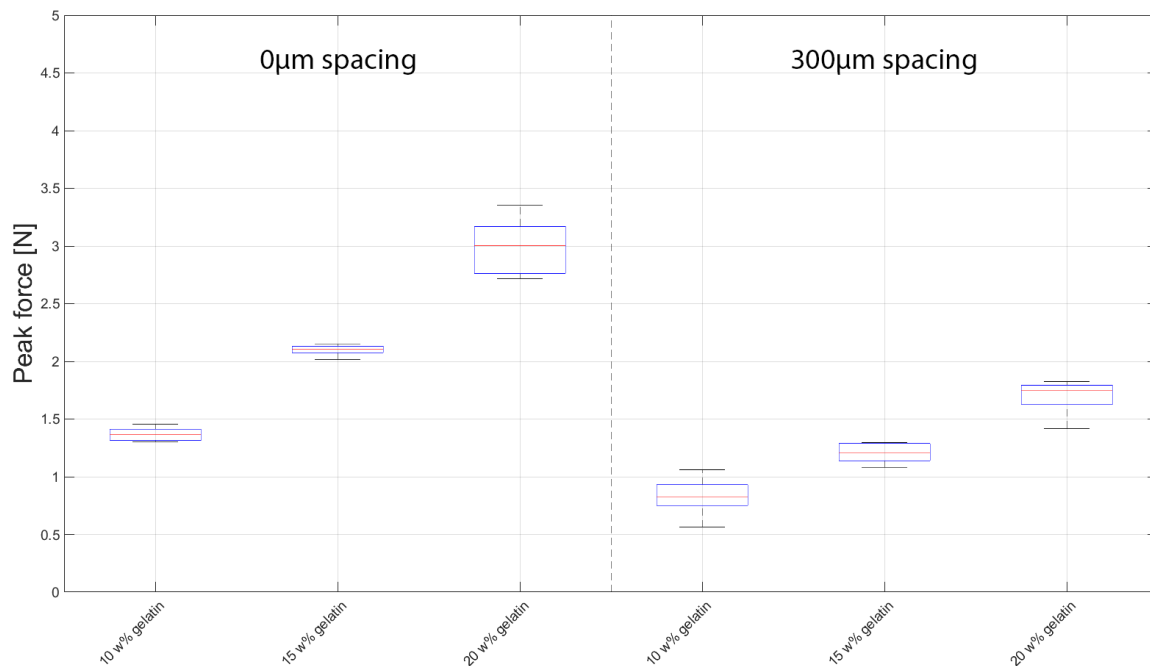


Figure 14 – Friction forces measured with a sample with 4 fibers directly touching each other (i.e., no spacing) and a sample with 4 fibers spaced at 300 micrometers on 10, 15, and 20 w% gelatin substrates.

### 3.1.2. Experiment

#### Friction force

Figure 15 shows the friction forces on various gelatin substrates for samples with various stiffness degrees and fiber densities. It can be seen that friction force increased with substrate stiffness ( $F(2, 76) = 74.25$   $P < 0.001$ ). Post-hoc analysis showed that friction was significantly higher for 10 w% than for 20 w% gelatin for all fiber densities and stiffness degrees of the adhesive (all  $P < 0.001$ , after Bonferroni correction), whereas 10 w% gelatin led to higher friction ( $P < 0.001$ , after Bonferroni correction) than 15 w% gelatin only for the samples with 4 fibers (and for both stiffness degrees of the adhesive).

Friction force decreased with fiber density ( $F(2, 76) = 10.98$   $P = 0.0001$ ). However, no significant differences remained after post-hoc testing. The stiffness of the adhesive pad did not have a significant effect on the friction force ( $F(1, 76) = 0.07$   $P = 0.79$ ).

Figure 16 shows the friction forces on glass substrate. Friction forces were significantly higher on glass than on gelatin ( $F(3, 102) = 75.77$   $P < 0.001$ ). The forces measured on a glass substrate are characterized by large variation. On a glass substrate, friction force did not vary significantly as a function of fiber density and stiffness degree of the adhesive ( $F(2, 24) = 1.54$   $P = 0.234$ ). A non-significant ( $F(1, 24) = 0.87$   $P = 0.4317$ ) decline in friction force can be seen for an increase of fiber density for samples with 1:10 PDMS. For the samples with 1:20 PDMS, an increase in friction force can be seen for an increase in fiber density.

No significant interactions between fiber density, adhesive pad stiffness, and substrate stiffness were observed.

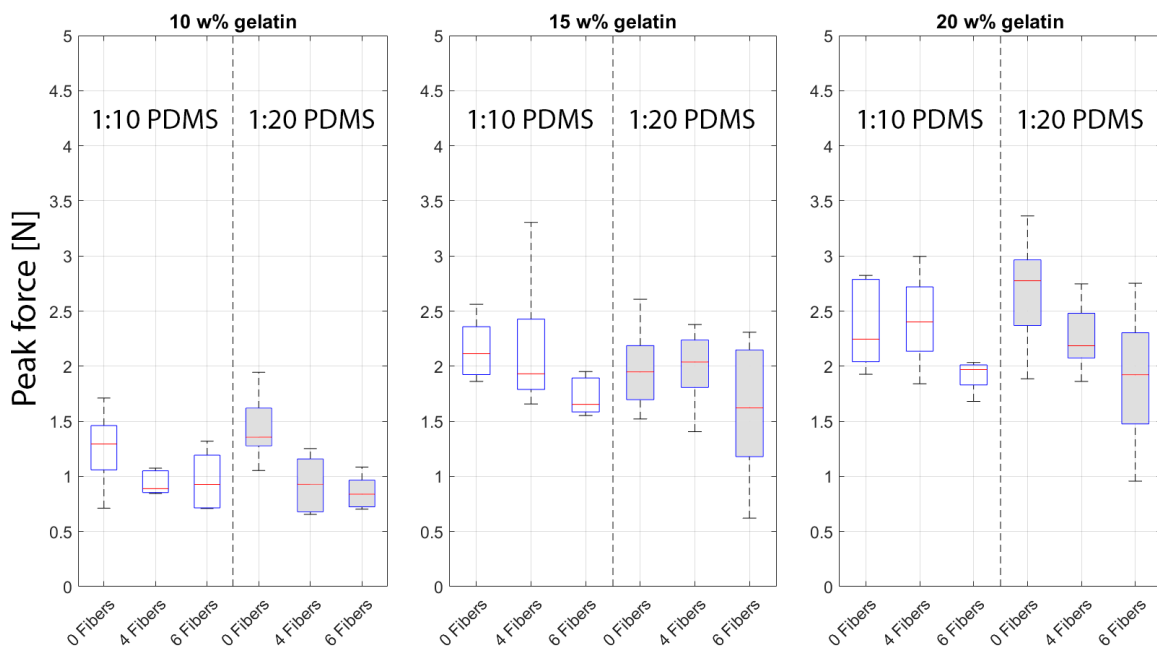


Figure 15 – Friction forces measured with samples with 0, 4, and 6 fibers, 1:10 and 1:20 PDMS, on 10, 15, and 20 w% gelatin substrates in Experiment 1.

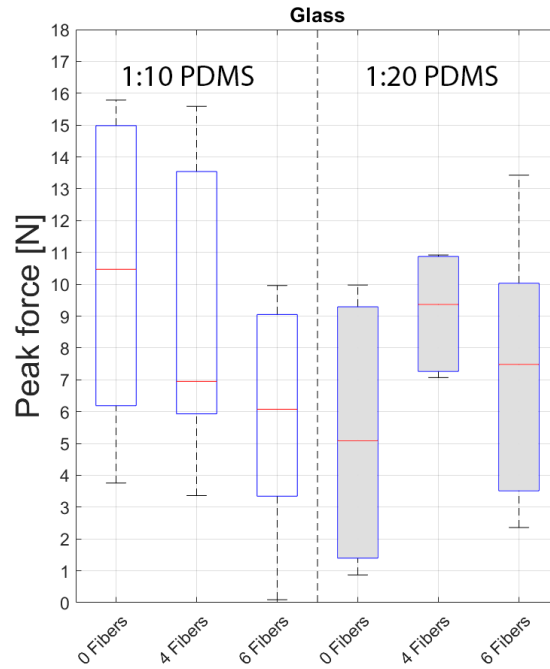


Figure 16 – Friction forces measured with samples with 0, 4, and 6 fibers, 1:10 and 1:20 PDMS, on glass substrate in Experiment 1.

#### Adhesion force

The adhesive forces as a function of the pad stiffness degree and fiber density are shown in figure 17. No significant differences were found between gelatin substrates ( $F(2,76) = 3.08$   $P = 0.0519$ ), fiber densities ( $F(2, 76) = 0.47$   $P = 0.624$ ), or adhesive pad stiffness degrees ( $F(1,76) = 1.09$   $P = 0.3$ ). Large variance was observed for the samples tested on glass substrate. For samples with a 1:10 PDMS pad on glass substrate, adhesion reduced with fiber density ( $F(2, 24) = 4.15$   $P = 0.0283$ ). Contrastingly, for the samples with 1:20 PDMS on glass substrate, adhesion was higher for samples with 4 fibers compared to 0-fiber and 6-fiber samples. Adhesion was significantly higher on glass than on gelatin ( $F(3, 102) = 26.43$   $P < 0.001$ ). A significant interaction between the adhesive pad stiffness and the fiber density was found ( $F(2,24) = 6.15$   $P = 0.007$ ).

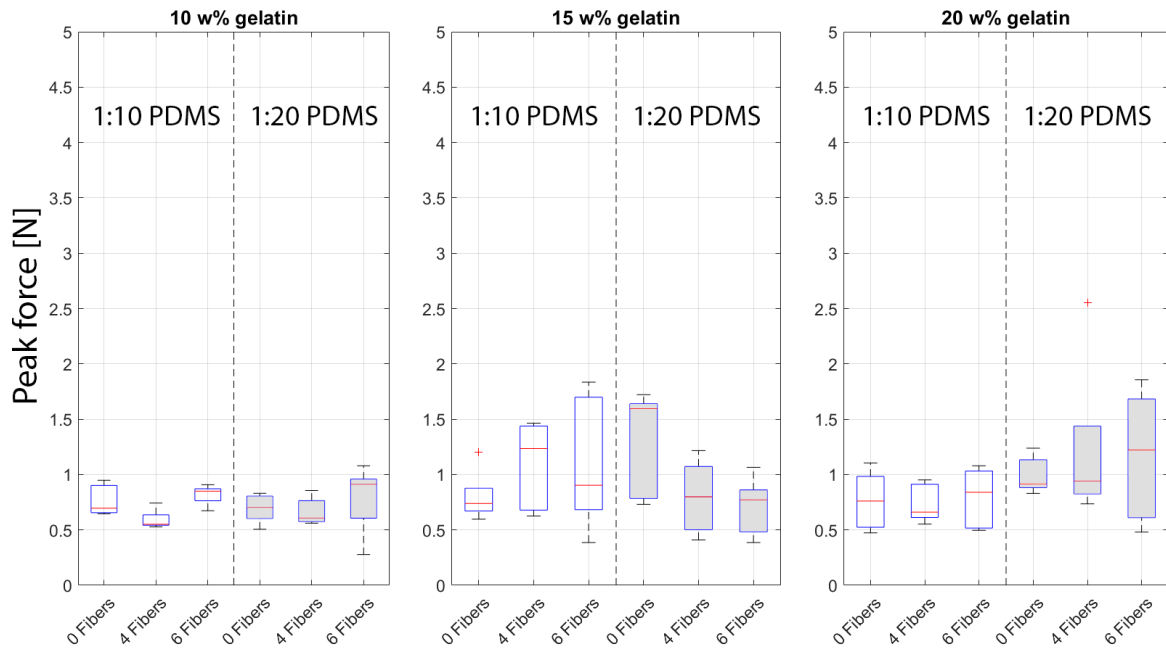


Figure 17 – Adhesive forces measured with samples with 0, 4, and 6 fibers, 1:10 and 1:20 PDMS, on 10, 15, and 20 w% gelatin substrates in Experiment 1.

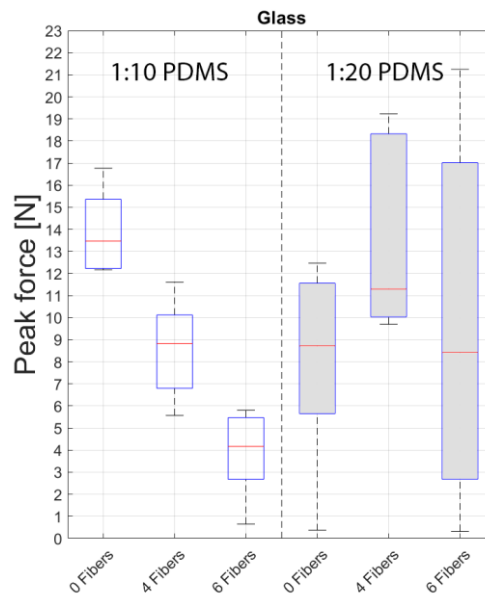


Figure 18 – Adhesion forces measured with samples with 0, 4, and 6 fibers, 1:10 and 1:20 PDMS, on glass substrate in Experiment 1.

### 3.2. Experiment 2

Figure 19 shows the friction forces on various gelatin substrates for samples with various stiffness degrees and fiber densities. It can be seen that friction force increased with substrate stiffness ( $F(2, 121) = 66.86$   $P < 0.001$ ). Post-hoc analysis showed that friction was significantly higher for 10 w% than for 20 w% gelatin for all fiber densities and stiffness degrees of the adhesive (all  $P < 0.001$ , after Bonferroni correction), whereas 10 w% gelatin led to higher friction ( $P < 0.001$ , after Bonferroni

correction) than 15 w% gelatin only for the samples with 4 fibers (and for both stiffness degrees of the adhesive).

Friction force decreased with fiber density ( $F(2, 121) = 3.19$   $P = 0.0448$ ). The stiffness of the adhesive pad did not have a significant effect on the friction force ( $F(1,121) = 0.12$   $P = 0.735$ ).

Figure 20 shows the friction forces on glass substrate. Friction forces were significantly higher on glass than on gelatin ( $F(3, 102) = 26.43$   $P < 0.001$ ). On glass, the fiber density did not significantly affect friction force ( $F(1, 39) = 2.41$   $P = 0.103$ ).

No significant interactions between the fiber density, adhesive pad stiffness and substrate were found.

