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Investigation of Bioinspired Gecko Fibers to Improve Adhesion of HeartLander Surgical Robot

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Abstract

In this paper, a way for improving adhesion of a mobile robot (HeartLander) on biological tissue is presented, that integrates bioinspired gecko adhesive fibers on the robot surface. HeartLander is a medical robot proposed to perform clinical procedures on a beating heart, overcoming limitations of current cardiac procedures. Biologically inspired gecko fibers have been proposed for adhesion on surfaces. The aim of this work is to assess the advantages of integrating these structures for enhancing the grip between the artificial device and the myocardial tissue. Experimental *in vitro* tests have been carried out assessing the performance of the HeartLander attached to muscular tissue. The effect of the adhesive fibers on improving the adhesion behavior on a slippery surface has been investigated, obtaining a friction increase of 57.3 %.

I. Introduction

Heart therapies through a minimally invasive approach are being developed for a large number of procedures. Minimally invasive approaches allow benefits for the patients including a lower risk of infections and shortened recovery times. Thoracoscopic and transvenous procedures coexist, and are supported by surgeons and cardiologists, respectively. Whereas the former already showed a decreased invasiveness compared to open surgery when carried out robotically [1], transvenous approaches are intrinsically even less invasive and can rely on innovative techniques [2]. In general, thoracic procedures are difficult to perform on a beating heart. Stabilizing mechanisms and other hardware and software solutions have been proposed to allow easier access to the beating heart [3], [4]. On the other hand, transvenous procedures present the problem of widespread drug delivery during therapy.

A miniature mobile robot, HeartLander, has been proposed that adheres to the epicardium, thus providing a tool for precise and steady interaction with the beating heart [4]. The beating heart is a challenging environment for a mobile robot because of its biomechanical characteristics and variable morphology. The presence of adipose tissue and physiological fluids make the heart surface unpredictable and slippery, and hydrostatic pressure due to the surrounding organs is considerable, making progress difficult. Some solutions have been proposed for improving the locomotion, such as robot design variations and synchronization of locomotion with the heartbeat [5], [6]. Despite some success, step efficiency remains relatively low due to slippage during the anchoring phase, i.e. when the suction is active for anchoring the robot to the tissue.

Bio-inspired artificial microfabricated structures that tune adhesion by means of topographical polymeric patterns have been tested on flat surfaces [7]. However, there has been relatively little study of the interaction between these structures and biological tissue. Some works have been carried out on robotic devices integrating microfabricated patterns to enhance the grip between the robot and the tissue, for realizing [8] or improving locomotion [9].

This work presents a preliminary investigation of the use of such a material adhesive to improve friction of the HeartLander crawling robot to the epicardial surface. Adhesion on the tissue surface during the anchoring phase plays a key role for the locomotion of HeartLander. Adhesion is achieved thanks to suction, which depends on the applied vacuum pressure and chamber configuration. Without removing this system, a possible way of improving adhesion of the robot has been investigated in this work, using gecko-inspired adhesive fibers integrated in the suction chambers. Experiments *in vitro* have been performed on muscle tissue in order to investigate the effectiveness of the technique.

II. Materials and Method

A. HeartLander: Overview

HeartLander, shown in Fig. 1, is a mobile robot designed for crawling the heart; it comprises two tandem bodies that independently attach to the epicardial surface. HeartLander realizes inchworm locomotion thanks to the suction chambers located in each body, using push-wire actuation [4]. The current prototype of HeartLander has a front body 11 mm in length, 8 mm in width and 5.5 mm in height, and a rear body 9 mm in length, 8 mm in width and 6 mm in height. Suction chambers are 6 mm diameter and 3 mm width and they are realized in the central parts of the front and rear body.

B. Adhesive fibers

1) Background—Geckos are able to adhere to surfaces and support their own weight due to the cumulative action of van der Waals intermolecular forces between the tips of each of the millions of micro/nanoscale high aspect ratio setae lining their feet and the adhering surface [10]. These passive adhesive systems look promising for biomedical applications, since biocompatible materials can be used to form the fibers and the soft nature of the micrometer-scale hairs will not damage the body’s tissues during adhesion and detachment. A wet environment such as the myocardial surface poses further significant challenges for the performance of fibers because it weakens the inter-surface physical adhesive forces (i.e. van der Waals forces).

