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

Giuseppe Tortora, *Student Member, IEEE*, Paul Glass, Nathan Wood, *Student Member, IEEE*, Burak Aksak, Arianna Menciassi, *Member, IEEE,* Metin Sitti, *Senior Member, IEEE,* Cameron Riviere, *Senior Member, IEEE*

***Abstract*—HeartLander is a medical robot proposed for minimally invasive epicardial intervention on the beating heart. To date, all prototypes have used suction to gain traction on the epicardium. Gecko-foot-inspired micro-fibers have been proposed for repeatable adhesion to surfaces. In this paper, a method for improving the traction of HeartLander on biological tissue is presented. The method involves integration of gecko-inspired fibrillar adhesives on the inner surfaces of the suction chambers of HeartLander. Experiments have been carried out on muscle tissue *ex vivo* assessing the traction performance of the modified HeartLander with bio-inspired adhesive. The adhesive fibers are found to improve traction on muscle tissue by 57.3 %.**

I. Introduction

Minimally invasive approaches are being developed for a large number of cardiac interventions. Such approaches provide benefits for the patients, including a lower risk of infection and shortened recovery time. 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 inchworm-like mobile robot, HeartLander, has been proposed that adheres to the epicardium using suction, thus providing a platform for precise and steady interaction with the beating heart [4]. The intrapericardial space is a challenging environment for a mobile robot because of its biomechanical characteristics and variable morphology. The beating motion and the pericardial fluid 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 traction phase, i.e., when the suction is active to anchor one of the "feet" of 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 traction of the HeartLander crawling robot on the epicardium. Adhesion to the tissue surface during the traction 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 have been performed on muscle tissue *ex vivo* in order to investigate the effectiveness of the technique.

II. Materials and Methods

A. HeartLander

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 flexible 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 in diameter and 3 mm high, and they are located in the central parts of the front and rear body.

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G. T. (e-mail: g.tortora@sssup.it) and A. M. are with The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy.

P. G. is with nanoGriptech LLC, Pittsburgh, PA, USA.

B. A. is with the Mechanical Engineering Department, Texas Tech University, Lubbock, TX, USA.

M. S. is with the Mechanical Engineering Department, Carnegie Mellon University, Pittsburgh, PA, USA.

N. W. and C. R. (e-mail: camr@ri.cmu.edu) are with the Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, USA.

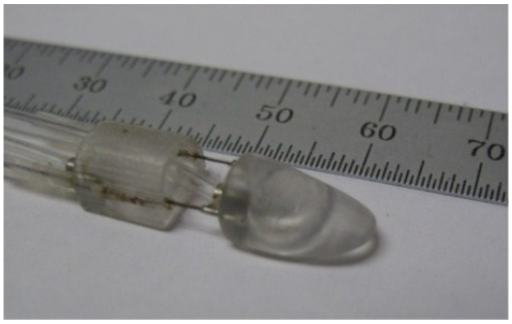

Figure1. HeartLander robot.

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 tissue during adhesion and detachment. A wet environment such as the pericardium 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 is higher than that of flat and rigid control surfaces, like those currently used in HeartLander [8], [12]. For this reason we propose to exploit the same strategy to improve the traction of HeartLander on the epicardium in a safe manner (i.e., without increasing suction). By integrating into the robot feet micro-structures with high coefficients of friction with the heart, traction may be increased, while suction pressure is kept the same, or perhaps even 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 assessed 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 elastomer (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.

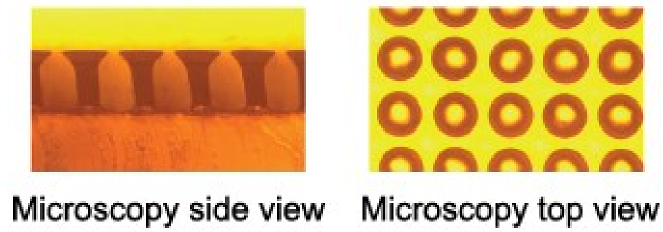

Figure 2. Side view and top view optical microscopy images of bioinspired polyurethane fibers. The fibers are 126 μm in height, 42 μm in stalk diameter, and 98 μm in tip diameter.

C. *Fiber integration*

Several designs for integrating adhesives fibers in the HeartLander have been investigated. Since the aim was to reduce slippage by combining the effects of the suction and the fibers during the traction phase, 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).

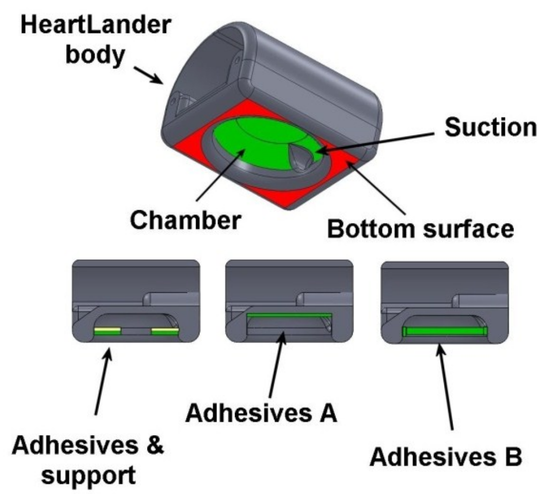

Figure 3. Schematics of adhesive fibers positioning: overview (top) and cross sections for the 3 adhesives configurations (bottom).

In particular, three configurations have been investigated.