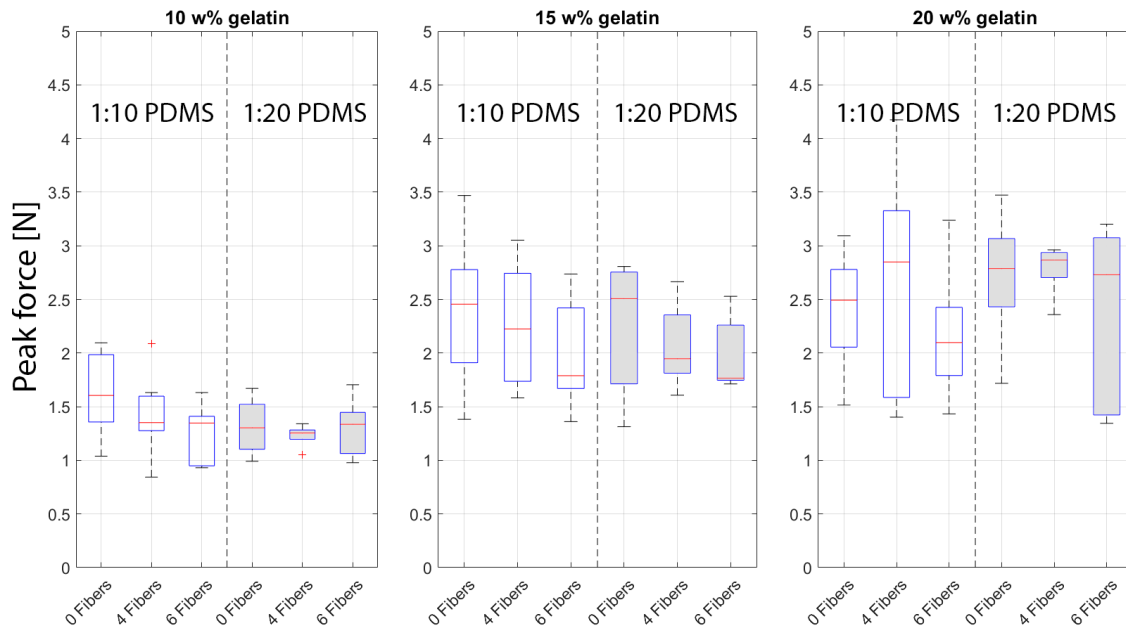


Figure 19 – Friction forces measured with samples with 0, 4, and 6 fibers, 1:10 and 1:20 PDMS, on 10, 15, and 20 w% gelatin substrates in Experiment 2.

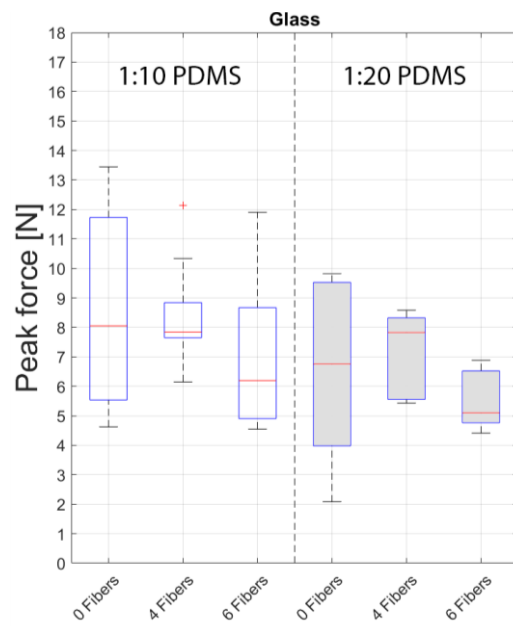


Figure 20 – Friction forces measured with samples with 0, 4, and 6 fibers, 1:10 and 1:20 PDMS, on glass substrate in Experiment 2.



### 3.3. Experiment 3

The friction forces measured in Experiment 3 are shown in figure 21. PDMS stiffness did not affect friction forces significantly ( $F(2, 166) = 1.03$   $P = 0.359$ ). Introducing fibers to the structure increased the friction force significantly ( $F(2, 166) = 71.05$   $P < 0.001$ ) on both glass and gelatin substrates. Post-hoc analysis showed that friction was significantly higher for both 12K and 3K carbon fiber composite adhesives compared to fiber-less adhesives on glass substrate for all adhesive pad stiffness degrees ( $P < 0.001$ , after Bonferroni correction), whereas both 12K carbon fiber fabric with 1:30 PDMS and 3K carbon fiber fabric with 1:20 PDMS led to higher friction compared to fiber-less adhesives on 15 w% gelatin ( $P < 0.001$ , after Bonferroni correction).

No significant difference in friction force was observed between 3K and 12K carbon fiber fabrics on either glass or gelatin substrates ( $F(1,110) = 1.45$   $P = 0.231$ ).

Friction force was significantly higher on glass than on gelatin ( $F(1, 166) = 56.1$   $P < 0.001$ ). Post-hoc analysis showed that friction force was significantly higher on glass than on 15 w% gelatin for 3K carbon fiber fabric with both 1:10 and 1:20 PDMS adhesive pad stiffness ( $P < 0.001$ , after Bonferroni correction).

A significant interaction between the PDMS adhesive pad stiffness and the fiber density was found ( $F(4, 166) = 3.01$   $P = 0.02$ ). No significant interactions between the adhesive pad stiffness and the substrate stiffness or between the fiber density and the substrate stiffness were found.

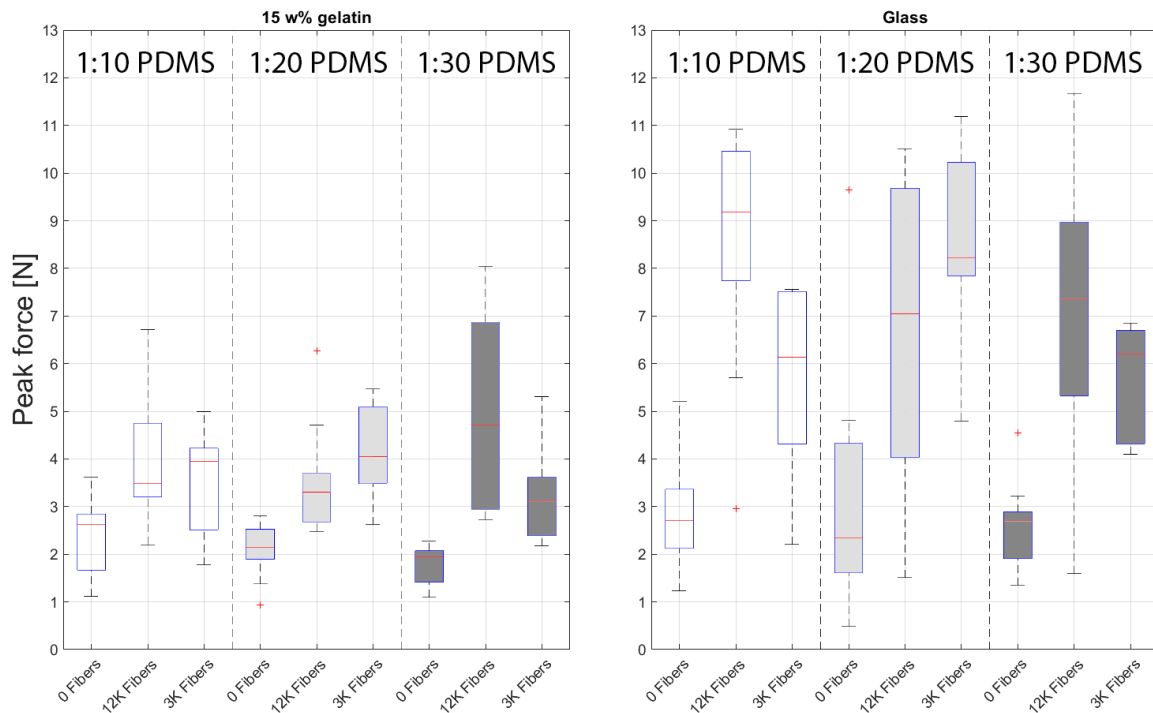


Figure 21 – Friction forces measured with samples with 0, 3K, and 12K carbon fiber fabric, 1:10, 1:20 and 1:30 PDMS, on 10, 15, and 20 w% gelatin substrates in in Experiment 3.

## 4. Discussion

In the current study, we investigated whether mimicking the stiff tendons found in the toe pads of geckos and tree frogs positively contributes to grip on soft substrates. We hypothesize that:

- Provided that a good contact between an adhesive and a soft substrate is made, adding stiff fibers to the adhesive at a direction parallel to the substrate reduces the compliance of the composite in this direction, thereby preserving the established contact and thus increasing peak friction forces.
- An adhesive composite with stiff fibers and soft pad generates higher peak friction forces on hard (i.e. glass) substrate compared to soft substrate.

Two 3D-printed fiber patterns and two carbon fiber fabrics with different degrees of fiber stiffness were used. These fibers were encapsulated in PDMS with varying degrees of stiffness. The fabricated adhesive composites were tested on gelatin substrates with varying stiffness degrees and on a glass substrate.

We found that the adhesive composites with 3D-printed fibers exhibited significantly lower peak friction and adhesion force on all substrates compared to adhesives without fibers. The adhesive composites with carbon fiber fabric exhibited significantly higher peak friction force than adhesives without fibers on gelatin and glass substrate. The stiffness of the encapsulant did not seem to significantly affect the peak friction and adhesion force on any of the substrates and for any fiber type.

### Experiments 1 and 2

#### *Pilot test*

During pilot tests, we found that for any of the fabricated structures, friction and adhesion forces on a wet substrate and without preload were too low to be measured. This is likely because the liquid film prevented intimate contact, leading to aquaplaning instead (Persson et al. 2005).

#### *Adhesion forces*

In both Experiments 1 and 2, we found that adding to the adhesive 3D-printed fibers parallel to the substrate did not have a significant effect on the peak adhesion force measured on gelatin substrates. Persson and Tosatti (2001) have shown that contact and thus peak adhesion force of an adhesive reduced with the roughness of the substrate. In this line, it is likely that the increased roughness of gelatin substrates compared to glass substrate allowed for too little initial contact, which in turn explains why no significant effects on the peak friction force were found as a function of fiber presence of density. In other words, assuming that the role of fibers is to *preserve* the contact that has already been *made*, in our samples there was too little contact to be preserved by the fibers. We also found no significant effect of the degree of stiffness of the adhesive pad on peak adhesion, which opposes our expectation that reducing the adhesive pad stiffness results in more intimate contact on the rough surfaces compared to a stiffer adhesive pad. We suspect that the effect of the varying stiffness degrees of the adhesive pads might have been diminished by the low stiffness, and thus conformability, of the substrate itself.

On the glass substrate, we found that increasing the fiber density in composites using 1:10 PDMS adhesive pads resulted in significantly lower peak adhesion forces. A possible explanation of this finding is that higher fiber density increases the stiffness of the adhesive composite, leading to smaller initial contact. For the composites with 1:20 PDMS adhesive pads, no conclusion could be drawn for the role of fiber density, because of large variation of measurement data.

### *Friction forces*

We found that peak friction forces reduced with increasing fiber density on both gelatin and glass substrates for the samples tested in Experiments 1 and 2. There might be three possible explanations for this behavior:

- The 3D-printed fibers used in Experiments 1 and 2 were fabricated with a rather high out-of-plane stiffness, possibly limiting the so-called draping effect, therefore reducing conformability of the adhesive composite at the large scale and thus inhibiting the amount of contact with the substrate (Bartlett et al. 2012).
- In Experiments 1 and 2, a plexiglass sample holder was used to move the sample. This holder becomes essentially part of the adhesive system that moves along the substrate, influencing the compliance of the system. In other words, the sample holder might have functioned as a stiff layer at the top of our composite, reducing the total compliance and draping ability of the adhesive composite. It is important to note that the effect of the sample holder is not systematic, but situation dependent: (1) When we pilot tested the carbon fiber fabric with the sample holder, lower peak friction forces were measured compared to directly loading the carbon fiber fabric without the sample holder. (2) Contrastingly, when we tested the 3D-printed fiber samples with and without sample holder, no difference on the peak friction force was found.
- The thickness of the adhesive pads might have influenced the measured peak friction forces. As discussed in section 1.4.2, the thickness of the adhesive pad is critical for the peak friction forces. The samples fabricated for Experiments 1 and 2 consisted of a thick PDMS adhesive pad, which might have changed the deformation inside the adhesive from shearing deformation to bending deformation (Bartlett, Croll, and Crosby 2012). This is supported by observations of pilot testing before Experiment 3, in which adhesives with carbon fiber fabric and a thick PDMS adhesive pad generated lower peak friction forces than adhesives using carbon fiber fabric with a thin PDMS adhesive pad.

Finally, we did not find a difference in the peak friction forces generated by the composites in Experiments 1 and 2, despite the fact that the stiffness of the 3D-printed fibers increased in Experiment 2. It is likely that the difference in stiffness between these two types of fibers was too small to make any significant difference in the peak friction force, which is in line with findings of King and Crosby (2015).

## Experiment 3

The results of Experiment 3 showed that peak friction force of adhesives with carbon fiber fabric is significantly higher than adhesives without fiber fabric on glass substrate, in line with the theory and experimental findings by Crosby and coworkers (Bartlett et al. 2012; King 2015; Bartlett and Crosby 2014; King et al. 2017; King and Crosby 2015). We further found that the positive effect of adding a carbon fiber fabric in an adhesive also holds for peak friction forces on gelatin, although these forces were lower than the forces measured on glass substrate. This confirms our hypothesis that adding stiff fibers with low in-plane stiffness to an adhesive increases peak friction forces not only on hard substrates but also on substrates with low stiffness.

No significant difference in peak friction force was measured between the 3K and 12K carbon fiber fabric. These fabrics differed in the number of threads and weave pattern but had comparable Young's moduli and tensile strength, which may explain why they did not lead to different peak forces.

For all friction experiments we found that increasing the stiffness of the substrate resulted in higher peak friction force. This is expected, as a lower Young's modulus of a less stiff material implies a higher strain energy release rate of the substrate, resulting in faster crack formation between the substrate and the adhesive as described in section 1.4.1 (Bennett, Devries, and Williams 1974; Maugis and Barquins 1989).

Lastly, we found no significant statistical interactions or peak friction force effects of the stiffness degree of the adhesive pad and the substrate. Due to the low roughness of glass, maximum contact is made for all degrees of adhesive pad stiffness tested. On the rougher gelatin substrates, on the other hand, we suspect that the low stiffness, and thus conformability of the substrate diminished the effect of the varying stiffness degrees of the adhesive pads. In a pilot test we performed with carbon fiber fabric encapsulated with a stiff polyurethane pad, no initial contact on glass substrate was formed. This suggests that a polymer stiffer than 1:10 PDMS might result in reduced initial contact. In future work, substrates with high stiffness and high roughness could be included to elucidate the effects of these variables on peak friction forces.

## Limitations and recommendations for future work

One limitation in our work is that, due to the exploratory nature of our work, a limited number of repetitions was performed per condition, in order to allow us to make quick adjustments to our research design. Larger sample sizes are recommended in future iterations, to reduce the variance of the results and help drawing more solid conclusions.

A second limitation is that in this work, we did not test the durability of the samples. It remains thus unknown how the quality of the adhesive might be affected by multiple cycles of adhering and releasing—an important property for reversible and reusable adhesives. Moreover, the effects of relaxation and degradation of the adhesives over time have not been tested. It is therefore recommended that in future work the performance of the adhesives is tested in multiple cycles.

Another limitation of our work is the small number of different degrees of stiffness tested for both the adhesive pad and the fibers. King and Crosby (2015) have shown that the stiffness of all parts of the adhesive composite are critical, leaving room for future studies to test a large number of combinations of materials for both the adhesive pad and the fibers tested on soft substrates. Additionally, in future work rough and stiff surfaces could be included to test the effects of varying the adhesive pad stiffness on generating initial contact. Also, we recommend that the tested materials are subjected to mechanical testing in order to understand specific material interactions.