Considerable research has explored the development of biologically-inspired micro/nanopatterned adhesives [11]. Preliminary tissue friction studies have demonstrated that the coefficient of friction of micro-patterned materials in contact with porcine gastrointestinal (GI) tissue are higher than flat control surfaces, like those currently used in HeartLander [8],

[12]. For this reason we propose to exploit the same strategy for improving adhesion, in a safe manner, between the HeartLander robot and the epicardium. By integrating into the robot feet micro-structures with high coefficients of friction with the heart, the suction pressure needed to anchor HeartLander in place can be reduced, thus resulting in less risk of patient bruising or tissue damage.

2) Fabrication—For this study, micron-scale fibers with mushroom-shaped tips were fabricated using previously published optical lithography, micro-molding, and dip transfer techniques [13], [14]. To accelerate the fabrication process and to facilitate changes in fiber material, female molds with the mushroom tip geometry were fabricated by mixing, degassing, and pouring a flexible two-part silicone-based elastomer (HS-II, Dow Corning) over a fabricated microstructure and then allowing the silicone to cure. Once the resulting negative female mold had cured, it could be used to rapidly produce arrays of mushroom-tipped microstructures. A 2-part polyurethane (ST-1060, BJB Enterprises) was mixed, degassed, and poured into the female silicone mold. Excess material was removed and pressure was applied to the mold, to result in complete fiber filling. Optical microscopy images of a fabricated array are shown in Fig. 2.

C. Fiber integration

Several designs for integrating adhesives fibers in the HeartLander have been investigated. Our aim was to improve the adhesion by merging the effects of both the suction and the fibers during the anchoring phase. For these reasons, the positioning of the fibers inside the chamber rather than on the bottom surface of the body was preferred (green and red areas of Fig. 3, respectively). In particular, 3 configurations have been proposed. The first configuration (adhesives & support) consisted of the adhesives placed on a ring support. Thus, the suction was forced to work through the central diameter. In this case, the effective chamber width (i.e. the distance between bottom and adhesives surfaces) was decreased due to the presence of the ring. The second configuration (adhesives A) has been designed to maximize both the chamber width and the fiber surface. The last configuration (adhesives B) is based on fiber strips placed along the side walls of the chamber. Both configurations A and B keep an effective chamber width of 3 mm. A section of the HeartLander body shows the positioning of the fibers; their characteristics are reported in Table I. The 3 configurations are shown in Fig. 3, where adhesive fibers are shown in green.

D. Experiment

For assessing the possible improvement of the adhesion during the anchoring phase due to gecko fibers, experimental tests on biological muscular tissue were performed. The adhesive fibers and the HeartLander robot have been fully characterized separately [4], [8]. Here, our aim here was to assess how adhesive fibers and the robot work together for improving adhesion during the anchoring phase.

An experimental bench for force measurement including a linear slide and a load cell has been set up. For performing the adhesion experiments, the bare body of HeartLander with and without adhesives was connected to the load cell by a thin nylon wire, and suction was activated. Experiments *in vitro* on biological samples have been performed to assess the performance of adhesive integration in a working scenario with real tissue. Each test was repeated ten times per fiber sample, in order to improve statistical significance. All experiments were carried on at room temperature. After each trial, the state of the tissue area has been visually checked to evaluate tissue deformation. In particular, tissue deformation is one of the main limitations of a model *ex vivo*, resulting in an increased superficial tissue deformation compared to conditions *in vivo*, when the tissue is generally more elastic. Adhesion experiments have been performed using the rear body of HeartLander to investigate the involved forces generated by the suction and the adhesive fibers. HeartLander was connected to a monoaxial load cell (MBD-2.5, Transducer Techniques, Temecula, CA, USA) mounted on a linear stage (MFA-CC, Newport, Irvine, CA, USA). By means of customized software, the stage was activated to pull HeartLander across the substrate surface while the suction was activated with a vacuum pressure of 400 mmHg. A speed of 20 mm/s was selected, approximating the speed of the robot in working conditions. The experimental setup is shown in Fig. 4.

