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Human-Compliant Body-Attached Soft Robots Towards Automatic Cooperative Ultrasound Imaging

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***Abstract*— Ultrasound imaging procedures are deemed as one of the most convenient and least invasive medical diagnostic imaging modalities and have been widely utilized in health care providers, which are expecting semiautomatic or fully-automatic imaging systems to reduce the current clinical workloads. This paper presents a portable and wearable soft robotic system which has been designed with the purpose of replacing the manual operation to cooperatively steer the ultrasound probe. This human-compliant soft robotic system, which is equipped with four separated parallel soft pneumatic actuators and is able to achieve movements in three directions. Vacuum suction force is introduced to attach the robot onto the intended body location. The design and fabrication of this soft robotic system are illustrated. To our knowledge, this is the first body-attached soft robot for compliant ultrasound imaging. The feasibility of the system is demonstrated through proof-of-concept experiments.**

Keywords—ultrasound imaging; soft robot; vaccum suction force; compliant robot;

I. INTRODUCTION

During medical diagnostic and intervention procedures, e.g. stent delivery, needle insertion, and minimally invasive surgery, medical practitioners need to obtain the images of the internal targeted area. Nowadays, X-ray radiograph based imaging approaches have been widely used to provide images of the internal targeted area. However, being put under prolonged period of X-ray is found to generate significant radiation exposure to both patients and medical practitioners [1],[2]. Ultrasound imaging, known as the least harmful and noninvasive real-time imaging of the internal targeted organ, is an alternative scanning in those medical procedures. This paper aims to develop a portable ultrasound probe steering apparatus, which seeks to streamline the current ultrasound imaging procedures with less human interventions.

Ultrasound imaging procedure through the use of ultrasound probes in existing applications involves steering the ultrasound probe on the targeted surfaces. The ability of ultrasound imaging to collect qualified images are challenged by the force and angle the ultrasound probe placed on the surface of the body. Generally, different medical procedures require different contact forces and angles [3]. According to Salcudean et al, the required contact force to do the carotid artery ultrasound is up to 6.4 N [4].Furthermore, experiments have also been conducted to show an abdominal ultrasound imaging would require a contact force of up to 20 N [5]. Such results imply the difficulties in obtaining a consistency in various ultrasound imaging procedures. For current ultrasound scanning procedures which are conducted by medical practitioners to manually steer the ultrasound probe, the quality of ultrasound images is determined by human factors [6]. A study on the accuracy of ultrasound imaging shows Year 2 postgraduate house-officers attaining a result of an overall accuracy of 94.6% as compared to 65% obtained from persons without extended training [7]. The result shows a correlation between the quality of images obtained from ultrasound and the experience of the practitioner.

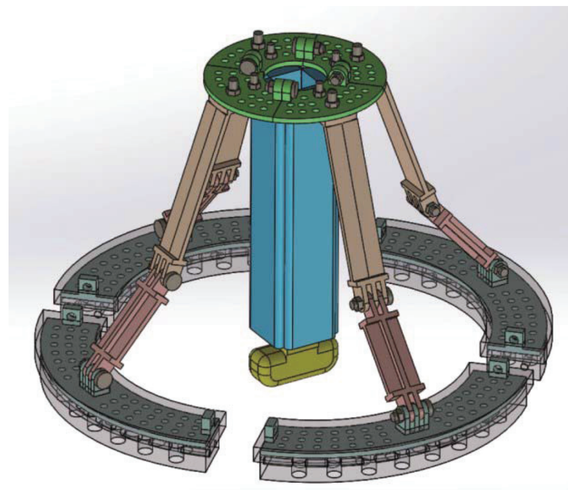

Figure 1. CAD model of the prototypical robotic system

Developing a wearable soft robotic system (Figure 1), which is capable of mimicking the procedure of probe steering and optimizing the contact force and angle according to the specific conditions, has great significance of reducing the reliance of the ultrasound imaging on the

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experience of operators and obtaining images with high quality.