A limitation in our measurement setup was the use of a stiff sample holder in the first two experiments. We recommend using a method of actuating the samples directly on the fibers while minimizing the effect on the compliance of the adhesive system. An additional limitation related to our measurement method was the way the preload was applied in the first two experiments. A rolling preload might result in a more complete initial contact compared to a static preload (M. Bartlett, personal communication, October 6, 2017).

Lastly, we recommend decorating the adhesive composites with a surface microstructure similar to that on the tree frog toe pads (Persson 2007). Such a microstructure could help channel liquid away from the surface (cf. drainage), allowing contact with the substrate to be made and restoring the adhesive capabilities of the adhesive structure under wet conditions. Additionally, such a structure would help reduce crack propagation by contact splitting, increasing the peak friction force.

An artist impression of a possible implementation of the adhesive composites investigated in this paper is shown in figure 22. Based on our findings, to be able to generate high grip, the instrument needs to load the fibers of the adhesive composite directly and with an angle of  $0^\circ$  to the tissue surface.

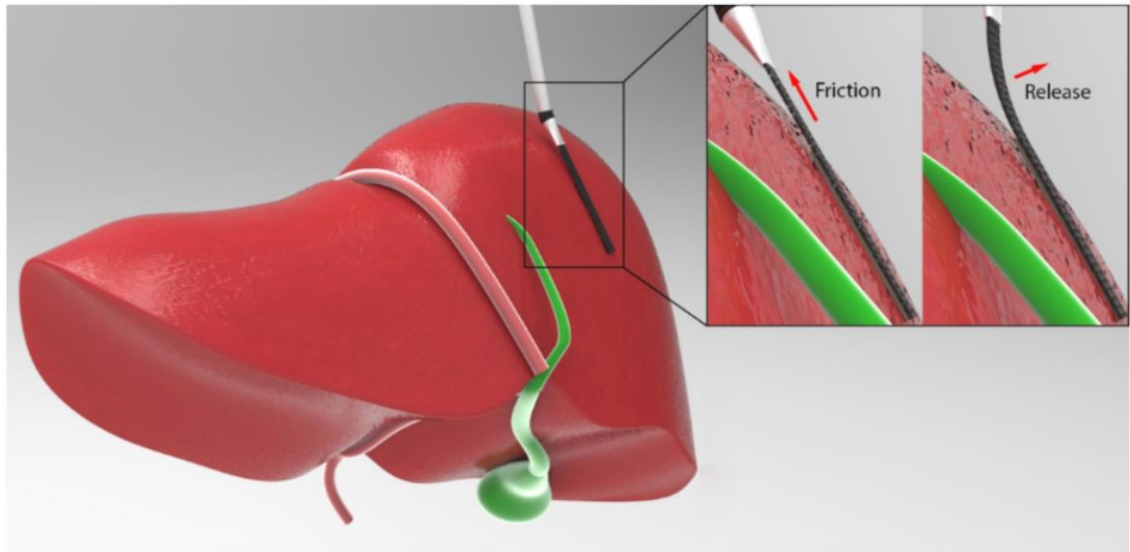


Figure 22 – Artist's impression of a minimally invasive grasper using our biomimetic adhesive composite.

## 5. Conclusion

Grasping instruments in current minimally invasive surgical practice are error-prone. Therefore, new approaches for soft-tissue grip are welcome. We developed adhesive composites consisting of stiff fibers encapsulated in a soft pad, and we experimentally showed that such adhesive composites have potential for generating grip on soft substrates. Further work is needed in order to maximize the adhesive contact (e.g., by decorating the adhesive composites with a surface microstructure) as well as to identify the combination of stiffness of the soft pad and the internal fibers required for preserving the established contact. We expect that an instrument featuring such an adhesive composite can be a safe and viable addition to the surgical instrumentarium currently used in minimally invasive surgery.

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## Product Information Electronics



### Sylgard<sup>®</sup> 184 Silicone Elastomer

#### **FEATURES & BENEFITS**

- Flowable
- Room temperature and heat cure
- Good dielectric properties
- Rapid, versatile cure processing controlled by temperature
- High transparency allows easy inspection of components

#### **COMPOSITION**

- Two-part
- 10 to 1 mix ratio
- Polydimethylsiloxane elastomer

Transparent encapsulant with good flame resistance

#### **APPLICATIONS**

Sylgard<sup>®</sup> 184 Silicone Elastomer is suitable for:

- LED Lighting encapsulation
- Power supplies
- Connectors
- Sensors
- Industrial controls
- Transformers
- Amplifiers
- High voltage resistor packs
- Relays
- Adhesive/encapsulant for solar cells
- Adhesive handling beam lead integrated circuits during processing

#### **TYPICAL PROPERTIES**

Specification Writers: These values are not intended for use in preparing specifications. Please contact your local Dow Corning sales office or your Global Dow Corning Connection before writing specifications on this product.

Property	Unit	Result
One or Two Part		Two
Color		Colorless
Viscosity (Base)	cP	5100
	Pa-sec	5.1
Viscosity (Mixed)	cP	3500
	Pa-sec	3.5
Thermal Conductivity	btu/hr ft °F	0.15
	W/m °K	0.27
Specific Gravity (Cured)		1.03
Working Time at 25°C (Pot Life - hours)	hours	1.5
Cure Time at 25°C	hours	48
Heat Cure Time at 100°C	minutes	35
Heat Cure Time at 125°C	minutes	20
Heat Cure Time at 150°C	minutes	10
Durometer Shore		43
Dielectric Strength	volts/mil	500
	kV/mm	19

## TYPICAL PROPERTIES (Continued)

Property	Unit	Result
Volume Resistivity	ohm <sup>3</sup> cm	2.9E+14
Dissipation Factor at 100 Hz		0.00257
Dissipation Factor at 100kHz		0.00133
Dielectric Constant at 100 Hz		2.72
Dielectric Constant at 100 kHz		2.68
Linear CTE (by DMA)	ppm/°C	340
Tensile Strength	PSI	980
	MPa	6.7
	Kg/cm <sup>2</sup>	69
Refractive Index	@ 589 nm	1.4118
Refractive Index	@ 632.8 nm	1.4225
Refractive Index	@1321 nm	1.4028
Refractive Index	@ 1554 nm	1.3997
UL RTI Rating	°C	150

### DESCRIPTION

*Dow Corning*<sup>®</sup> brand silicone 10 to 1 encapsulants are supplied as two-part liquid component kits. When liquid components are thoroughly mixed, the mixture cures to a flexible elastomer, which is well suited for the protection of electrical/electronic applications. *Dow Corning* silicone encapsulants cure without exotherm at a constant rate regardless of sectional thickness or degree of confinement.

*Dow Corning*<sup>®</sup> silicone elastomers require no post cure and can be placed in service immediately following the completion of the cure schedule. Standard silicone encapsulants require a surface treatment with a primer in addition to good cleaning for adhesion while primerless silicone encapsulants require only good cleaning.

### APPLICATION METHODS

- Automated metered mixing and dispensing
- Manual mixing

### MIXING AND DE-AIRING

The 10 to 1 mix ratio these products are supplied in gives one latitude to

tune the modulus and hardness for specific application needs and production lines. In most cases de-airing is not required.

### PREPARING SURFACES

In applications requiring adhesion, priming will be required for many of the silicone encapsulants. For best results, the primer should be applied in a very thin, uniform coating and then wiped off after application. After application, it should be thoroughly cured prior to application of the silicone elastomer. Additional instructions for primer usage can be found in the information sheets specific to the individual primers.

### PROCESSING/CURING

Thoroughly mixed *Dow Corning* silicone encapsulant may be poured/dispensed directly into the container in which it is to be cured. Care should be taken to minimize air entrapment. When practical, pouring/dispensing should be done under vacuum, particularly if the component being potted or encapsulated has many small voids. If this technique cannot be used, the unit should be evacuated after the silicone encapsulant has been

poured/dispensed. *Dow Corning* silicone encapsulants may be either room temperature (25°C/77°F) or heat cured. Room temperature cure encapsulants may also be heat accelerated for faster cure. Ideal cure conditions for each product are given in the product selection table.

### POT LIFE AND CURE RATE

Cure reaction begins with the mixing process. Initially, cure is evidenced by a gradual increase in viscosity, followed by gelation and conversion to a solid elastomer. Pot life is defined as the time required for viscosity to double after base and curing agent are mixed and is highly temperature and application dependent. Please refer to the data table.

### USEFUL TEMPERATURE RANGES

For most uses, silicone elastomers should be operational over a temperature range of -45 to 200°C (-49 to 392°F) for long periods of time. However, at both the low and high temperature ends of the spectrum, behavior of the materials and performance in particular

# Appendix B

## POLYJET MATERIALS DATASHEET

### RIGID OPAQUE MATERIALS

VERO PUREWHITE RGD837, VEROGRAY RGD850, VEROLACKPLUS RGD875, VEROWHITEPLUS RGD835, VEROYELLOW RGD836, VEROCYAN RGD841, VEROMAGENTA RGD851

	ASTM	UNITS	METRIC	UNITS	IMPERIAL
Tensile strength	D-638-03	MPa	50-65	psi	7250-9450
Elongation at break	D-638-05	%	10-25	%	10-25
Modulus of elasticity	D-638-04	MPa	2000-3000	psi	290,000-435,000
Flexural Strength	D-790-03	MPa	75-110	psi	11000-16000
Flexural Modulus	D-790-04	MPa	2200-3200	psi	320,000-465,000
HDT, °C @ 0.45MPa	D-648-06	°C	45-50	°F	113-122
HDT, °C @ 1.82MPa	D-648-07	°C	45-50	°F	113-122
Izod Notched Impact	D-256-06	J/m	20-30	ft lb/inch	0.375-0.562
Water Absorption	D-570-98 24hr	%	1.1-1.5	%	1.1-1.5
Tg	DMA, E-	°C	52-54	°F	126-129
Shore Hardness (D)	Scale D	Scale D	83-86	Scale D	83-86
Rockwell Hardness	Scale M	Scale M	73-76	Scale M	73-76
Polymerized density	D792	g/cm3	1.17-1.18		
Ash content VeroGray, VeroWhitePlus	USP281	%	0.23-0.26	%	0.23-0.26
Ash content VeroBlackPlus	USP281	%	0.01-0.02	%	0.01-0.02

### RIGID OPAQUE MATERIALS

VEROBLUE RGD840

	ASTM	UNITS	METRIC	UNITS	IMPERIAL
Tensile strength	D-638-03	MPa	50-60	psi	7250-8700
Elongation at break	D-638-05	%	15-25	%	15-25
Modulus of elasticity	D-638-04	MPa	2000-3000	psi	290,000-435,000
Flexural Strength	D-790-03	MPa	60-70	psi	8700-10200
Flexural Modulus	D-790-04	MPa	1900-2500	psi	265,000-365,000
HDT, °C @ 0.45MPa	D-648-06	°C	45-50	°F	113-122
HDT, °C @ 1.82MPa	D-648-07	°C	45-50	°F	113-122
Izod Notched Impact	D-256-06	J/m	20-30	ft lb/inch	0.375-0.562
Water Absorption	D-570-98 24hr	%	1.5-2.2	%	1.5-2.2
Tg	DMA, E-	°C	48-50	°F	118-122
Shore Hardness (D)	Scale D	Scale D	83-86	Scale D	83-86
Rockwell Hardness	Scale M	Scale M	73-76	Scale M	73-76
Polymerized density	D792	g/cm3	1.18-1.19		
Ash content	USP281	%	0.21-0.22	%	0.21-0.22

### SIMULATED POLYPROPYLENE MATERIALS

DURUS WHITE RGD430

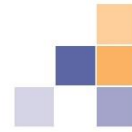
	ASTM	UNITS	METRIC	UNITS	IMPERIAL
Tensile strength	D-638-03	MPa	20-30	psi	2900-4350
Elongation at break	D-638-05	%	40-50	%	40-50
Modulus of elasticity	D-638-04	MPa	1000-1200	psi	145,000-175,000
Flexural Strength	D-790-03	MPa	30-40	psi	4350-5800
Flexural Modulus	D-790-04	MPa	1200-1600	psi	175,000-230,000
HDT, °C @ 0.45MPa	D-648-06	°C	37-42	°F	99-108
HDT, °C @ 1.82MPa	D-648-07	°C	32-34	°F	90-93
Izod Notched Impact	D-256-06	J/m	40-50	ft lb/inch	0.749-0.937
Water Absorption	D-570-98 24hr	%	1.5-1.9	%	1.5-1.9
Tg	DMA, E-	°C	35-37	°F	95-99
Shore Hardness (D)	Scale D	Scale D	74-78	Scale D	74-78
Rockwell Hardness	Scale M	Scale M	no data	Scale M	no data
Polymerized density	D792	g/cm3	1.15-1.17		
Ash content	USP281	%	0.10-0.12	%	0.1-0.12

RIGUR RGD450

	ASTM	UNITS	METRIC	UNITS	IMPERIAL
Tensile strength	D-638-03	MPa	40-45	psi	5800-6500
Elongation at break	D-638-05	%	20-35	%	20-35
Modulus of elasticity	D-638-04	MPa	1700-2100	psi	246,000 - 305,000
Flexural Strength	D-790-03	MPa	52-59	psi	7500 - 8500
Flexural Modulus	D-790-04	MPa	1500-1700	psi	217,000 - 246,000
HDT, °C @ 0.45MPa	D-648-06	°C	49-54	°F	120-129
HDT, °C @ 1.82MPa	D-648-07	°C	45-50	°F	113-122
Izod Notched Impact	D-256-06	J/m	30-35	ft lb/inch	0.561-0.856
Tg	DMA, E-	°C	48-52	°F	118-126
Shore Hardness (D)	Scale D	Scale D	80-84	Scale D	80-84
Rockwell Hardness	Scale M	Scale M	58-62	Scale M	58-62
Polymerized density	D792	g/cm3	1.20-1.21		
Ash content	USP281	%	0.3-0.4	%	0.3-0.4



## Materials



### AB Materials - ABflex and ABS-tuff

EnvisionTEC's AB Materials are the closest prototype resins to production grade ABS Plastic. Finally, rapid prototyping/3D printing has a true production representation of ABS with the launch of the AB materials from EnvisionTEC. Combining AB Materials with patented DLP technology exclusively from EnvisionTEC gives you the absolute closest 3D representation available in the industry.

ABS-tuff is a high grade rapid prototyping resin providing the structural representation of ABS plastic.

ABflex provides the same structural representation of AB plastic with new flexibility characteristics.

#### Material Comparisons of Mechanical Properties\*

Comparison Type	ABS-tuff	ABflex	ABS Plastic
Tensile Strength	48.6 MPa	28.6 MPa	45 MPa
Elongation at Break	7%	14.6%	10%
Flexural Strength	2100 MPa	1400 MPa	2300 MPa
Hardness Shore D	83	N/A	77
Resin Specific Gravity	1.10 - 1.12 g/cm <sup>3</sup>	N/A	1.10 - 1.12 g/cm <sup>3</sup>

\*All data provided is preliminary data and must be verified by the individual user.