The tissue was fixed in order to prevent slipping and each sample was maintained in contact with the tissue for 15 seconds before starting the force experiment, since effective adhesion is related also to a certain settling time between tissue and robot feet. Vacuum pressure produced full contact between the tissue and the walls of the suction chamber. The different adhesive configurations have been investigated on HeartLander in order to define the best solution for friction enhancement. It has been found that the variation of the chamber design by including additional mechanical structures in the chamber may negatively affect the adhesion force [6]. For this reason, adhesive configurations that minimally affect the original shape of the suction chamber, namely, adhesive configurations A and B, were preferred for experiments. Three samples for configuration A (i.e. I, II, III) and one sample for configuration B were tested on tissue. The adhesives were mounted in the HeartLander chamber and measurements were repeated until the measured performance decreased. Adhesives fibers sheet have been cut accordingly to Table I using a laser cutter. Adhesives placed on the support have a diameter of 6 mm with an internal diameter of 3.4 mm. Adhesives A have a diameter of 6 mm with a 30° circular sector missing, while the B configuration consists of a strip 1.5 mm wide all around the circumference of the chamber. Fig. 5 shows the arrangement in the HeartLander prototype.

The maximum detaching force has been considered as a reference parameter for assessing the performance of the robot with adhesives, and experimental values have been obtained as a mean of the force peaks obtained for each measurement.

III. Results

The typical force trends measured for the different configurations and control support are shown in Fig. 6. Samples I and III for the configuration A showed average peak force values of 1.11 N and 1.29 N, respectively, during the first 5 trials, with maximum values of 1.14 N and 1.43 N, respectively. The control showed a force value of 0.82 N. This means a maximum increase of 57.3%. There is a statistically significant difference between Adhesives A-I and A-III and the control (*t*-test $p = 0.0015$, $p = 0.004$, respectively). Experiments on configuration B have been performed as well. Although interesting results have been found, the positioning of the strips in a repeatable way was problematic, possibly affecting the results. Fig. 7 depicts the mean and standard deviation of the results of the experiment.

IV. Discussion

In this work, we have presented a technique for improving adhesion of the HeartLander epicardial crawling robot on biological tissue by integrating gecko-inspired adhesive fibers. The design of HeartLander has been modified to allow the integration of the fibers. After fiber integration, experimental *in vitro* tests on tissue showed an increase of 57.3% on measured force after integration of adhesives A.

Because incorporation of additional structures in the suction chamber may degrade performance, it is essential to integrate the adhesives without changing the design of the vacuum chamber in order to keep the advantages of both suction and gecko fibers.

Ample settling time of 15 s (more than is generally needed [6]) was used for this work in order to avoid any possibility of transient effects distorting the results. Preloading time significantly affects adhesion to the tissue and must be taken into account for future experiments.

Further assessment of the locomotion performance is needed. In particular, the evaluation of indirect parameters such as the robot speed would be useful, starting from these findings. The native design of HeartLander can be further modified to better integrate gecko adhesive for improving performance without dramatically changing the chamber design.