From various reviews and research, there exist systems with regard to the operation of the ultrasound transducer [4]-[13]. However, many of the systems require an operator to manually operate the system. One of the products designed by Gilbertson et al, consist of a device with a one degree-of-freedom (DOF) movement attached onto an operator arm [5]. The procedure will be carried out as per normal, however, providing a force feedback to the user and allow it to operate at a range of strength. Other designs involve the use of large robotic arms when conducting the ultrasound examination. One of the designs by Salcudean et al involves the use of a large robotic arm fixed to the side of the operating table and provides a 6 DOF movement during the operation [4]. Degoulange et al also design a "Hippocrate" involving the operation of an ultrasound transducer attached to a robotic arm [10]. The design provides user with 6 DOF and is able to provide the strength intended by the operator. However, such design often involves the use of heavy machinery, in this case large robotic arms, which makes such system costly not portable and will require a very large working space. One design by AvilaVilchis et al involves a holder for the transducer and provides motion to the transducer in 6 DOF. The probe will be held suspended over the patient's body, connecting to the linkage to provide for the mechanical actuation of the system [11]. Similar to the design of AvilaVilchis, Naja and Sepehri created a transducer holder whereby operations require attachment to equipment suspended over a patient's body [12]. A design by Troccaz presents an equipment that will provide the transducer with a 3 DOF while being strapped on to the patient when in operation [13]. The device is strapped onto the body and is powered by motor. Such operations requires sophisticated add-on product like those equipment to suspend the system over the body and is difficult to operate, requiring strapping of sophisticated belt system before operation.

All these designs are approved not suitable for practical use due to following reasons. Firstly, there is no spare space in the operating room for bulky robotic systems. Secondly, these complex designs are too difficult for medical practitioners to operate. Thirdly, robotic systems made of hard materials easily result in unexpected dangers when working on human bodies. The desired robotic system should be portable, ease of use and ensure safe human-robot interaction.

Aiming at automatizing the ultrasound scanning procedure and based on our earlier research and development in soft robotics [14]-[18], this paper for the first time presents a portable soft robot system, as shown in Figure 1, which is capable of manipulating the ultrasound probe and scanning a large area of the targeted surface. It is believed to possess the ability to provide users and medical practitioners the consistency required by various medical procedures. The originality and applicability of the system is justified by the development of a soft robotic ultrasound-probe steering system.

The rest of this paper is organized as follows. Section II describes design details of this robotic system. Section III illustrate the experiments conducted on this robotic system. The experimental results are also discussed in this section. Finally, Section IV concludes this paper.

II. ROBOT DESIGN AND FABRICATION

A. Overview

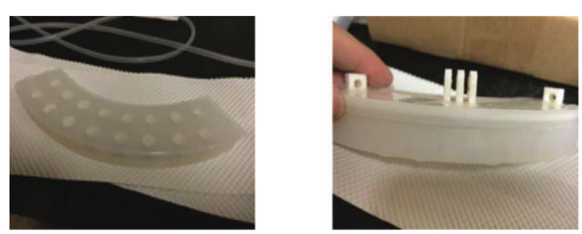
The most critical and difficult step of the ultrasound imaging procedure is that medical practitioners change the contact force and angle between the probe and the targeted surface of the patient body to obtain accurate and precise images of internal organs [19],[20]. The robotic system should have the ability to provide movements with multi DOFs for the probe and adjust the contact force and angle between the probe and targeted surfaces flexibly and rapidly according to the actual situation. In order to improve the practical value of this design, the entire system should be portable and simple. It can be used in various medical procedures and reduce the training time needed by medical practitioners to operate it. Moreover, previous designs with regarding to probe steering system all use traditional mechanical actuators. While these actuators have sophisticated control strategies and can provide enough payload, they are not suitable for applications requiring friendly human-robot interaction. Soft pneumatic actuators have been verified to be able to confer the compliance to human-robot interactions [23],[24]. Stability of the robotic system on a targeted surface is another important factor that influences the quality of scanned images. In this design, the robotic system should be attached to the targeted surface and remain stationary when the probe is scanning the patients' bodies. The desired robotic system should be portable, stable, ease of use and ensure safe human-robot interactions.