#### Recommended Machines

Perfactory® 4 Standard with ERM, Perfactory® 4 Standard XL with ERM, Perfactory® 4 Mini XL with ERM, Perfactory® 4 Mini with ERM, Perfactory® 3 Mini Multi Lens, Perfactory® Xtreme and Perfactory® Xede

#### Applications

Aerospace, Animation and Entertainment, Architecture and Art, Automotive, Consumer Packaged Goods, Education, Electronics, Manufacturing, Sporting Goods, Toys

### Material Properties

- » Closest prototype resin to production grade ABS Plastic
- » Provides sharpest production representation of AB plastic
- » Best utilized for functional prototypes
- » Best quality and value in industry
- » Extreme durability or flex capability
- » Best value per kilogram in industry



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info@envisiontec.com

# Appendix D

<b>TECHNICAL DATASHEET</b>	
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**Article:** Style 427  
**Setting (Thr/cm):** 2,5/2,5  
**Weave:** Plain  
**Finish:** loomstate

<u>Construction:</u>	Warp	Weft
Yarn material <sup>1)</sup> :	Carbon 12K	Carbon 12K
Yarn number <sup>1)</sup> :	800 tex	800 tex

<u>Technical Data:</u>		Unit	Target	+/-	Tolerance
Fibre density <sup>1) 3)</sup>	Warp	g/cm <sup>3</sup>	1,80	+/-	0,04
	Weft	g/cm <sup>3</sup>	1,80	+/-	#
Linear density <sup>1)</sup>	Warp	tex	800	+/-	40
	Weft	tex	800	+/-	40
Twist <sup>1)</sup>	Warp	T/m		+/-	
	Weft	T/m		+/-	
Setting	Warp	Thr./cm	2,5	+/-	0,1
	Weft	Thr./cm	2,5	+/-	0,1
Weave			Plain		
Weight		g/m <sup>2</sup>	400	+/-	20
Dry weight		g/m <sup>2</sup>	400	+/-	20
Moisture content		%	0,5	+/-	max.
Thickness <sup>2)</sup>		mm	0,64	+/-	0,06
Width		cm	as ordered	+/-	1

<sup>1)</sup> = n.G. = depending on order and yarn specification  
<sup>2)</sup> = approximate value, not for release

<sup>3)</sup> = no measure, certified by supplier

<b>Remarks:</b>
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<b>Date</b> 10.08.2009	<b>Q.A.</b> Monika Dassel	<b>This Datasheet does not include Revision Service.</b>
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# Appendix E

<b>TECHNICAL DATASHEET</b>	
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**Article:** Style 450  
**Setting (Thr/cm):** 5,0/5,0  
**Weave:** Plain  
**Finish:** loomstate

<u>Construction:</u>	Warp	Weft
Yarn material <sup>1)</sup> :	Carbon 3K	Carbon 3K
Yarn number <sup>1)</sup> :	200 tex	200 tex

<u>Technical Data:</u>		Unit	Target	+/-	Tolerance
Fibre density <sup>1) 3)</sup>	Warp	g/cm <sup>3</sup>	n.G.	+/-	n.G.
	Weft	g/cm <sup>3</sup>	n.G.	+/-	n.G.
Linear density <sup>1)</sup>	Warp	tex	200	+/-	10
	Weft	tex	200	+/-	10
Twist <sup>1)</sup>	Warp	T/m		+/-	
	Weft	T/m		+/-	
Setting	Warp	Thr./cm	5,0	+/-	0,2
	Weft	Thr./cm	5,0	+/-	0,2
Weave			Plain		
Weight		g/m <sup>2</sup>	200	+/-	8
Dry weight		g/m <sup>2</sup>	200	+/-	8
Moisture content		%	0,5	+/-	max.
Thickness <sup>2)</sup>		mm	0,30	+/-	0,04
Width		cm	as ordered	+/-	1

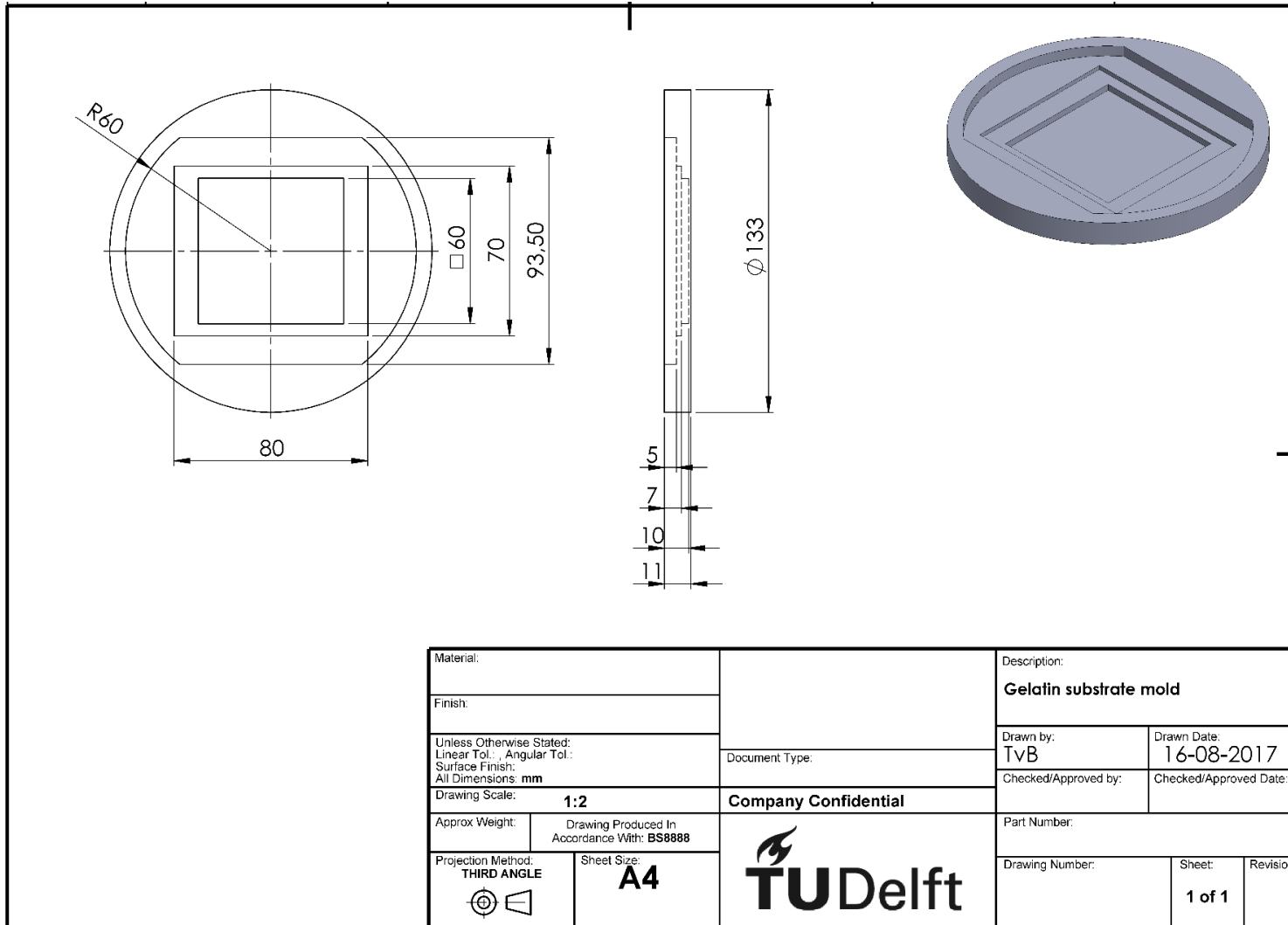
<sup>1)</sup> = n.G. = depending on order and yarn specification  
<sup>2)</sup> = approximate value, not for release

<sup>3)</sup> = no measure, certified by supplier

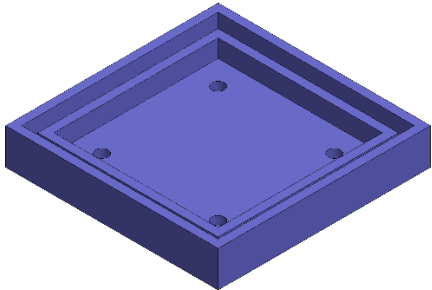
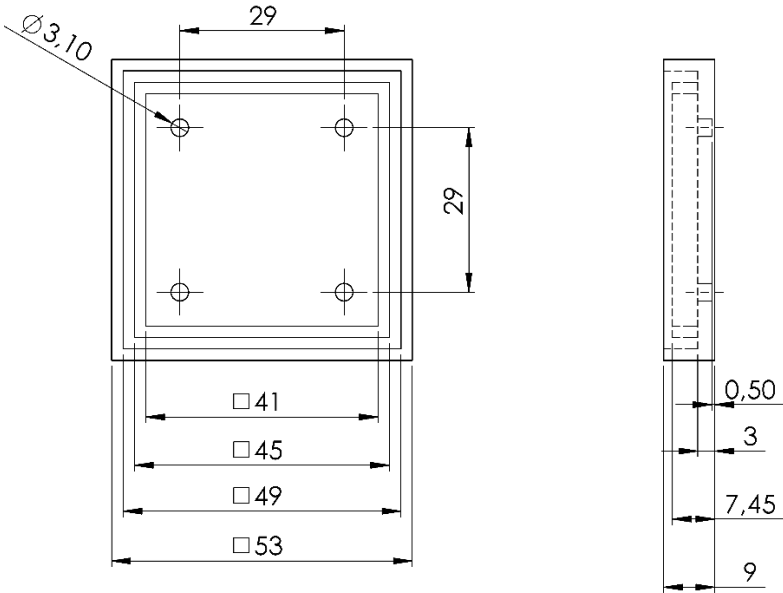
<b>Remarks:</b>
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<b>Date</b> 14.08.2009	<b>Q.A.</b> Monika Dassel	<b>This Datasheet includes Revision Service.</b>
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# Appendix F

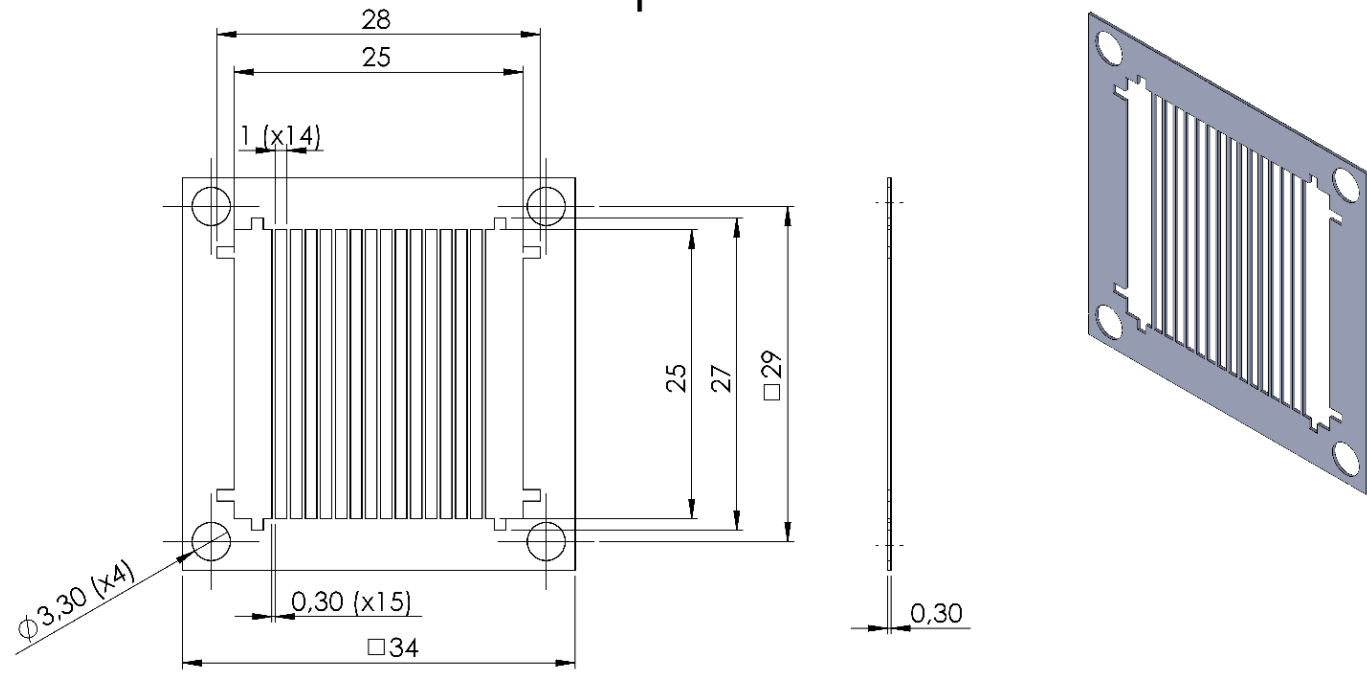


# Appendix G



Material:		Description:	
Finish:		<b>PDMS mold</b>	
Unless Otherwise Stated: Linear Tol.: . Angular Tol.: Surface Finish: All Dimensions: <b>mm</b>		Document Type:	Drawn by: <b>TvB</b>
Drawing Scale: <b>1:1</b>		Drawn Date: <b>16-08-2017</b>	
Approx Weight: <b>Kg</b>		Checked/Approved by:	
Drawing Produced In Accordance With: <b>BS8888</b>		Checked/Approved Date:	
Projection Method: <b>THIRD ANGLE</b>		<b>Company Confidential</b>	
Sheet Size: <b>A4</b>		Part Number:	
		Drawing Number:	
		Sheet: <b>1 of 1</b>	Revision:

# Appendix H



Material:		Description: <b>PDMS mold</b>	
Finish:		Drawn by: TvB	Drawn Date: 16-08-2017
Unless Otherwise Stated: Linear Tol.: , Angular Tol.: Surface Finish: All Dimensions: <b>mm</b>		Document Type: <b>Company Confidential</b>	
Drawing Scale: <b>2:1</b>		Checked/Approved by: Checked/Approved Date:	
Approx Weight: Kg	Drawing Produced In Accordance With: <b>BS8888</b>	Part Number:	
Projection Method: <b>THIRD ANGLE</b>	Sheet Size: <b>A4</b>	Drawing Number:	Sheet: <b>1 of 1</b>
		Revision:	