Acknowledgments

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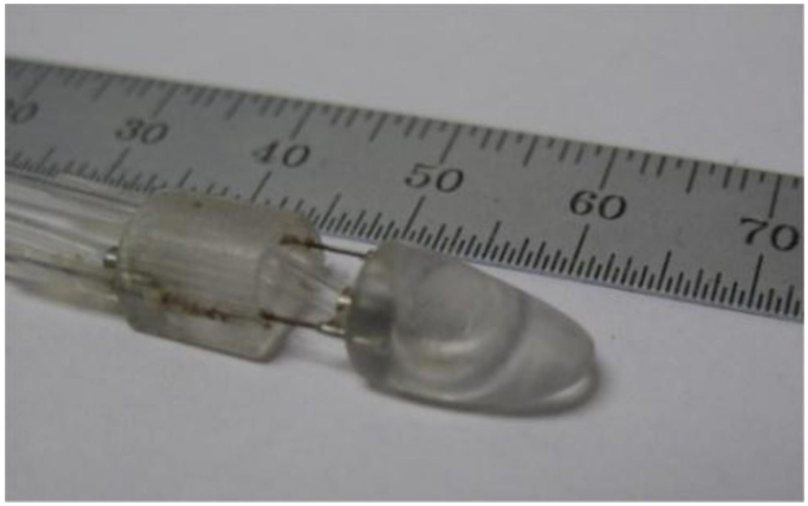

Figure 1.
HeartLander robot.

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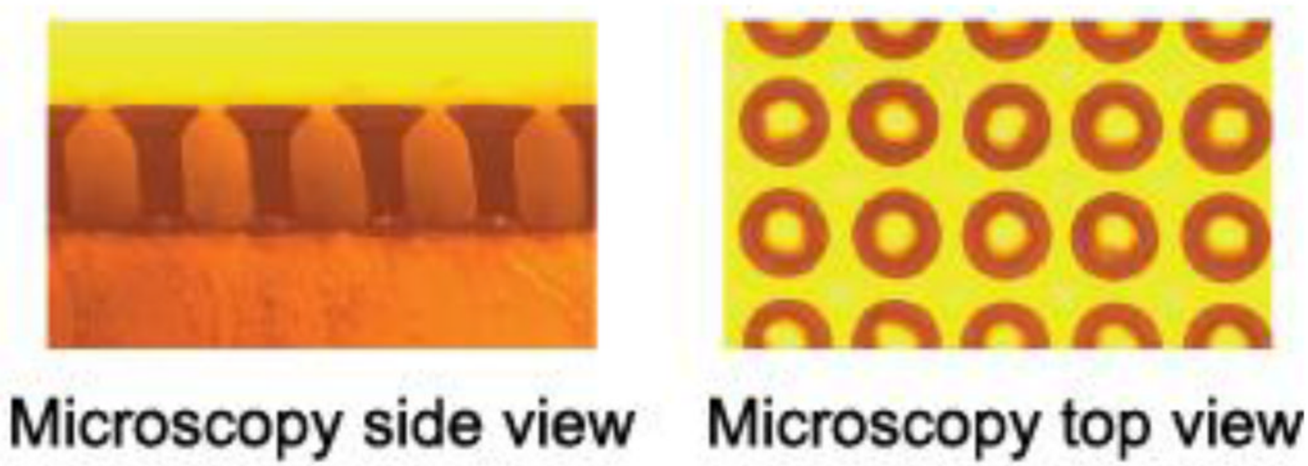

Figure 2.
Side view and top view optical microscopy images of bioinspired polyurethane fibers. The fibers are 126 μm in height, 42 μm in stalk diameter, and 98 μm in tip diameter.