To satisfy above requirements, the final design, as shown in Figure 1, is composed of three major parts: suction cups, support structures, and soft pneumatic actuators.

B. Design and fabrication

1). Suction cups

The magnetic force and vaccum suction force are two most commonly used mechanims applied in attaching devices to targeted surfaces [21],[22]. For medical procedures, the magnetic field may generate some side efftecs on other equippemens. Therefore, vaccum suction force has been selected in this design to attach the device to patient's body. Empiracally, 50 N of suction force is necessary for stablizing the entire device. The weight of the deice accounts for about 15N and the max force of 25 N is required to steer the probe to obtain the ultrasoun images. A 25% safety factor has been included in the estimation of the suction force in case of the occurrence of some uncertenties. Additionally, the maximum suction pressure should be restricted to 25 KPA in order to prevent patients from suffering any injuries or damage during the scanning procedure [25]-[28]. Emperimental results show that 64



(a) (b)

Figure 2. Silicon block with suction cups

(a) (b) (c)

Figure 3. Support structure of the device

suctions cups are needed for this device.

As illustrated in fingure 1, the device consists of four sperate segments containg suction cups. Therefore, 16 sucntion cups are incorparated into one silicon block (see Figure 2a). A silicon tube is inserted into the silicon block with two purposes. One is that linking all suction cups in order to make each suction cup genrate the same suction force. The other resason is to strenthen the air passage and prevent the collapse of the silicon when vaccum pressuren is introduced. This silicon block will be attached to the bottom plate of the support struction(see Figure 2b).

2). Support structure

The support structure (see Figure 1), whose functions include maintaining balance of the entire device on targeted surfaces and connecting the suction part and soft actuators, is composed of a top plate, connecting rods, and a bottom plate.

The top plate is made up of four quadrants, which are secured together using bolts and nuts. Each quadrant holds one soft pneumatic actuator. Fasteners instead of permanent adhesion are employed to attach the actuator to the plate (see Figure 3a). There are additional holes in the top plate, allowing the location of the actuator in the top plate to be adjusted as required.

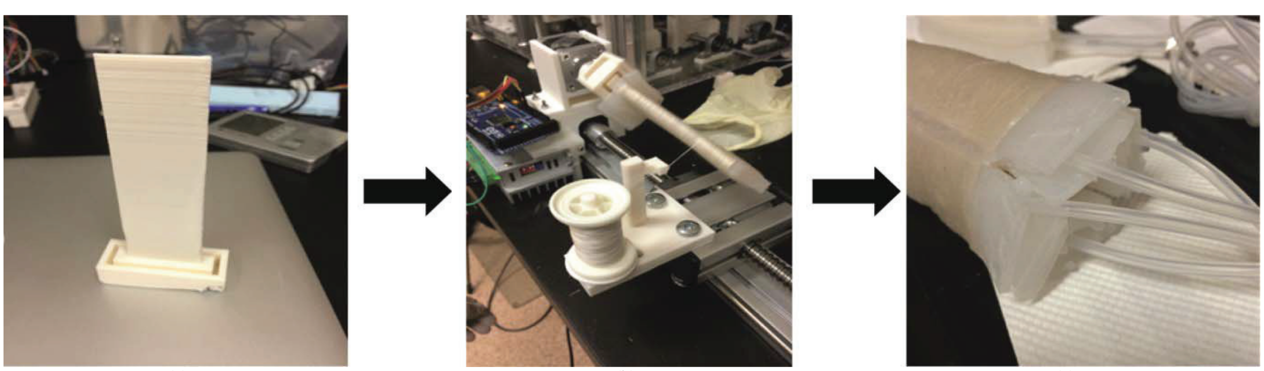
As shown in Figure 3b, an additional DOF has been added to the connecting rod with the purpose of increasing the flexibility of the complete device. With this DOF, the height and angle between the top part and the bottom part can be varied arbitrarily.