# Appendix I

Fibers			Elastomer				Force capacity	Curing	Reference
Type	Thickness	E modulus	Type	Thickness	E modulus	Shear modulus			
Stiff unidirectional 12k 11oz fabric	0.4mm		PU - ST1060	0.6 mm	3.8 MPa		2950 N	Cured at room temperature for 24 hours, and then at 70 °C for 24 hours. Cured at room temperature for 3 days. Cured at room temperature for 3 days. Cured at room temperature for 3 days. Cured at room temperature for 3 days.	(Bartlett et al. 2012)
Carbon fiber/Kevlar plain weave 3k 4.8 oz fabric			1:10 PDMS						
Plain weave polyester			1:10 PDMS						
Plain weave nylon fabric			1:10 PDMS						
-			1:10 PDMS						
24K unidirectional carbon fiber tape	0.3 mm	33 GPa	PU - ST1060	0.4 mm	3.1 MPa		±2700N	Samples are cured at room temperature overnight (at least 12 h) and then placed in a 70 °C oven for at least 12 h	(King and Crosby 2015)
24K unidirectional carbon fiber tape	0.3 mm	33 GPa	PU - F15	0.4 mm	0.35 MPa		±930N		
24K unidirectional carbon fiber tape	0.3 mm	33 GPa	PU - ST3040	0.4 mm	1.0 Mpa		±1390N		
24K unidirectional carbon fiber tape	0.3 mm	33 GPa	PU - ST1075	0.4 mm	6.9 MPa		±1810N		
24K unidirectional carbon fiber tape	0.3 mm	33 GPa	PU - ST1085	0.4 mm	22.1 MPa		±1740N		
24K unidirectional carbon fiber tape	0.3 mm	40 Gpa	PU - ST1060	0.42 mm	3.1 MPa		±2600N	Samples were cured at room temperature overnight (at least 12 hours), then placed in a 70 °C oven for 24 hours.	(King et al. 2014)
24K unidirectional carbon fiber tape	0.3 mm	40 GPa	PU - ST3040	0.9 mm	0.3 MPa		±580N		
24K unidirectional carbon fiber tape	0.3 mm	40 GPa	PU - F15	0.41 mm	1 MPa		±1700N		
3K plain weave carbon fiber fabric		20 GPa	PU - ST1060						
3K plain weave carbon fiber fabric		20 GPa	PU - ST3040						
3K plain weave carbon fiber fabric		20 GPa	PU - F15						
Satin weave S-glass fabric		10 GPa	PU - ST1060						
Satin weave S-glass fabric		11 GPa	PU - ST3040						
Satin weave S-glass fabric		12 GPa	PU - F15						

24K unidirectional carbon fiber tape	0.3 mm		PU - ST1060		3.1 MPa		1750N	The samples were cured overnight at room temperature.	(King et al. 2017)
24K unidirectional carbon fiber tape	0.3 mm		PU - F15		0.4 MPa				
24K unidirectional carbon fiber tape	0.3 mm		PU - ST3040		1 MPa				
3K carbon fiber/Kevlar composite fabric	0.21 mm		PU - ST1060		3.1 MPa		875N		
3K carbon fiber/Kevlar composite fabric	0.21 mm		PU - F15		0.4 MPa				
3K carbon fiber/Kevlar composite fabric	0.21 mm		PU - ST3040		1 MPa				
Glass fiber fabric	0.3 mm		PU - ST1060		3.1 MPa		1250N		
Glass fiber fabric	0.3 mm		PU - F15		0.4 MPa				
Glass fiber fabric	0.3 mm		PU - ST3040		1 Mpa				
plain weave nylon fabric	0.2 mm		PU - ST1060		3.1 MPa		700N		
plain weave nylon fabric	0.2 mm		PU - F15		0.4 MPa				
plain weave nylon fabric	0.2 mm		PU - ST3040		1 MPa				
1K plain weave carbon fiber fabric		1.36 MPa	1:10 PDMS			0.45 Mpa		The sample was cured at 70 ° C for 14 h.	(Bartlett, Croll, and Crosby 2012)
Fine Hemp Linen 5.3 oz	0.5 mm		natural rubber latex		1.1 MPa		720N	The latex is allowed to dry for at least 72 hours	(Bartlett and Crosby 2014)
100% Jute	0.5 mm		natural rubber latex		1.1 MPa		420N		
Cotton fabrics	0.5 mm		natural rubber latex		1.1 MPa		810N		

## Appendix J

```
% Author: Tim van Broekhoven
% Created: 13-11-2017

%% NOTE
%
% Use this script per single experiment only, or rename the files to show
the
% experiment you are working on!
% If you use the second option, adjust the length of the names in line 56!
%
%% Load all the data from a to be selected folder
clc, clear all, close all
Folder = uigetdir;
FileList = dir(fullfile(Folder, '*.mat')); % List of all MAT files
allData = struct();
for iFile = 1:numel(FileList) % Loop over found files
    Data = load(fullfile(Folder, FileList(iFile).name));
    Fields = fieldnames(Data);
    for iField = 1:numel(Fields) % Loop over fields of current
file
        aField = Fields{iField};
        if isfield(allData, aField) % Attach new data:
            allData.(aField) = [allData.(aField), Data.(aField)];
        else
            allData.(aField) = Data.(aField);
        end
    end
end
end

% Remove all unnecessary fields

Fields = {'constants', 'settings', 'position_mm', 'state'};
allData.(aField) = rmfield(allData.(aField), Fields);
allData = allData.(aField);
Fields = {'folder', 'date', 'bytes', 'isdir', 'datenum'};
FileList = rmfield(FileList, Fields);
[allData.names] = FileList.name;
%% clean up the signal

ks = 20; % Moving average filter kernel size [-]
for a = 1:length(allData)
    allData(a).sensor_V = maf(allData(a).sensor_V, ks);
end
clear a ks
%% Remove the offset of the signals
for a = 1:length(allData)
    allData(a).sensor_V = (allData(a).sensor_V -
(mean(allData(a).sensor_V(1:201,1))));
end
clear mean a
%% All names in one cell
for a = 1:length(allData)
    Names{1,a} = allData(a).names(1:13);
end
Names = Names'; % transpose
clear a
```

```

%% Convert the signal from Volt to Newtons
for a= 1:length(allData)
    if contains(Names(a,1),"GLS") == 1 % If the tests were performed on
glass
        allData(a).sensor_V = (allData(a).sensor_V*4.3258); % Update these
per experiment and calibration of the sensor!
    else % If tests were performed on gelatin
        allData(a).sensor_V = (allData(a).sensor_V*2.4728); % Update these
per experiment and calibration of the sensor!
    end
end
clear mean a
%% Save the data that has been filtered, offset corrected and converted to
Newtons
SaveFolder = uigetdir;
prompt = 'Name of the file?:'; % Give file name
Filename = input(prompt,'s');
Filename = strcat(Filename, '.mat');
save(fullfile(SaveFolder, Filename), 'allData');

clc, clearvars -except allData Names, close all
%% Extract all maxima
for a= 1:length(allData)
Maxima(1,a) = max(allData(a).sensor_V);
end
Maxima = Maxima'; % transpose
clear a
%% Struct with clusters per condition (Maxima are clustered per condition)
b = 1;
last = char(Names(1,1));
[Cluster(b).(last)] = Maxima(1,1);

for a= 2:length(allData);
    if isequal(Names(a,1),Names(a-1,1))==1;
        b = b+1;
        Cluster(b).(last) = Maxima(a,1);
    else
        last = char(Names(a,1));
        b = 1;
        Cluster(b).(last) = Maxima(a,1);
    end
end
clear a b last
%% Dividing the maxima from the struct in substrate groups
G10 = 1;
G15 = 1;
G20 = 1;
GLS = 1;
Fields = fieldnames(Cluster);

for a= 1:length(Fields)
    if contains(Fields(a,1),"G10") == 1
        BoxplotG10(:,G10) = [Cluster.(char(Fields(a,1)))];
        G10 = G10+1;
    elseif contains(Fields(a,1),"G15") == 1
        BoxplotG15(:,G15) = [Cluster.(char(Fields(a,1)))];
        G15 = G15+1;
    elseif contains(Fields(a,1),"G20") == 1
        BoxplotG20(:,G20) = [Cluster.(char(Fields(a,1)))];
        G20 = G20+1;
    elseif contains(Fields(a,1),"GLS") == 1

```



```

        BoxplotGLS(:,GLS) = [Cluster.(char(Fields(a,1)))];
        GLS = GLS+1;
    end
end

%% Boxplot graph drawing

figure
subplot(1,3,1)
boxplot(BoxplotG10)
grid on
ylim([0,5])
xlim([0.5,6.5])
xtickangle(45)
line([3.5 3.5], [0,5], 'LineStyle','--', 'Color',[0 0 0])
set(gca, 'YTick',0:0.5:5)
set(gca, 'XTickLabel',{'0 Fibers','4 Fibers','6 Fibers','0 Fibers','4
Fibers','6 Fibers'}, 'XTick',1:6,'FontSize', 14)
ylabel('Peak force [N]','FontSize', 22)
title('10 w% gelatin','FontSize', 16)

subplot(1,3,2)
boxplot(BoxplotG15)
grid on
ylim([0,5])
xlim([0.5,6.5])
xtickangle(45)
line([3.5 3.5], [0,5], 'LineStyle','--', 'Color',[0 0 0])
set(gca, 'YTick',0:0.5:5)
set(gca, 'XTickLabel',{'0 Fibers','4 Fibers','6 Fibers','0 Fibers','4
Fibers','6 Fibers'}, 'XTick',1:6,'FontSize', 14)
ylabel('Peak force [N]','FontSize', 26)
title('15 w% gelatin','FontSize', 16)

subplot(1,3,3)
boxplot(BoxplotG20)
grid on
ylim([0,5])
xlim([0.5,6.5])
xtickangle(45)
line([3.5 3.5], [0,5], 'LineStyle','--', 'Color',[0 0 0])
set(gca, 'YTick',0:0.5:5)
set(gca, 'XTickLabel',{'0 Fibers','4 Fibers','6 Fibers','0 Fibers','4
Fibers','6 Fibers'}, 'XTick',1:6,'FontSize', 14)
ylabel('Peak force [N]','FontSize', 26)
title('20 w% gelatin','FontSize', 16)

% figure
% subplot(1,2,1)
% boxplot(BoxplotGLS)
% grid on
% ylim([0,23])
% xlim([0.5,6.5])
% xtickangle(45)
% line([3.5 3.5], [0,23], 'LineStyle','--', 'Color',[0 0 0])
% set(gca, 'YTick',0:1:23)
% set(gca, 'XTickLabel',{'0 Fibers','4 Fibers','6 Fibers','0 Fibers','4
Fibers','6 Fibers'}, 'XTick',1:6,'FontSize', 14)

```

```

% ylabel('Peak force [N]','FontSize', 26)
% title('Glass','FontSize', 16)
%% Grouping of the conditions for the Anova
Group = Names(:,1);
Group = char(Group);
A = Group(:,1:3); %Variable 1 (example: P10 for the pad stiffness)
A = cellstr(A);
B = Group(:,5:6); %Variable 2 (example: F0 for the number of fibers)
B = cellstr(B);
C = Group(:,8:10); %Variable 3 (example: G10 for gelatin substrate)
C = cellstr(C);
clc
clear Group

% NOTE: this will generate a Anova with glass included, change the files
% loaded for this to load only gelatin substrates, also it handles only
% when using the correct amount of variables
%% Anova with a tiedrank included (remove if distributed normally!)
XR=tiedrank(Maxima);
[PR,TR,STATSR,TERMSR]=anovan(XR,{A B C},'model','interaction'); % Remove or
add groups for more or less variables tested!
figure
[c,m,h,nms] = multcompare(STATSR,'dimension',[1 2 3]);

```

# Appendix K

Delf University of Technology  
Faculty Of Mechanical, Maritime And Materials Engineering  
Department Of BioMedical Engineering

Literature Review

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## Analysis of the performance of graspers in minimally invasive surgery

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November 13, 2017

# Abstract

Since the transition from open surgery to minimally invasive surgery, errors made with graspers by using too much or too little force when manipulating tissue have increased. Our study aims to find out which surgical grasping tasks are most critical with regards to surgical errors and which forces need to be successfully controlled to improve current grasper performance. To answer this question a literature review was performed. We found that of the 12.4 errors on average made per procedure, 2.21 (17.8%) were made due to the use of insufficient force and 0.28 (2.3%) due to excessive force. These errors have shown to result mostly in an extended surgery time and less often in harmful consequences for the patients. Results of our review of surgical task analyses show that most of the insufficient and excessive force errors occurred while translocating tissue, followed by the stretching and grasp-and-holding of tissue. We have not found an obvious difference in required pinching force between the basic grasper tasks to explain these increased number of dropped translocations, which suggests that there might be an additional factor resulting in the dropping of tissue. The pinch forces of the graspers required to perform four basic grasper tasks, palpating-, grasp-and-holding -, stretching- and translocating tissue, have been found to be less than 6N. However, the actual pinch force required to prevent slip of the tissue are largely influenced by the grasper design and pulling force on the tissue, often resulting in high forces exerted on the tissue. We found that serious tissue damage occurs when using forces above 7N. We therefore conclude that the use of current instrumentation results in a fine band of 0.5 to 5N in which tissue can be safely manipulated, depending on grasper geometry and pull forces on the tissue. The use of appropriate force has therefore become a delicate task for the surgeons, which we found currently only improves with experience. We conclude that there is room for the design of a new type of instrument-tissue interface, removing the dependency on surgeon experience to learn appropriate tissue interaction forces when performing grasping tasks.

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# 1. Introduction

For over a century surgeons have worked with forceps, scissors and scalpels, refining them to become simplistic instruments which are effective and easy to use (Kirkup 1981). In the last three decades a shift has been made from open surgery techniques to minimally invasive surgery (MIS) techniques (Lau et al. 1997). The main reasons for this change are the reduced trauma, recovery time and hospital stay associated with MIS as compared to open surgery (Cuschieri 1995, Keus et al. 2006, Reza et al. 2006, Sauerland et al. 2004). During this change the instrumentation used for open surgery has been adapted for laparoscopic instrumentation with very little change to the instrument tip (Berguer 1998). The use of MIS techniques has resulted in the loss of tactile feedback received from the instrument tip, limited the view of the working area, reduced the degrees of freedom of the instruments and has contributed to suboptimal ergonomics of the instrumentation (Patkin & Isabel 1995). Friction inside the laparoscopic instruments and between the instrument and the trocars reduce the transmission of the force to the tissue and back to the user, resulting in a loss of feeling of the forces applied by the surgeon to the tissue (Breedveld et al. 1999, Tholey et al. 2005). The surgeons have shown to adapt to the restricted view offered by the endoscope and the indirect contact with the tissue by using visual cues (Bholat et al. 1999). However, the use of the MIS instrumentation still often results in tissue damage (Kimura et al. 1996, Marucci et al. 2000a, van der Voort et al. 2004).

One of the instruments which has become more difficult to use with the introduction of MIS techniques, is the grasping forceps. The surgical graspers have transformed from direct contact instruments to long, slender, rigid instruments with reduced efficiency (Patkin & Isabel 1995). The introduction of MIS has been linked to an increase in forces used with these graspers and consequently has resulted in tissue damage (Wagner et al. 2002, den Boer et al. 2001). Additionally, a prolonged operative time is often mentioned as one of the drawbacks of MIS (Colon Cancer Laparoscopic or Open Resection Study Group 2005, Sjoerdsma et al. 2000, Seshadri et al. 2001). Some studies suggest that part of the reason behind this increase in operative time is related to the increased number of errors made while grasping with MIS grasping instruments compared to open surgery (Eubanks et al. 1998, Catchpole et al. 2007). These errors are for example the dropping of tissue when using too little force or damaging tissue when using too much force, which both require additional actions to be fixed. The errors discussed here are defined as “the failure of planned actions to achieve their desired goal” (Richards, 1995). Moreover, an increased number of surgical errors resulting in prolonged operative time also has been linked an increase in surgeon fatigue and discomfort for the surgeon (Berguer et al. 1997).

In the last decade, a lot of research has been published (Ahmed et al. 2011) using surgical outcome (Cuschieri et al. 1991), time-motion-analysis (Sjoerdsma et al. 2000) and modified Human Reliability analysis (HRA) (Joice et al. 1998) to investigate the surgical performance of MIS. Results have shown that graspers are often the cause of errors (Joice et al. 1998). The human reliability analysis uses direct observation to record and categorize errors which occur during surgical procedures, giving an insight into both surgeon and instrumentation performance. We have used these analyses to extract relevant available error data to verify which errors are most common with MIS grasping instruments.