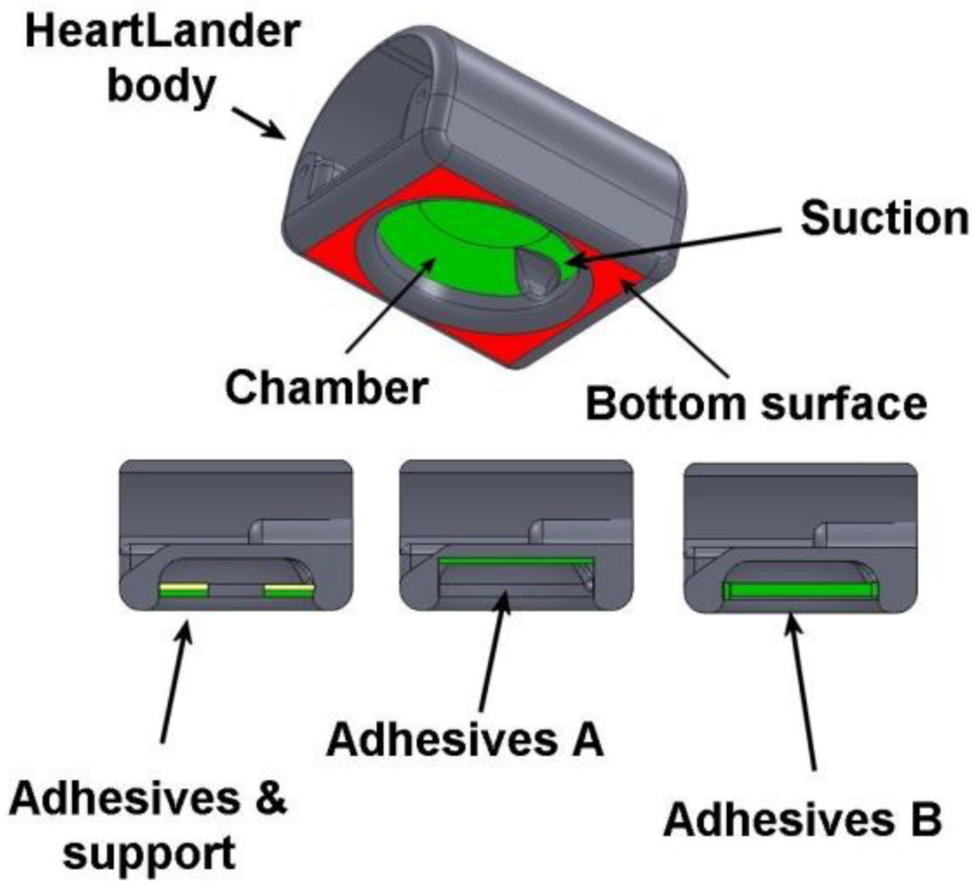

Figure 3.
Schematics of adhesive fibers positioning: overview (top) and cross sections for the 3 adhesives configurations (bottom).

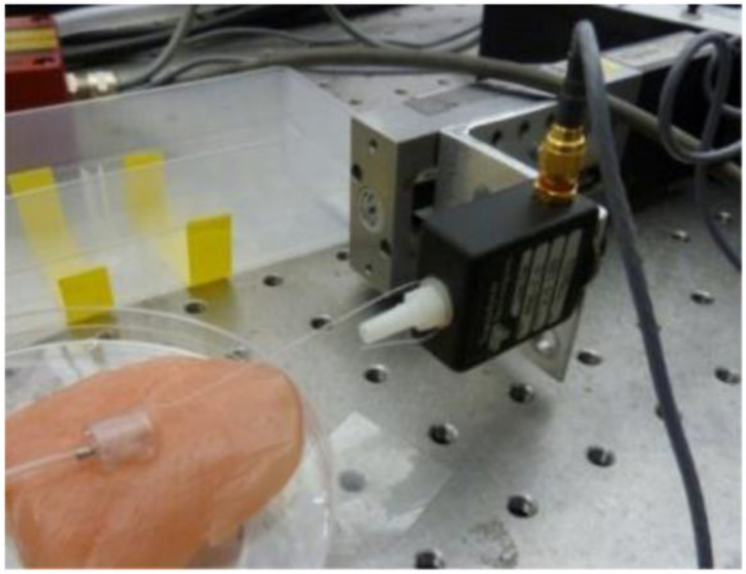

Figure 4.
Experimental setup for force measurement.