Similar to the top plate, the bottom plate is also made up of four quadrants. However, these pieces work independently because the targeted surfaces are not plat in most conditions. The divided plate is able to generate a better adaptation to a complex surface. As shown in Figure 3c, a lot of holes are in the bottom plate, which are reserved with the purpose of better attachment with the suction part.

3). Soft pneumatic actuators

Soft pneumatic actuators used to steer the ultrasound probe are the core of this design. Four identical soft pneumatic actuators are adopted for this device. For each actuator, it should be capable of generating the fabrication procedure is the same, which is depicted in Figure 4. The first step is to design and manufacture the mold making preparation for the fabrication of the main body of the actuator. The mold (see Figure 4a) is the product of a 3D printer. Liquid silicon (Eco-Flex 0030) is then poured into the mold. The vacuum pump (CIMO DZF-6020) and oven (BIOBASE BOV-35F) are utilized to remove air bubbles in the silicon and accelerate the solidification process respectively. Next step is to thread the main body of the actuator (see Figure 4b). The cotton thread wound around the main body is able to effectively prevent the circumferential inflation. Additional liquid silicon is required to apply on the surface of these threads. Air is introduced to the completed actuator to detect any air leakage. The last step (see Figure 4c) is to insert the 4 mm silicon tube into the air passage and seal the opening. The four soft pneumatic actuators stick to each other with the silicon adhesive and form a four-side actuator, which has been verified that is well fitted to a wide range of ultrasound probes available in the market.

The fabricated robotic system is presented in Figure 5.



(a) (b) (c)

Figure 4. Fabrication procedure of the soft pneumatic actuator

During the work, four pieces of silicon block with suction cups attach the robot system to the targeted surface of a patient's body. The height and angle between the top part and the bottom part are adjusted manually. Combined soft actuators have three degrees of freedom and are able to steer the probe sweep over the targeted surface through a variety of movements. Moreover, the force and angle between the probe and the surface are able to be changed arbitrarily by soft actuators to provide more compliance during human-robot interactions.

Figure 5. A soft robotic ultrasound probe steering system

III. EXPERIMENTS AND DISCUSSION

A. Overall

To evaluate the performance including stability of this soft robotic system, a series of experiments have been carried out. Comparative trials have been conducted between threaded actuators and untreated (non-threaded) actuators to show the priority of the fabrication method in this design. Kinematic experiments have been executed to test the dexterity of the system. The maximum force and angle generated by this robotic system has been obtained to further verify the feasibility of this soft robotic system.

B. Equipments

A pneumatic driving system with single channel (see Figure 6) has been designed and fabricated for actuating and controlling the soft robotic system. This driving system is composed of a syringe, a stepper motor, a motor driver, a pressure gauge, a control board, a power supply, some electro components and support materials. The syringe acts as the air source. The piston of the syringe is able to be moved by a stepper motor. There is a pressure gauge (SMC ISE30A-C4H-E) used for measuring the pressure of the pressurized air input to actuate soft actuators is installed and connected to the outlet of the syringe. The measured pressure would be translated into digital signals by the pressure gauge, which are received and used as feedback signal by the control board (ARDUINO MEGA2560). The control board adjusts the position of the piston to get desired air pressure by controlling the stepper motor. The power

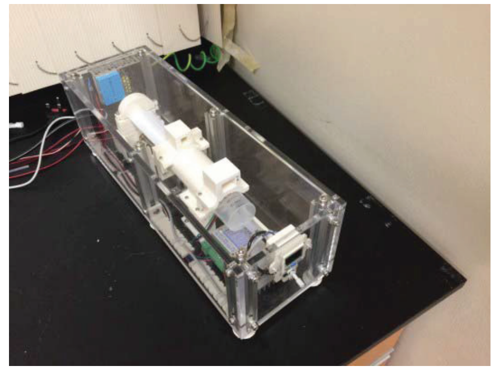


Figure 6. Pneumatic driving system with single channel

supply provides power to all electrical devices, including the stepper motor, the motor driver, the control board, and the pressure gauge. The PID control strategy has been adopted and achieves desirable experimental results. There are two driving systems employed in experiments. One is used to pump soft actuators. The other is utilized to generate the suction pressure.