A closely related research field is focused on the interaction of the MIS graspers with the tissue. This research is mostly aimed to better understand the relevant forces used in surgery to successfully manipulate tissue and to identify when this force results in tissue damage or slippage. This slippage and damage has been shown to occur when the surgeons use too much or too little force (Heijnsdijk et al. 2004a). We have used this research to generate a table of required forces per surgical action and to identify what the limits of the use of these forces are.

Our aim is to link these research fields to explain the occurrence of errors with the current use of forces during surgical procedures. This gives more insight into the performance of current surgical graspers and can help in designing future requirements to perform MIS even more safely and efficiently.

Additionally, we have reviewed task analyses to determine the frequency of performance of four basic grasping actions which form the basis of every grasping action. We used this information to identify in which basic grasping task surgical errors most often occur. Moreover, we have related this data to the forces used during the grasping tasks. We have used these to find indications of the cause of the misuse of force. The final goal of our study is to identify which surgical grasping tasks are most critical with regards to surgical errors and which forces need to be successfully controlled to improve current grasper performance.

## 2. Surgical errors made with MIS graspers

### 2.1. Methods

#### 2.1.1. Definitions

Errors are defined as "the failure of planned actions to achieve their desired goal" (Richards, 1995). Events are defined as "any deviation from usual medical care that causes an injury to the patient or poses a risk of harm" (World Health Organization, 2005). In some of the studies, events are defined as "consequential errors". Graspers are defined as basic teathed laparoscopic retraction/grasping forceps used to palpate, translocate, hold and stretch tissue. The errors related to graspers can be divided in two categories: errors due to insufficient force and errors due to excessive force. Insufficient force is defined as the use of too little force with the grasper to handle the tissue safely and securely. The use of insufficient force results in slippage and often dropping of tissue and other objects during the procedure. Excessive force is defined as the use of too much force with the grasper to handle the tissue safely and securely. The use of excessive amounts of force leads to tissue damage and often results in tearing of tissue.

#### 2.1.2. Information sources

A literature search was conducted in Google Scholar, PubMed and Scopus to retrieve studies assessing grasping errors during every surgical step of laparoscopic and endoscopic surgical procedures. A non-systematic search was performed in the three databases with the keywords "observational clinical human reliability analysis (OCHRA)", "technical surgical error analysis", "surgical skill metrics" "human competency assessment", "surgical task analysis", and combinations of these. Additionally, the reference lists of the retrieved studies were reviewed to identify studies missed from the initial search queries.

#### 2.1.3. Eligibility criteria

Studies assessing the number of errors made with laparoscopic graspers were eligible for inclusion. Studies focusing on non-organic material and (virtual reality) simulations were excluded. Studies assessing errors only in specific parts of the surgical procedures and studies which provided laparoscopic grasper data with combined metrics or which combined multiple error types were also excluded. No language and publication date restrictions were imposed. Only journal articles, conference proceedings and PhD dissertations were included. The abstracts and full texts of the retrieved studies were read to determine if the studies fulfilled the eligibility inclusion criteria set.

#### 2.1.4. Data synthesis and analysis

Nine studies featuring grasper errors in surgical procedures were identified. From each study, the following information was extracted: surgical procedure type, number of assessed procedures,



number of surgeons, experience of the surgeons involved, total number of errors made, occurrence of events per procedure and a clustering of errors with excessive or insufficient force used with graspers.

The total number of errors, total number of events and total number of excessive and insufficient errors presented in our study have been normalized by the number of errors per procedure, resulting from the formula shown in equation 1.

$$\text{Normalized no. of errors} = \frac{\text{Total amount of errors}}{\text{Total amount of procedures assessed}} \quad (1)$$

The averaged total number of errors, averaged total number of events and averaged total number of excessive and insufficient errors presented have been weighted by the sample size of the studies as is shown in equation 2.

$$\overline{\text{Errors}} = \frac{\sum_{i=1}^n \text{Sample size}_i * \text{errors}_i}{\sum_{i=1}^n \text{Sample size}_i} \quad (2)$$

## 2.2. Results

### 2.2.1. Grasper errors

Table 1 shows for each of the included studies, the surgical procedure type, the number of assessed procedures, the number of surgeons, the experience of the surgeon, the total errors and events made per procedure and a clustering of errors in insufficient or excessive force used with the grasper. Except Tang et al. (2005), all included studies report surgical performance on living animals. Tang et al. (2005) performed their study on a restructured pig tissue model.

A total of 409 separate, on error analyzed surgical procedures have been included in this review. These included 347 laparoscopic cholecystectomies, 50 laparoscopic pyloromyotomies and 12 endoscopic dacrocystorhinostomies.

### 2.2.2. Total number of errors

The weighted average number of errors made per procedure was 12.4 errors with a minimum average of 6.2 [n=50] errors reported for laparoscopic pyloromyotomies performed by experts and a maximum average of 28.4 [n=20] errors reported for inexperienced residents performing a laparoscopic cholecystectomy. A weighted average of 3.51 errors resulted in a so-called event. In other words, 28.2% of the total amount of errors per procedure resulted in an injury or some form of tissue damage.

### 2.2.3. Insufficient force errors

On average, errors due to using insufficient force occurred 2.21 times per procedure with a minimum average of 0.42 [n=50] times and a maximum average of 3.58 [n=12] times per procedure. Insufficient force errors account for 17.8% of the mean amount of total errors made during surgical procedures.

### 2.2.4. Excessive force errors

Excessive force errors occurred on average 0.28 times per procedure, with a minimum of 0.08 [n=50] times and a maximum of 0.65 [n=20] times per procedure. Excessive force errors account for 2.3% of the mean amount of errors made during surgical procedures.

A visualization of the specific grasper error data is given in Figure 1 as a function of the experience level of the participants (residents vs. experts).

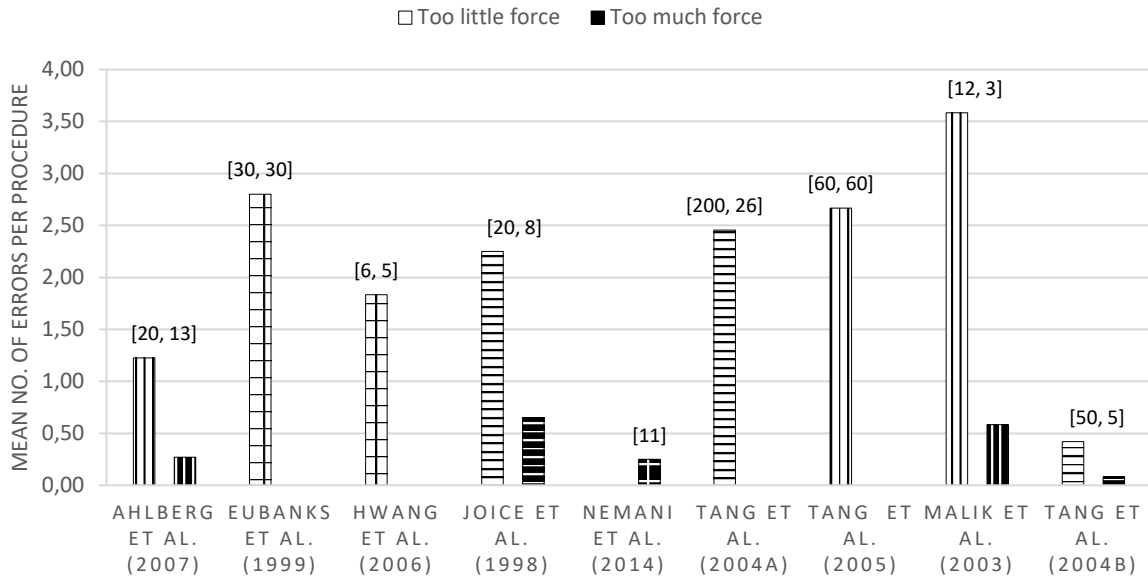


Figure 1 - Summary of grasping errors found per study. Horizontal stripe pattern shows expert surgeons, vertical stripe pattern shows resident surgeons, block pattern shows the combination of expert and resident surgeons, additionally the numbers on top of each bar depict respectively the number of procedures and the number of surgeons performing the procedures. All studies except the studies performed by Malik et al. (2003) and Tang et al. (2004b) examine the errors in laparoscopic cholecystectomies. Malik et al. (2003) and Tang et al. (2004b) examine respectively dacryocystorhinostomy and pyloromyotomy

## 2.2.5. Errors in laparoscopic cholecystectomy

An average of 13.50 errors were made in the 347 laparoscopic cholecystectomies analyzed for errors. Of these errors, an average of 3.76 errors resulted in some form of injury and were classified as an event by the reviewer. Moreover, an average of 2.42 errors per procedure were attributed to the use of insufficient grasping force. Conversely, 0.41 errors per procedure were attributed to applying excessive force on the tissue. The use of insufficient and excessive force was responsible for 18% and 3.1% of the average total number of errors made during cholecystectomy procedures, respectively.

## 2.2.6. Errors in endoscopic dacryocystorhinostomy

In Malik et al. (2003), 13 endoscopic dacryocystorhinostomies were analyzed. All procedures were performed by residents. An average of 10.83 errors were identified per procedure, of which 5.75 qualified as an event. Of these errors an average of 4.75 were caused by using excessive force to manipulate the tissue.

Table 1 - Mean grasper errors per procedure in laparoscopic surgery<sup>1</sup>.

Surgical procedure type	No. of procedures	No. of surgeons	Surgeon level	Total Errors	Total Events	Insufficient force errors	Excessive force errors	Ref
Laparoscopic cholecystectomy	20	13	Residents	28.4		1.23	0.27	Ahlberg et al. (2007)
Laparoscopic cholecystectomy	30	30	Residents (28), experts (2)			2.8		Eubanks et al. (1999)
Laparoscopic cholecystectomy	6	5	Residents (3), experts (2)	11		1.83		Hwang et al. (2006)
Laparoscopic cholecystectomy	20	8	Experts	9.45	1.95	2.2	0.65	Joice et al. (1998)
Laparoscopic cholecystectomy	11		Residents, experts				0.25	Nemani et al. (2014)
Laparoscopic cholecystectomy	200	26	Experts	11.21	3.42	2.46		Tang et al. (2004a)
Laparoscopic cholecystectomy	60	60	Residents	17.78	5.52	2.67		Tang et al. (2005)
Endoscopic dacryocystorhinostomy	12	3	Residents	10.83	5.75	3.58	0.58	Malik et al. (2003)
Laparoscopic pyloromyotomy	50	5	Experts	6.2	1.54	0.42	0.08	Tang et al. (2004b)

<sup>1</sup> The data presented by Ahlberg et al. (2007) and Nemani et al. (2014) have been extracted from one or multiple graphics and might slightly differ from the original data. All other data has been extracted from tables or text presented in the studies. Additionally, for Ahlberg et al. (2007) only the results of the VR-trained group have been used, because the results compare better to the other data.

### 2.2.7. Errors in laparoscopic pyloromyotomy

In Tang et al. (2004b), 50 laparoscopic pyloromyotomies were analyzed. All the procedures were performed by experts. An average of 6.2 errors were identified per procedure of which 1.54 qualified as an event. Of these errors an average of 0.42 were caused by using insufficient force to manipulate the tissue and 0.08 of the errors per procedure were caused by using excessive force.

## 2.3. Discussion

Nine studies on grasper errors in laparoscopic and endoscopic surgery were identified. The most common error we found with the laparoscopic graspers was the slipping of tissue due to the use of insufficient force when grasping objects or tissue. Insufficient force was used on average 2.2 times per procedure. The use of excessive force on the tissue was the cause of the other identified errors. Excessive force was used on average 0.3 times per procedure.

Some excluded studies support our results regarding the number of errors made with grasping type instruments. For example, studies performed by Bonrath et al. (2013), Husslein et al. (2015) and Miskovic et al. (2012) focused on errors made in respectively laparoscopic Roux-en-Y gastric bypass surgery, laparoscopic hysterectomy and laparoscopic colorectal resection. The results of these studies were not included in the review because they did not meet the criteria we formulated for our review. However, their results show similar trends of alarmingly high number of errors made due to the use of insufficient or excessive force. Bonrath et al. (2013) reported that 34% of errors observed resulted from the use of too little force or distance (not reaching the targeted tissue) with graspers and dissectors and 4% due to too much force or distance used (overshooting the targeted tissue). Results from the study by Husslein et al. (2015) showed that 35% of errors found could be attributed to the use of graspers and dissectors. Miskovic et al. (2012) showed that 17% of errors recorded were caused by too much force applied on the tissue. These results show that the use of grasping instrument for dissection and retraction also account for many errors in other procedures and might require redesign. However, it is not possible to draw any concrete conclusions from these three studies because the data is not clear on how exactly these errors are generated. Additionally, higher forces and more healthy tissue damage can be expected with the addition of dissecting instruments to the grasping instrument cluster, because they are designed and used to cut and tear tissue. We conclude that current laparoscopic graspers are responsible for a substantial amount of inappropriate force errors during laparoscopic surgery.

### 2.3.1. Consequential errors

Of the errors identified in the studies, only a few were labeled as consequential errors. Tang et al. (2004b, 2005) show that 5.7% and 14.2% of the errors observed with the use of graspers had consequence and were classified as an event, respectively. These results are in line with our expectation that little consequential errors are generated with laparoscopic graspers, since complications are rarely reported. For example, a meta-analysis performed by van der Voort et al. (2004) on bowel injury as a complication of laparoscopic surgery shows that in the 237 recorded bowel injuries, the grasping forceps only has been marked as the responsible instrument in three instances. This means that grasping forceps were found to be the cause of only 1.1% of all bowel injuries recorded.

We observed that the errors caused by inappropriate use of force results more in an increase of operative time rather than in complications for the patient. Eubanks et al. (1999) have shown that the operative time increases as the incidence of errors increases, which, according to these authors, suggest that technical skill improvement will decrease operative time due to a reduction of errors. We can therefore conclude that the errors made with graspers mostly result in a longer operative time rather than in serious consequences.

Conversely, our results seem to contradict a claim made by twenty experienced surgeons in the study published by den Boer et al. (2002) that grasping instruments are one of the most dangerous instruments used in laparoscopic surgery. Results from a questionnaire provided by Den Boer et al. (2002) show that the grasping forceps are thought to be the cause of complications in 53% of cases and are labeled with a high risk of causing gastrointestinal and solid organ injuries. However, den Boer does warn that the results of her questionnaire should be interpreted with care due to the subjectiveness of the claims. We therefore conclude that the objectively received data on grasper does not stroke completely with the experience of the users on the dangers encountered while using laparoscopic graspers and might have changed in the last 15 years due to procedural or instrumental changes.