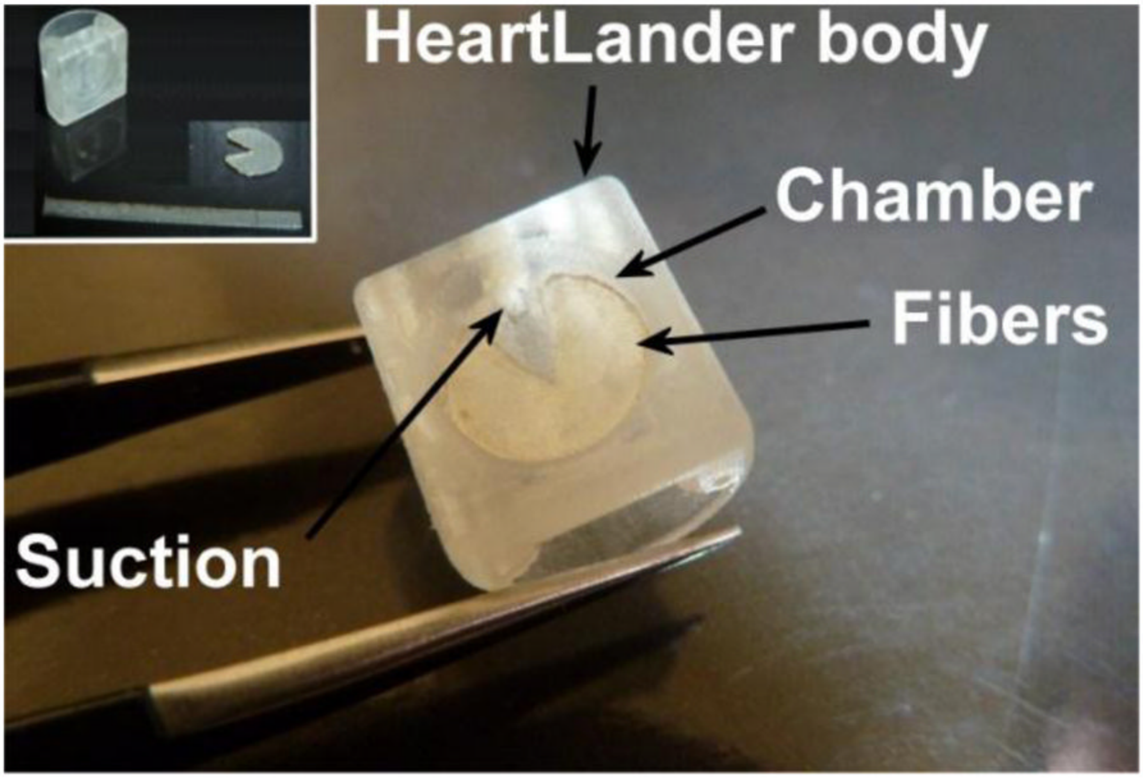

Figure 5.
Fiber arrangements in HeartLander body; Inset: configurations of laser-cut fibers compared to HearLander body.

