A Lymphatic Drainage Robot for Lymphedema Rehabilitation*

Manthan Pawar, Hassam Khan Wazir, and Vikram Kapila

***Abstract*— Lymphedema is a medical condition that causes swelling and discomfort in human arms or legs. It is caused due to the build-up of lymph fluid in the tissues under the skin. Lymphedema commonly affects one of the arms or the legs and it is an incurable condition that requires treatment for control. A common treatment is manual lymphatic drainage (MLD), an expensive massage therapy to remove the excess lymphatic fluid out of the tissues back into the lymphatic vessels. This paper proposes a portable and mobile device, Lymphatic drainage robot (LDR), as an alternative to MLD. The prototype LDR, a combination of soft and hard robotic hardware, stimulates the lymphatic system. The robot climbs up the human limb, i.e., an arm or a leg, while applying radial pressure on the skin to remove the excess lymph fluid into the lymph vessels towards the upper side of the limb. The preliminary design of the device stipulated in this paper can be transformed into a product that can be mass-produced and provided directly to the rehabilitation clinics and lymphedema patients.**

***Clinical relevance*— This paper presents a working prototype of an autonomous robotic product that performs MLD towards the rehabilitation of lymphedema condition.**

I. INTRODUCTION

The lymphatic system, a part of the human immune system, facilitates the circulation of the lymph fluid throughout the body via the lymph vessels. Damage to the lymphatic system can block the lymph vessels and cause the accumulation of the lymph fluid in the tissues under the skin, leading to swelling. This condition is called lymphedema [1], [3] and it frequently occurs in post-operative breast cancer patients due to the surgical removal of the lymph nodes from the lymphatic system [2], [4]. Therapy exercises exist [5], [6] that can lower the risk of post-operative lymphedema. Methods such as markerless motion capture [7] and gravity-based sensors [8] have been explored to monitor compliance with preventive therapy. However, post-lymphedema treatment requires different modalities that depend on the stage of lymphedema. Depending on the volume of the obstructed lymph fluid, lymphedema is classified into two stages. The stage 1 lymphedema consists of the abnormal flow of lymph fluid in the lymphatic system and stage 2 lymphedema is characterized by limb swelling due to lymph fluid accumulation. While stage 2 lymphedema is more common than stage 1, both are treated with a manual lymphatic drainage (MLD) massage. If lymphedema is left untreated, it can create complications such as skin damage and cancer.

*This work was not supported by any organization

Authors are with the Department of Mechanical and Aerospace Engineering, New York University Tandon School of Engineering, Brooklyn, NY 11201, USA (corresponding author: 646-997-3161; e-mail: vkapila@nyu.edu).

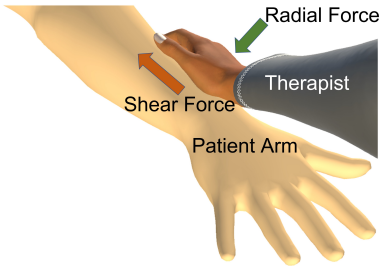


Fig. 1: Manual lymphatic drainage (MLD) massage therapy.

MLD is a massage therapy that includes light touch and rapid motion to remove and promote the outflow of the excessive lymph fluid out of the tissues. MLD is performed by trained therapists at rehabilitation clinics. The method involves performing rhythmic movements to open up the lymph vessels and create a passage for the lymph fluid to flow along the direction of the massage (Fig. 1). MLD sessions last from 20 to 45 minutes and the therapy causes the patient's limb to return to its normal diameter. Nonetheless, the MLD treatment is expensive since the therapy has to be administered 4 to 5 times a week, depending on the type of MLD and the amount of limb swelling. To make the therapy affordable and improve therapy adherence, several self-care modalities have been explored [ref].

The field of soft robotics, which originated from McKibben muscles, known as pneumatic artificial muscles (PAM) [16], has demonstrated several benefits over traditional robotics, especially in devising robot-assisted rehabilitation. The compliant behavior of soft robots renders them as an ideal choice for safe human-robot interaction. Such robots consist of pneumatically actuated deformable actuators that change shape when air is supplied using compressors or pumps.

Several available devices can perform automatic lymphatic drainage (ALD) [9], [10]. While are primarily used by athletes, such devices have seen utility in treating lymphedema. ALD devices are based on sequential pneumatic actuation (Fig.2a), which applies radial pressure sequentially to different zones to simulate MLD. A major drawback of current ALD devices is that they are not meant for lymphedema rehabilitation and are too bulky for use as mobile devices. Recently, [9] considered a design specifically for lymphatic drainage by utilizing a Z-folded sequential pneumatic actuator (Fig. 2b) that applies both normal force and shear force. However, the prototypes developed using Z-fold actuators also suffer from bulkiness, and to the best of our knowledge, there exists no such device that can massage the entire length of a limb using a single Z-fold actuator.