- *Adhesives & support:* Adhesives were placed on a ring support near the bottom of the suction chamber. The outer diameter of the ring was 6 mm, and the inner diameter was 3.4 mm. In this case, the effective chamber height (i.e., the distance between bottom and adhesive surfaces) was decreased due to the presence of the ring.
- *Adhesives A:* To maximize both the width of the chamber and the fiber surface, this involves a circular pad of adhesive lining the ceiling of the suction chamber. The pad was 6 mm in diameter, with a 30° circular sector removed for the suction tube connection (see Table I).
- *Adhesives B:* A strip of adhesive (1.5 mm x 18.85 mm) lined the vertical side walls of the chamber.

TABLE I
ADHESIVE FIBER CONFIGURATIONS

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

Both configurations A and B maintain the effective chamber height of 3 mm. Adhesive fiber sheets were cut according 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. The 3 configurations are shown in Fig. 3, where adhesive fibers are shown in green. A section of the HeartLander body shows the positioning of the fibers; their characteristics are reported in Table I. Fig. 4 shows the arrangement in the HeartLander prototype.

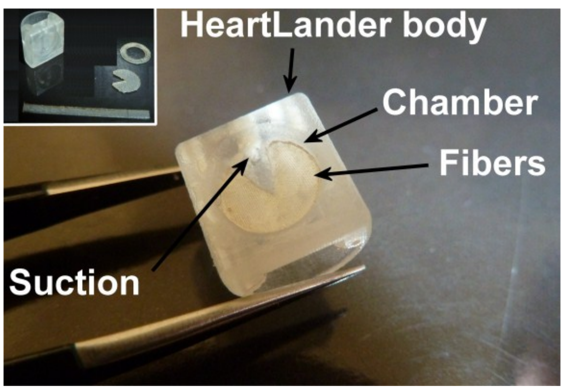

Figure 4. Fibers arrangements in HeartLander body; Inset: configurations of laser-cut fibers compared to HeartLander body.

D. *Experiment*

To assess 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]. In this paper, our aim 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 five 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 was 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. The HeartLander foot 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. The experimental setup is shown in Fig. 5.

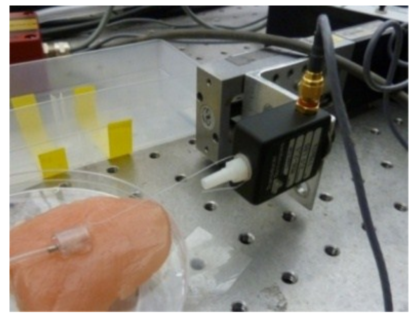

Figure 5. Experimental setup for force measurement.

The tissue was fixed in order to prevent slippage and each sample was kept 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. This time was chosen specifically for this experimental session; a shorter time is used in real working conditions. Vacuum pressure produced extensive 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, Adhesives A and B, were preferred for experiments. Three samples for Adhesives A (i.e., I, II, III) were tested on tissue. Only one sample for Adhesives B was tested on tissue, due to assembly difficulties. The critical shear detachment force (i.e., traction force) was measured for each trial, and mean values for each configuration were computed.

III. RESULTS

The typical force trends measured for the different configurations and control support are shown in Fig. 6. Samples I and III for Adhesives A showed average peak force values of 1.11 N and 1.29 N, respectively, 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 and p = 0.004, respectively). For Adhesives B, although interesting results were obtained, the positioning of the strips in a repeatable way was problematic due to the current design of the robot; thus further experimentation is needed here. Fig. 7 depicts the mean and standard deviation of the traction force results.

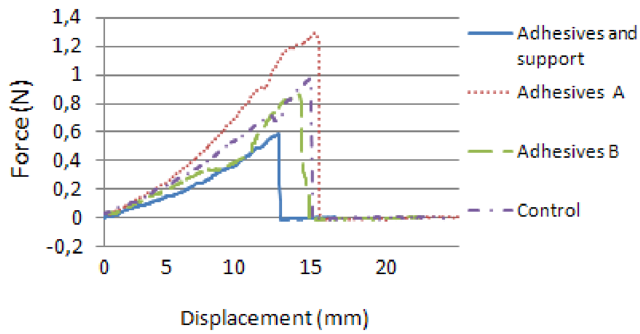

Figure 6. Typical force trends in during experiments on tissue.

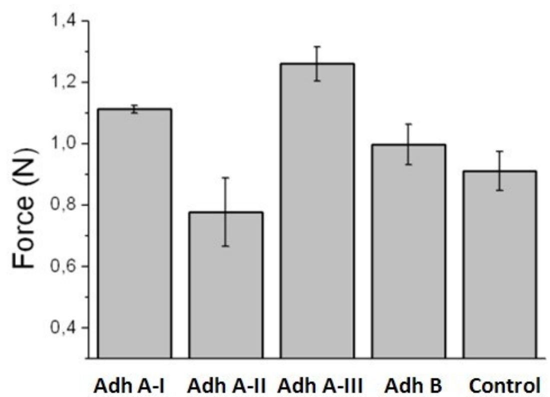

Figure 7. Adhesion experiments performed on tissue.

IV. DISCUSSION

In this work, we have presented a technique for improving traction 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, experiments on muscle tissue *ex vivo* showed an increase of 57.3% in traction force in the best case (Adhesives A-III). This may be a feasible technique to achieve further reductions in slippage on the epicardium, beyond the reduction that has already been achieved by synchronization with the heartbeat and respiration [6].

Because incorporation of additional structures in the suction chamber may degrade performance, further investigation should consider the degree, if any, to which it is possible to modify the suction chamber design to better integrate the adhesives without degrading the performance of the suction.

Ample settling time of 15 s (more than is generally needed) 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.

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