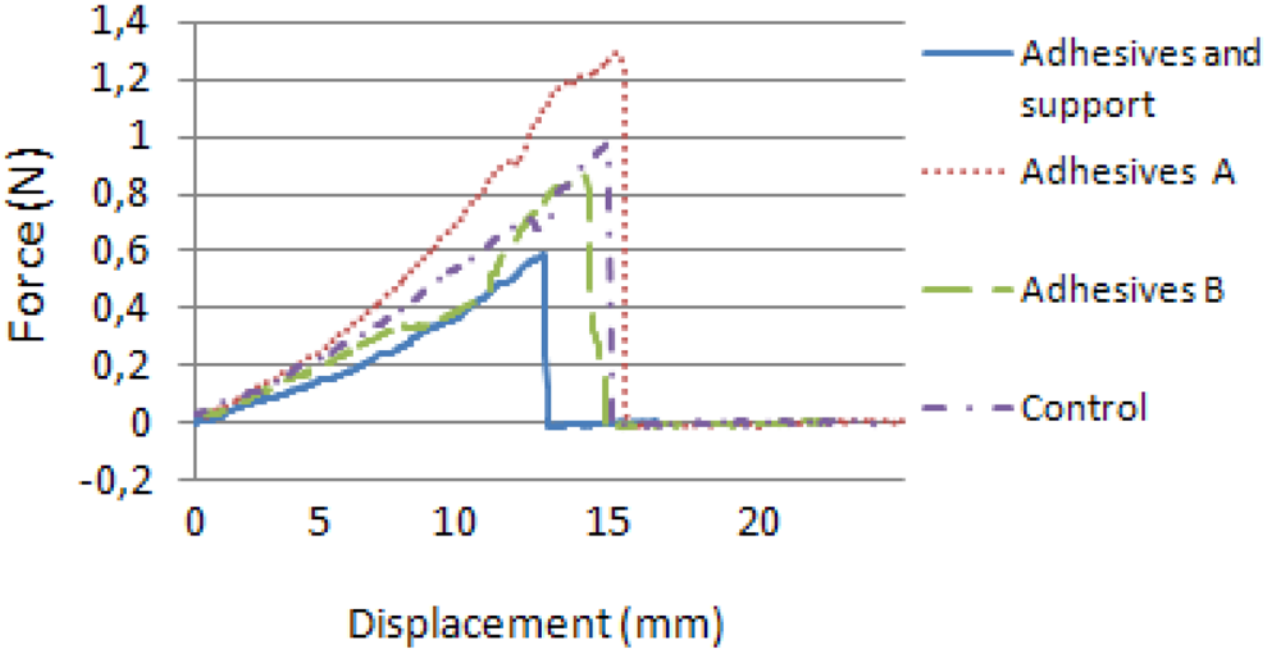

Figure 6.
Typical force trends in during experiments on tissue.

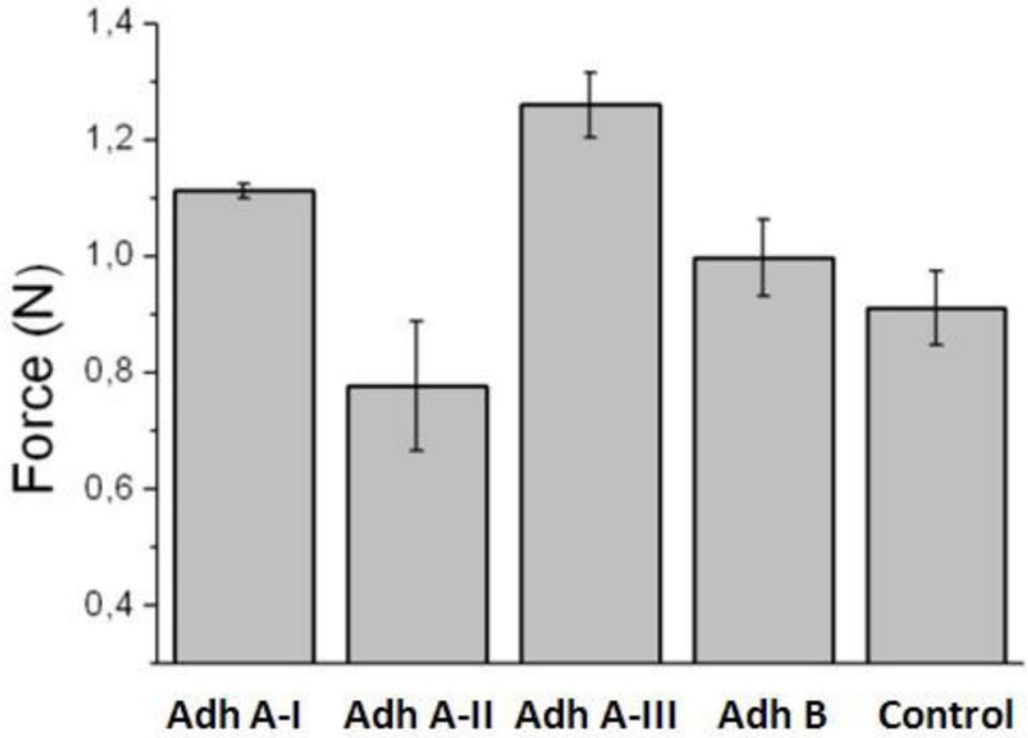

Figure 7.
Adhesion experiments performed on tissue.

TABLE I

Adhesive Fiber Configurations

Adhesives	Shape	Area (mm^2)
Adhesives and support		19.20
Adhesives A		25.92
Adhesives B		28.27