C. Experiments and results

1). Comparative trials

Soft actuators required by this robotic system should generate motion that is stable and controllable. The range of motion of the actuator should be large enough to satisfy different requirements. Different from commonly used soft fabrication methods, cotton threads are chosen to wind around the soft actuators. The effects of this step added to the fabrication process are verified by comparative trials. As shown in Figure 7, the left actuator is untreated and the right actuator has winded threads. Pressurized air simultaneously input to these two actuators. At only 3 kPa, the untreated actuator seriously inflated as shown in the picture. When the pressure of the input air was increase to 6 kPa, the left actuator eventually failed. Nevertheless, the threaded actuator was able to obtain small radial expansion at as high as 20 kPa (see Figure 7). Continuing to increase the pressure, the threaded actuator was still capable of generating desired and controllable motion. The experimental results show that actuators with winded threads are able to work at a much higher pressure and have better abilities to constrain the radial inflation and bend towards the fixed direction.

Figure 7. Inflation of different actuators

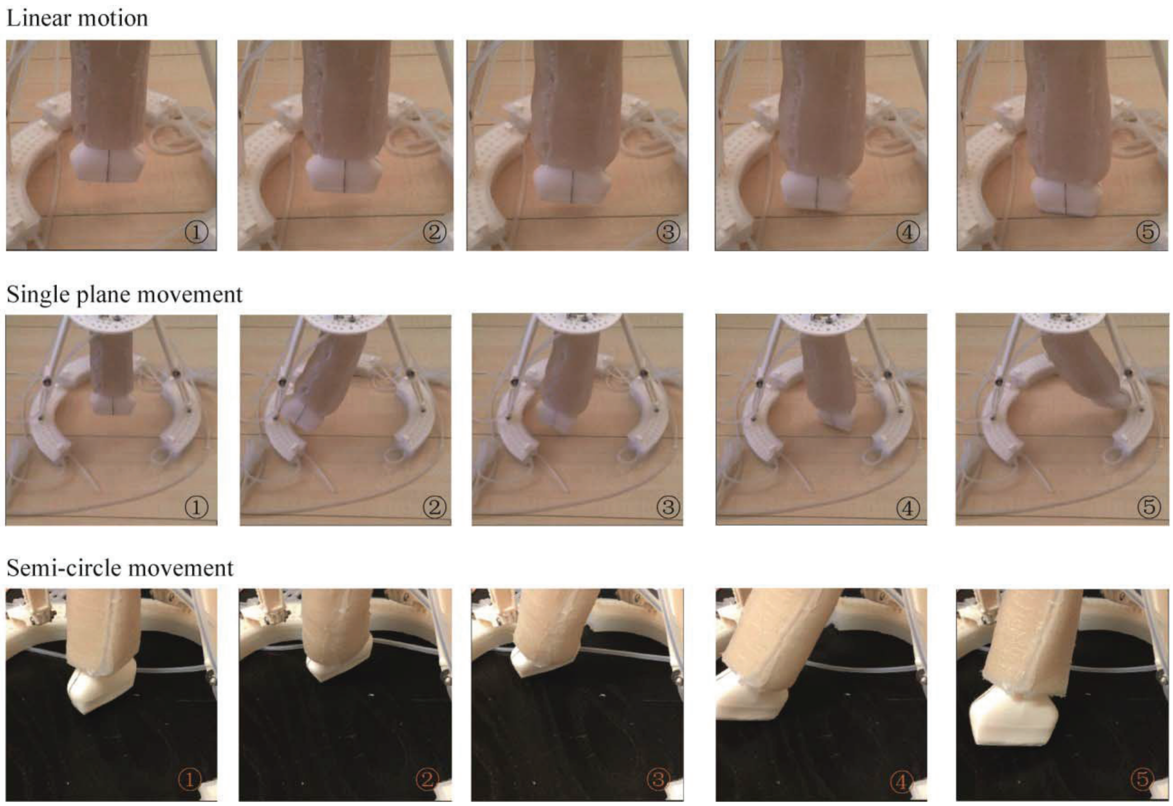


Figure 8. Snapshots of movements generated by the soft robotic system

2). Kinematic analysis

In practical medical procedures, ultrasound probes are usually manipulated to sweep over a surface in various ways in order to get the optimal images. Therefore, the dexterity is an important criterion used to determine the feasibility of this soft robotic system. In this design, four soft actuators work cooperatively to manipulate the probe. When any two actuators work at the same pressure, the robotic system is able to generate linear motion. The distance of the linear motion is only proportional to the pressure of the introduced air. The force between the probe and the contacted surface can be varied and controlled by the linear motion. In the case that one actuator is actuated first and then the opposite actuator starts to work, the probe can be steered to sweep over a simple plane. Three adjacent work together in proper order can manipulate the probe to complete semi-circle movement. Figure 8 illustrates these three kinds of movements completed by this soft robotic system. It is believed that more actuators collaborate with each other and work in more complicated orders can result in more complex movements.

Table 1. The relationship between the force and pressure