### 2.3.2. Expert versus residents

Expert surgeons seem to have learned to utilize suboptimal instrumentation to safely perform complex procedures. This is supported by the fact that expert surgeons seem to have a much better notion of how much force will result in trauma. As a result, very little high forces are generated on the tissue with the atraumatic techniques currently used by the expert surgeons. However, to not exceed the threshold of safe tissue handling, we see that often too little force is exerted on the tissue, resulting in slippage. A trend described by Zhou et al. (2008) shows that experts use more force and make shorter contact with the tissue compared to residents when performing a probing task, suggesting that expert surgeons have a better feeling for the required force to manipulate tissue without performing errors. Additionally, Hannaford et al. (1999), Rosen et al. (2001), Richards et al. (2000) and Trejos et al. (2014) show that experts use lower forces/torques and have an overall shorter operation time when performing cholecystectomies and nissen funduplications, suggesting that the surgeons have a learning curve for acquiring skill in safely manipulating tissue and getting used to reduced force feedback with suboptimal instrumentation.

We therefore conclude that there is an important learning curve for surgeons to get used to reduced force-feedback and suboptimal instrumentation.

### 2.3.3. Quality of the data

The quality of the data used in this review has been limited by three factors. Firstly, the data from the studies included in the review have been performed by surgeons with different levels of experience. Some of these studies do not make a distinction in the results between the number of errors made based on the experience level of the surgeon performing the procedure.

Secondly, the categorization of the errors made the extraction of data difficult. Most studies used a modified version of the External Error Modes (EEMs) founded by Embrey (1986) to categorize the errors made. However, this technique clusters errors with different metrics. The error mode "Step is done with too much (speed, force, distance, time, rotation, depth)" and "Step is done with too little (speed, force, distance, time, rotation, depth)" feature five different metrics, making it hard to distinguish which kind of error was exactly identified. This resulted in the loss of a lot of data because it is impossible to distinguish if the error was caused by the instrument being inserted too far or using a too high force on the tissue. Additionally, some of the studies did not specify which instrument was responsible for the tissue damage that was identified. Due to this constraint, some consequential errors might not have been attributed to the use of graspers where they might have actually been responsible.

Lastly, a lack of standardization of errors influenced the quality of the data retrieved for this review. The results of the literature review show that on average 12.42 errors are made in every laparoscopic surgery. However, the total amount of errors differed greatly per paper due to the definitions of the errors. Some papers include an extended list of error definitions, while others only included the external error modes used in the study. For example, some of the studies used lack of progress and a takeover by the supervisor as an error type, while others focus only on procedural errors like steps not performed during the procedure. This lack of standardization results in a more generalized conclusion instead of a solid comparison of results.

## 3. Task analysis of grasping actions in MIS

### 3.1. Methods

#### 3.1.1. Definitions

A task analysis is defined as “any process that identifies and examines the tasks that must be performed by users when they interact with systems.” (Kirwan et al., 1992) Hierarchical decomposition of surgical procedures is a task analysis technique and is defined as a “decomposition hierarchy of surgical procedures, with increasing levels of detail, from surgical steps, sub-steps, tasks, sub-tasks, down to the level of motions” (Nagy et al., 1999).

#### 3.1.2. Information sources

A literature search was conducted in Google Scholar, PubMed and Scopus to retrieve studies focusing on task analysis of laparoscopic procedures. A non-systematic search was performed in the three databases with the keywords “Hierarchical task decomposition”, “Laparoscopic task analysis”, “Laparoscopic operative steps”, “task and motion analysis in MIS”, and combinations of these with specific surgical procedures. Additionally, the reference lists of the retrieved studies were reviewed to identify studies missed from the search query.

#### 3.1.3. Eligibility criteria

Studies presenting a complete task analysis of procedural steps in minimally invasive procedures were included in the search. Studies presenting part of a task analysis were also included. Books featuring surgical procedure steps were also included. Studies focusing on task analysis of robotic surgery were excluded. No language and publication date restrictions were imposed. Only journal articles, conference proceeding, PhD dissertations and books were included. The abstracts and full texts of the results were read to determine if the retrieved studies fulfilled the inclusion criteria set.

### 3.1.4. Data synthesis and analysis

28 texts featuring task analysis of a surgical procedure were identified. From each study, the surgical procedure and recorded grasper actions were extracted. The resulting grasper actions were clustered into four basic grasper tasks. These four basic grasper tasks are the psychomotor grasping skills used in the virtual reality training of surgeons first introduced by Wilson et al. (1997). The basic psychomotor skills used are touching, grasping, stretching and translocation as presented by Schijven et al. (2004). Touching is defined as the palpation of tissue, which is for example used to identify the tissue structures (Munz et al. 2004). Grasping is defined as the grasping of tissue and holding it in place, for example for holding tissue out of surgical site during the procedure (Aggarwal et al. 2004; Hamilton et al. 2002). Stretching is defined as the grasping and stretching of tissue without tearing, for example in order to dissect or wrap tissue (Aggarwal et al. 2004; Munz et al. 2004). Translocation of tissue is defined as moving tissue from one location to the other, for example in the extraction of tissue from the surgical site (Sherman, 2005).

## 3.2. Results

28 task analysis of a combination of nine laparoscopic and endoscopic procedures have been retrieved and assessed. The task analysis concerned the following types of minimally invasive procedures: cholecystectomy, pyloromyotomy, Roux-en-Y gastric bypass procedure, appendectomy, nissen fundoplication, salpingectomy, dacrocystorhinostomy, colorectal resection and jejunostomy.

### 3.2.1. Operative step clustering

The table in appendix A gives an overview of the operative steps performed clustered into four basic grasper tasks; touching, grasping, stretching and translocation. In the 9 assessed surgical procedures, a total of 62 grasper actions/movements were identified, of which 7 were classified as palpitation actions, 11 as grasp and hold actions, 31 as stretching actions and 13 as translocation actions.

### 3.2.2. Error clustering

For every error assessment study, the identified errors were analyzed and classified into one of the basic grasper tasks. For example, the removal of the gallbladder from the operation site was classified a translocation action. Table 1 provides an overview of the basic grasper tasks plotted against the four basic psychomotor tasks. Crosses depict errors identified due to insufficient force exerted on tissue, circles depict errors identified due to the use of excessive force used on the tissue and the combination of marks and circles depict the identification of errors related to both the use of insufficient and excessive force on the tissue.

Nemani et al. (2014) did not specify in which task the errors were encountered and their study is therefore not represented in Table 1.

Insufficient force errors were most often observed in the translocation of tissue (2.58 times per procedure), followed by grasping and holding of tissue (1.17 times per procedure); the remained of such errors were identified in the stretching of the tissue (1.54 times per procedure). Excessive force errors were observed most often in translocation (0.4 times per procedure), followed by the stretching of tissue (0.3 times per procedure); the remained of such errors were identified in the grasp-and-hold tasks (0.01 times per procedure).

Table 2 - Errors found in error studies plotted against the four basic grasper tasks.

The + represents errors caused by using too little force, o represents errors caused by using too little force, represents error caused by both too little and too much force present.

	Ahlberg et al. (2007)	Eubanks et al. (1999)	Hwang et al. (2006)	Joice et al. (1998)	Malik et al. (2003)	Nemani et al. (2014)	Tang et al. (2004a)	Tang et al. (2004b)	Tang et al. (2005)
<b>Touching (palpation)</b>									
<b>Grasp and hold</b>							x	⊗	x
<b>Stretching</b>	o			⊗					x
<b>Translocation</b>	x	x	x	⊗	x				



### 3.3. Discussion

The errors identified in the error analysis show that most errors are made with an inappropriate use of force. To get a better view of the general actions performed with the laparoscopic graspers we reviewed task analyses of different procedures. Our review of these hierarchical task analysis studies has resulted in a clustering of grasper manipulations into four basic tasks: touching, grasping, stretching and translocation. Additionally, we used the results of the error analysis to identify the most error prone psychometric tasks in laparoscopic and endoscopic procedures.

#### 3.3.1. Psychomotor actions

We found that the stretching of tissue is the most performed psychomotor task, followed by translocation of tissue from the surgery site. Grasping and holding of tissue is the next most performed action, whereas palpation of tissue is the least often recorded action. Data gathered by Sjoerdsma et al. (2000) about time-motion analysis of actions performed in laparoscopic cholecystectomy corresponds with our findings of the number of basic psychometric actions during cholecystectomies. Sjoerdsma et al. observed that in five observed laparoscopic procedures an average of 278 actions were performed of which 74 actions were aimed at stretching tissue, 6 at palpating tissue and 33 at retracting tissue. Their study did not specify the grasp-and-hold action we have identified, but they have incorporated these actions in the stretching of the tissue. We can conclude that the stretching of the tissue is the most common basic task, performed in every reviewed procedure. A classification of the laparoscopic cholecystectomy procedure performed by Kurita et al. (2013) also seems to support our results. Kurita et al. (2013) found that during the cholecystectomy, grasping of tissue is responsible for 8% of the grasper actions, displacement of the tissue is performed in 18% of the actions, and 65% of the grasper movements are focused on the stretching of the tissue. The high percentage of stretching movements is in line with our expectation since this basic task is used in combination with dissecting, handling of surrounding tissue and other manipulations. The palpation of tissue was recorded less than we expected, but this might not have been recorded in every study as a specific step and might therefore be performed more often than our study shows.

#### 3.3.2. Error identification

Our results from the error clustering shows that most errors identified in the reviewed studies are made during the basic motor task of translocation of the tissue. We reckon that this occurs because this basic psychomotor task consists of safely grasping relatively large masses with inefficient graspers. The amount of recorded stretching failures is reported less often than expected. We feel that one possible explanation might be the difficulty for reviewers to identify the intentions of the surgeon with a specific grasping motion. This is more clearly defined for the retraction and dropping of a tissue than for the stretching of tissue in a specific direction. Another possible explanation is the difficulty of the surgeons to keep the tissue in view during the extraction.

#### 3.3.3. Quality of the data

The hierarchical task analysis studies we reviewed had varying quality and extensiveness. Moreover, some studies went into great depth on the tasks performed during the procedure with identification of instruments used, while others were less extensive. Therefore, we have tried to use as much literature as available to generate an as complete as possible list of grasping actions encountered in the procedures.

Additionally, some surgical steps consist of multiple basic psychomotor tasks in one operative step. These operative steps have been added to all relevant basic psychomotor clusters in order to guarantee a complete overview.

## 4. Forces used during grasping tasks in MIS

### 4.1. Methods

#### 4.1.1. Definitions

The pinch forces are defined by Visser et al. (2002) as forces “required to provide enough friction or enclosure of the tissue (...) to transmit manipulation from the instrument to the tissue.” Tissue slip is defined by Heijnsdijk et al. (2002) as “(...) tissue slips out of the grasper because too little clamping force is applied in relation to the pulling force.” Slip force is defined by Heijnsdijk et al. (2004a) as “the pinch force minimally required to prevent slip while pulling”. Damage from grasping is defined by Heijnsdijk et al. (2002) as “tissue is damaged by pulling or pinching with too much force.” Damage force is defined by Heijnsdijk et al. (2004a) as “the maximal pinch force that can be exerted without damage while pulling”.

#### 4.1.2. Information sources

A literature search was conducted in Google Scholar, PubMed and Scopus to retrieve studies assessing instrument-tissue interaction during laparoscopic procedures. A non-systematic search was performed with key words “laparoscopic tool-tip force measurement”, “minimally invasive force-torque signatures”, “pinching forces used in laparoscopic surgery”, “mechanical forces in MIS”, “perforation forces in tissue grasping”, and combination of these. Additionally, the reference lists of the retrieved studies were reviewed to identify studies missed from the search query.

#### 4.1.3. Eligibility criteria

Studies measuring forces resulting from instrument-tissue interaction with in-vivo, ex-vivo tissue and artificial tissue were included. Additionally, studies focusing on slip forces, damage forces and tissue manipulation time were included. Studies focusing on instrument forces during dissection tasks were excluded. Studies measuring forces exerted on the instrument handle only were also excluded. Studies only presenting pull forces without required pinch forces and vice versa were also excluded. No language and publication date restrictions were imposed. Only journal articles, conference proceedings and PhD dissertations were included. The abstracts and full texts of the results were read to determine if the retrieved studies fulfilled the inclusion criteria set.

#### 4.1.4. Data synthesis and analysis

21 studies featuring instrument tip forces were identified. From each study, the following information was extracted: Performed task, surgeon level, mean pinch forces, maximum pinch forces, tissue type, duration of grasping, pull force, slip force and damage force. The results were clustered in the four basic grasping tasks: touching, grasping, stretching and translocation.

### 4.2. Results

21 studies regarding pinch forces were retrieved and divided into in-vivo porcine models and artificial tissue models.

#### 4.2.1. Pinching forces on in-vivo porcine models

Table 3 shows an overview of measured pinch forces from the instrument tip on the tissue in different studies for different surgical tasks and tissue types. All results have been measured in-vivo in different porcine models. The average pinch force required for a basic translocation task varied between 0.3N and 1.6N with a maximum force measured of 3.6N. The average pinch force required for a basic tissue stretching task varied between 0.9N and 3N with a maximum force measured of 4.3N.

Table 3 - Pinch forces measured in the manipulation of different types of tissues. <sup>2</sup>

Basic task	Tissue type	Mean pinch force	Max pinch force	Reference
Translocation	Colon	1.4	3.6	Barrie et al. (2016; 2017)
	Gallbladder	1.6	3.2	Barrie et al. (2016; 2017)
	Small bowel	0.6	1.6	Barrie et al. (2016; 2017)
	Bladder	1.2	1.5	Barrie et al. (2016; 2017)
	Rectum	1.3	3.1	Barrie et al. (2016; 2017)
	Stomach	0.58 ( $\pm 0.79$ )		Susmitha et al. (2015)
	Gallbladder	0.29 ( $\pm 0.56$ )		Susmitha et al. (2015)
	Liver	0.39 ( $\pm 0.53$ )		Susmitha et al. (2015)
	Small intestine	0.26 ( $\pm 0.30$ )		Susmitha et al. (2015)
	Spleen	0.35 ( $\pm 0.43$ )		Susmitha et al. (2015)
	Large intestine	0.37 ( $\pm 0.57$ )		Susmitha et al. (2015)
Stretching	Small bowel	0.9 ( $\pm 0.3$ )	2.4	Barrie et al. (2016; 2017)
	Bowel	3 ( $\pm 0.4$ )	4.3	Heijnsdijk et al. (2004b)

#### 4.2.2. Pinching forces on artificial tissue

Table 4 shows an overview of measured pinch forces on artificial tissues in different studies for different surgical tasks, as a function of the surgeon's skill level and the tissue material.

The average pinch force required for a basic translocation task varied between 1.8 and 3.6N.

The maximum pinch force required for basic grasp and hold tasks was 5.6N. The average pinch force required for basic stretching task varied between 1.6 and 5.4N. The average pinch force required for basic translocation tasks varied between 0.7N and 1.6N.

#### 4.2.3. Damage forces

Heijnsdijk et al. (2003) studied the pinching forces resulting in the perforation of bowel tissue. These authors concluded that a pinching force of 13.5N ( $\pm 3.7$ ), 11.0N ( $\pm 2.5$ ) and 10.3N ( $\pm 2.9$ ) resulted in perforation for respectively 14 porcine large bowels, 14 porcine small bowels and 7 human small bowels. Li et al. (2015) examined compression stress and strain response of porcine liver with different pinching forces and dragging speed. Almost no damage was observed with pinch forces up to 3N, obvious hyperemia appeared with pinch forces of 5 N, different levels of hemorrhage and hematoma started to appear between 7N and 11N, and the liver tissue was crushed when the pinch forces reached levels between 13N and 15N.