Pressure(kPA)	5	10	15	20	25	30	35
Force(N)	1.3	4.0	6.8	9.1	11.2	14.3	18.7

3). Force and angle measurements

The force exerted by soft actuators on a surface is an important parameter that determines the performance of the robotic system. In this research, the force that is related to the linear motion has been measured. The distance between the top plate and the force sensor equals to the free length of soft actuators with a probe. Then two soft actuators are actuated by pressurized air with the same pressure. Forces are obtained at different pressures, which are shown in Table 1. By plotting these results in a diagram (see Figure 9), the linear relationship between the force and the pressure is more intuitive. This result indicates that the force generated by soft actuators are variable and controllable.

Table 2 illustrates the bending angles produced by soft

Table 2. Bending angles of actuators at different pressures

Pressure (kPA)		5	10	15	20	25	30	35
Angle (°)	Single actuator	2.39	3.13	5.01	7.98	9.47	14.42	20.91
	Dual actuator	2.97	5.12	8.91	15.8	22.46	29.23	35.70

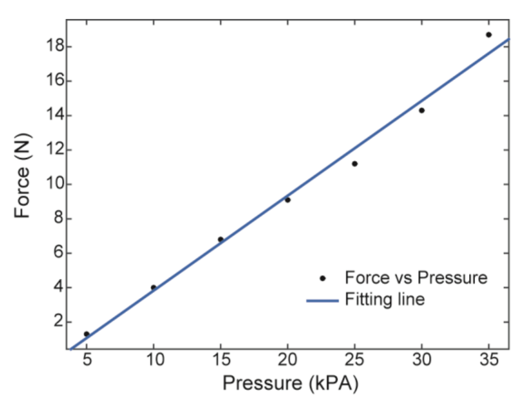


Figure 9. Linear fitting of the relationship between the force and pressure

actuators at different pressures. Single actuator and two adjacent actuators are respectively actuated at a series of pressures. As shown in the table, two adjacent soft actuators work together can generate higher bending angles compared with the single actuator at the same pressure. Additionally, this difference tend to be larger with the increase of the pressure. The maximum pressure before any leakage or failure of a single actuator is close to 100 kPa. Therefore, the range of motion of this robotic system can be further enlarged by good coordination of four soft actuators.

IV. CONCLUSION

In this article, we developed and fabricated a wearable and soft robotic system attached onto a human body to operate an ultrasound transducer in controllable contact with human body. The robot is able to manipulate the transducer and has three Degrees-Of-Freedom (DOFs) with compliant human-robot interactions. Soft robotics are being incorporated into the design of the robot, in place of mechanical robots that are present in the existing products, showcasing the feasibility and possibility of replacing mechanical movement by pressurized air actuated soft robotics. To the best of our knowledge, this is the first body-attached soft robotic system for human-compliant ultrasound imaging with adjustable orientations and contacts.

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