<sup>2</sup> The mean pinch forces from Barrie et al. (2016, 2017) have been retrieved from graphics presented in their paper. The median has been used because the mean was not presented.

Table 4 - Pinch forces measured in manipulating artificial tissues.<sup>3</sup>

Basic task	Surgeon level	Tissue material	Mean pinch force (N)	Max pinch force (N)	Reference
Palpitation	Novices	Silicone gel (15kPa, 7.5 kPa, 3,75 kPa)	1,77		Zhou et al. (2008)
	Residents	Silicone gel (15kPa, 7.5 kPa, 3,75 kPa)	3,6		Zhou et al. (2008)
Grasp and hold		Sponge with stiffness 10,5 kPa		2,5	Dalvand et al. (2013)
		Sponge with stiffness 17,7 kPa		3,8	Dalvand et al. (2013)
		Sponge with stiffness 26 kPa		5,6	Dalvand et al. (2013)
		PDMS		0,32	Sumer et al. (2017)
		Silicone rubber		0,5	Sumer et al. (2017)
		Chicken liver		0,6	Sumer et al. (2017)
		Chicken meat		0,5	Sumer et al. (2017)
Stretching	Novices	PVC	1,6		Gupta et al. (1996; 1997)
	Novices	Object with stiffness of 160N/m	5,4		Westebring-van der Putten et al. (2009)
	Novices	Object with stiffness of 160N/m	4,1		Westebring-van der Putten et al. (2009)
	Novices		3,8		Westebring-van der Putten et al. (2010)
Translocation	Novices	Ball of cotton	0,7		Gupta et al. (1996; 1997)
	Novices	Hard object	1,6		Gupta et al. (1996; 1997)

<sup>3</sup> The results from Gupta et al. (1996, 1997) have been retrieved from graphics presented in their paper and converted to Newtons. Their data might therefore differ from actual results.

#### 4.2.4. Slip forces

Heijnsdijk et al. (2004a) and Marucci et al. (2000b) have shown that the slip forces are largely dependent on the jaw design of the instrument used. Results by Heijnsdijk et al. (2004a) show that the slip forces of different grasper designs vary between 3N up to 22N while pulling on the cecum of pigs with 5N pulling force.

#### 4.2.5. Pull forces

The pull forces exerted on the tissue during laparoscopic surgeries have been studied by Visser et al. (2002), Picod et al. (2013), Hannaford et al. (1999) and Toledo et al. (1999). Visser et al. (2002) measured the pull forces exerted on the mesocolon, sigmoid and mesentery of 2.4N ( $\pm 1.1$ ) [n=144], 1.9N ( $\pm 0.6$ ) [n=48] and 0.6N ( $\pm 0.2$ ), respectively. Toledo et al. (1999) did not report which organs were grasped specifically but reported pull forces of 9.3N. Picod et al. (2013) measured the translational forces of manipulating the pelvic wall, abdominal wall, ovaries, gastrointestinal tract, reproductive organs and bladder wall, which resulted in pull forces between 0.1N and 10N. Hannaford et al. (1999) showed the same order of magnitude of pull forces measured during the grasping and pulling state of cholecystectomy and nissen fundoplication procedures.

#### 4.2.6. Duration of grasping

Barrie et al. (2016), Brown et al. (2004) and Heijnsdijk et al. (2002) have studied the tissue interaction and the average grasping time on the tissue during a running of the bowel task. Barrie et al. (2016) and Brown et al. (2004) reported that the manipulation time of the tissue in running the bowel are on average 3.9 seconds ( $\pm 1.5$ ) [n=25] and 2.29 seconds ( $\pm 1.65$ ) [n=150], respectively. Brown et al. (2016) also shows that 95% of all grasps during the running of the bowel were held for 8.86 seconds ( $\pm 1.5$ ) [n=150] or less. Heijnsdijk et al. (2002) showed that during 10 colectomies 28% of the clamping periods were less than 1 second and 89% of clamping periods were less than 60 seconds.

### 4.3. Discussion

To get a better understanding of the error mechanisms behind the dropping and tearing of tissue due to the use of inappropriate force we performed a review analyzing the relevant forces used in laparoscopic grasping tasks. We found that pinch and pull forces are most important when grasping tissue, which result in either slip or damage when used inappropriately.

#### 4.3.1. Pinch forces

Our results show that the pinching forces required to manipulate tissue in the four basic grasper tasks are all below 6N of force. The mean average pinch force used in surgeries to translocate (artificial) tissue atraumatically without slipping was between 0.3N and 1.6N. The stretching of (artificial) tissue required on average between 0.9N and 5.4N of pinch force to prevent slipping. Palpitation of artificial tissue required a pinch force of 1.8N up to 3.6N. Grasp and hold tasks required a maximum pinch force of 5.6N. We conclude that there is a higher pinch force required to effectively stretch tissue than there is needed to translocate tissue. This is remarkable, since most errors, 2.58 errors per procedure, are made with the use of insufficient force during the translocation of tissue. Conversely, only 1.17 errors per procedure are recorded for the stretching of tissue. This suggest that there are other difficulties with the grasper design resulting in dropping of objects.

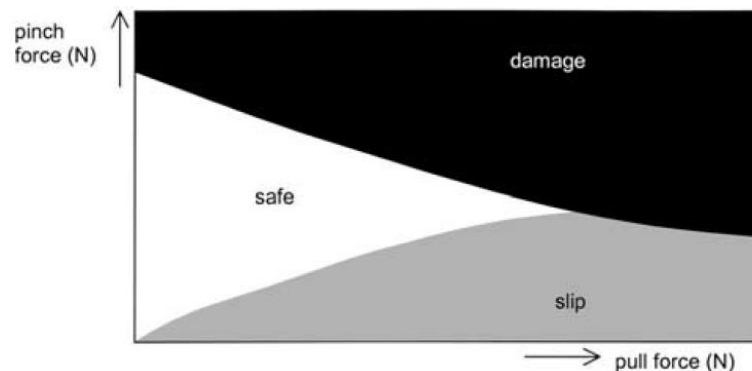
### 4.3.2. Slipping and damage forces

We have found that the slipping of the tissue is dependent on the pull force exerted on the tissue while lifting. Heijnsdijk et al. (2004a) have visualized the dependency of pull forces and pinch forces to generate safe lifting in Figure 2. Marruci et al. (2000) conclude that slip forces are largely dependent on the grasper tip design and the pull forces applied to the tissue. We found that pull forces vary between 0.1N up to 10N to manipulate different types of tissue. Heijnsdijk et al. (2004c) have shown that imprints and bowel perforation increased substantially by increasing pinch force as well when pull force is increased. Unfortunately, we did not find any studies examining the pinch and pull force relation in detail. Heijnsdijk et al. (2004a) did find that up to 22N is needed to keep the tissue from slipping from the grasper. These pinching forces are higher than the pinching forces which result in tissue perforation at around 10N for human bowels. Increasing the contact area of the grasper resulted in the increase from 15N to 37N pinch force before tissue damage occurred. Additionally, modifying the grasper design can result in a reduction of pinch force needed to prevent slip of tissue from 22 to 3 N. Also, the angle of the instrument during grasping has an important impact on tissue damage. Cartmill et al. (1999) concluded that peak pressures increased from 216 kPa to 643 kPa for different grasper designs when the angle of the instrument was increased from 0° to 135°. These pressures are a lot higher than the proposed stress thresholds by De et al. (2008) of 50-80kPa for necrosis in the liver and 150-180kPa for apoptosis in the bowel. This means that if the tissue is clamped with these high forces, damage is inevitable. Additionally, Marucci et al (2000b) found that toothed graspers had significantly higher chances of tearing the tissue grasped. We have concluded that grasper design is extremely important in reducing the use of excessive and insufficient force and should be optimized to reduce the peak pressures exerted on the tissue.

### 4.3.3. Appropriate force

The results we have found show that there is a fine line of about 0.5 to 5N between the use of insufficient, appropriate and excessive force, depending on the design of the grasper and the pulling force. These findings correspond with the amount of inappropriate force errors identified with the use of laparoscopic graspers. Studies performed by Sjoerdsma et al. (1997) and Den Boer et al. (1999) show that there is a low force transmission in current instruments, resulting in much higher forces exerted on the handles than actually actuated on the tissue. Additionally, the friction between the instrument and the trocars used further reduce the feel of the surgeons on forces exerted on the tissue. Multiple studies observed that the surgeons do get more proficient in using appropriate force over time, but our results show that it still often occurs that experienced surgeon use insufficient or excessive force.

Figure 2 - Dependency of safe lifting on pull and pinch forces. Adapted from Heijnsdijk et al (2004).



#### 4.3.4. Quality of the data

There is a very limited quantity of research available on the dependencies of slip, damage and safe working forces for laparoscopic graspers. One of the biggest reasons is the fact that these parameters depend on the design of the grasper used during testing. Due to the geometric differences and study designs making a fair comparison is challenging. We have therefore only presented a broader range of working forces per basic grasper task.

## 5. Conclusion

The goal of this review was to analyze the performance of current grasping instruments in laparoscopic surgery. There are multiple studies published using different techniques for objectively analyzing the technical skills of surgeons in the operation room. We want to add to the current available research by linking objectively observed errors, procedural task analysis and a fine-grained analysis of the observed errors to analyze the performance and limitations of specific instruments. In this study we have generated an in-depth overview of laparoscopic grasper errors in common surgical tasks in order to identify potential weaknesses.

The results from our review shows that experienced surgeons are aware of the limitations of MIS and try to use less force when manipulating tissue, often resulting in slippage of tissue. The exact forces used during these manipulations of tissue and slip parameters have shown to be hard to define. Additionally, there does not seem to be an obvious difference in required pinching force between the basic grasper tasks to explain the increased number of dropped translocations. Joice et al. (1998) suggest that the dropping of the gallbladder in their study occurred because “friction applied by the current designs of graspers jaws does not achieve an effective atraumatic grip over the range of different gallbladder wall thickness and consistency found in clinical practice.” Additionally, Tang et al. (2004b) conclude that “The security of the hold of the duodenum by the grasper depends on the force applied and the shape of the jaws. (...) this force appears to be poorly appreciated by the surgeon during use of the instrument.” Our results show that there is an overall lack of oversight of the force required for manipulation of the tissue with current instrumentation in all assessed procedures. Tang et al. (2005) conclude that “One of the essential features of skills training is for trainees to gain the delicate feel of the tissues during manipulation (...)” There seems to be a fine line of about 5N between using excessive or insufficient pinching force when manipulating tissue with current graspers, which currently only can be learned by performing lots of procedures and thus generating a lot of errors.

We conclude that there is room for the design of a new type of instrument-tissue interface, removing the dependency on surgeon experience to learn appropriate tissue interaction forces when performing grasping tasks. Moreover, additional research is required to see if specific grasper designs can lead to better grasping abilities, and thus reducing slippage of tissue due to insufficient force, without the added risk of damage to tissue caused by the use of excessive force. The results of this review can be used to form requirements for future laparoscopic grasper design.

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# Appendix A

Table 5 – 1. Bax et al. 2008, 2. Den boer et al. 2002, 3. Bonrath et al. 2013, 4. Cao 1996, 5. Chassin 2013, 6. Cristancho 2008, 7. Eubanks et al. 1999, 8. Götz et al. 1990, 9. Larsen et al. 2008, 10. MacKenzie et al. 2001, 11. Madani et al. 2015, 12. Malik et al. 2003, 13. McBeth et al. 2002, 14. Milsom et al. 2006, 15. Mishra et al. 2008 16. Miskovic et al. 2012, 17. Nguyen et al. 2012, 18. Ni et al. 2016, 19. Peyre et al. 2009, 20. Richards et al. 2000, 21. Sarker et al. 2006, 22. Schauer et al. 2003, 23. Schmink et al. 2012, 24. Talebpour et al. 2009, 25. White et al, 26. Wilson et al. 1997, 27. Wittgrove et al. 1994, 28 Zevin et al. 2013.

Cluster	Procedure	Task	Reference
<i>Touching (palpation)</i>	Cholecystectomy	Palpate tissue to obtain tissue characteristics	2, 11
	Appendectomy	Determine anatomy of mesoappendix and appendiceal base	17
	Nissen fundoplication	Palpate peritoneum	10
		Palpate crura	10
		Palpate short gastrics	10
	Colorectal resection	Inspect tissue for advanced disease	26
	Jejunostomy	Run the bowel	17
<i>Grasp and hold</i>	Pyloromyotomy	Grasp and stabilize the duodenum (pylorus)	1
	Roux-en-Y gastric bypass	Grasp transverse mesocolon	28
		Clamp Roux limb	28
		Appendectomy	Hold appendix for dissection
	Nissen fundoplication	Hold peritoneum for dissection	5
		Hold Crura for dissection	5
		Measure oesophagus wrap	10, 19
	Salpingectomy	Grasp fallopian tube	9
	Colorectal resection	Grasping of anvil	16
		Grasp colon to remove staple line	26
	Jejunostomy		



		Grasp proximal jejunum	17, 24
<i>Stretching</i>	Cholecystectomy	Retract adjacent organs	2, 11
		Grasp and stretch fundus	7, 11
		Grasp and stretch Hartmann's pouch	11, 15
		Retract the gallbladder	11, 15, 20, 21
	Roux-en-Y gastric bypass	Elevate the transverse colon cephalad	28
		Bring up Roux limb antecolic and antegastric	28
		Handling of the bowel	3
		Measure length of biliopancreatic limbs	3
		Pull Roux limb through the mesocolic defect	28
		Handling of the stomach	3, 27
		Pull fundus of stomach down	28
		Pull orogastric tube through gastric pouch	28
		Measure length of jejunum	22, 28
		Stretch suture for cutting	22, 28
		Measure length of roux limb	3, 22, 28
		Pull transverse colon up	28
		Appendectomy	Stretching mesoappendix
	Isolate appendix from surrounding organs and tissue		4
	Nissen fundoplication	Expose lower oesophagus and OG junction	4, 10, 19
		Stretch suture for cutting	4, 10, 19
		Elevate oesophagus	5, 10
		Handling of the stomach	5, 19
		Wrap fundus around the oesophagus	4, 5, 10, 20
		Pull the fundus of the stomach under oesophagus	4, 10
	Colorectal resection	Move small bowel out of operating field	14, 16, 25
		Tissue triangulation (1)	14
		Retract sigmoid colon	26
Pedicle control		18	
Jejunostomy	Tensioning of the suture line	22, 24	
	Displacement of transverse colon	24	
	Extend enterotomy	24	

<i>Translocation (Extract/move tissue)</i>	Cholecystectomy	Put gallbladder in retrieval bag	2,6, 13, 15, 21
		Extract tissue	1, 4, 6, 13,14, 21
	Roux-en-Y gastric bypass	Remove tubes from stomach	28
		Appendectomy	
	Appendectomy	Put appendix in extraction bag	23
		Extract tissue	23
	Salpingectomy	Put tissue in retrieval bag	9
		Extract tissue	9
	Dacrocystorhinostomy	Grasping/removing middle turbinate mucosa	12
		Grasping/removing cut uncinat process	12
		Grasping/removing frontal process fragments	12
		Grasping/removing canalicular probe	12
	Colorectal resection	Put colorectal tissue in bag	14, 25
Extract resected colon		14, 25	