Commercially, two main categories of devices are used

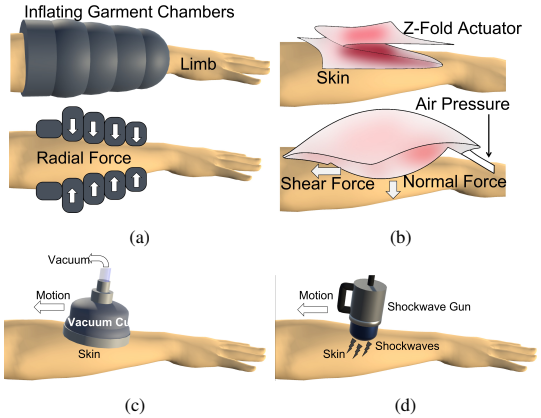


Fig. 2: Lymphedema rehabilitation therapy methods:(a) sequential actuation, (b) z-fold actuation, (c) vacuum, and (d) extracorporeal shockwave.

by therapists for MLD for effective rehabilitation. These include (*i*) devices that apply negative pressure (Fig. 2c) on the surface of the affected limb [11] to make a passage for the lymph fluid through the lymphatic vessels and (*ii*) devices that administer extracorporeal shockwave therapy (Fig. 2d) [12] that applies high frequency vibrations to the surface of the affected limb to stimulate the tissues holding the excess lymphatic fluid. These devices do not provide ALD and require a therapist for effective use with patients. This drives up the cost of lymphedema rehabilitation and consequently therapy adherence is degraded. The therapy cost and bulkiness of devices used for lymphedema rehabilitation present an opportunity for the development of a portable, light-weight, self-care, device for at home use.

In recent years, advancements in soft robotic rehabilitation devices have led to their use in hand [13], [14] and stroke [15] rehabilitation. However, a combination of active soft materials and classical robot design can make some new complex applications feasible. In this paper, we propose a combination of a mobile and soft robotic device that can be used for delivering ALD towards the rehabilitation of stage 1 and stage 2 lymphedema. The device includes two modules: (*i*) a soft silicone-based pneumatic actuator that rhythmically applies radial pressure to the limb to stimulate the lymphatic vessels just under the skin and (*ii*) a robotic climbing mechanism to drain the excess lymph fluid from the tissues and direct it towards the torso. The device is connected to a control module that houses components such as a digital display, an air pump, and a microcontroller that is responsible for controlling the various functions of the device.

II. MOBILE LIMB CLIMBING ROBOT DESIGN

A. Design motivation

According to the Centers for Disease Control and Prevention (CDC) and the American Cancer Society, MLD is performed by certified lymphatic therapists (CLT) as a part of the complete decongestive therapy (CDT). The expense associated with therapist visits and the heavy and non-mobile nature of the commercial devices available in the market for self-administered therapy warrant the development of a device that can address these issues and provide a low-cost

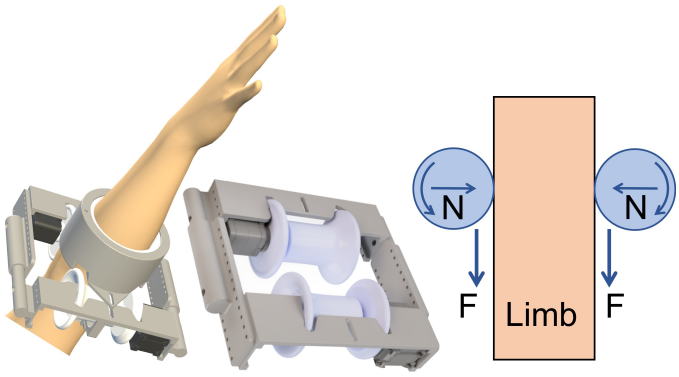


Fig. 3: Lymphatic drainage robot (LDR) with limb climber.

and effective alternative. The motivation behind designing a mobile limb climbing robot is to be able to apply MLD along the length of the limb using only a single soft pneumatic actuator instead of large multi-chambered actuators. While the soft pneumatic actuator provides sufficient pressure to apply MLD on the limb, the limb climbing mechanism allows the device to move along the limb length and push the lymph fluid to flow towards the direction of the movement of the robot.

B. Modeling of the limb climbing robot

We propose a mechanical assembly consisting of polylactic acid (PLA) parts housing two extension springs, two Dynamixel Ax-12 servo motors, and concave rollers that provide a better grip when in contact with the limb. The cylindrical spring housings hold extension springs using a bolted joint design. PLA parts provide rotational provision to the rollers, actuated by the servo motors. Additionally, two extension springs create a normal reaction force that is essential for the frictional force between the rollers and the limb. Since the climbing of the robot is facilitated by rotational friction force applied by the rollers, a rubber padding applied on the roller surface increases the friction coefficient between the rollers and the limb, which in turn mitigates slippage. The roller mechanism also delivers a squeezing effect to the surface of the skin due to the concave shape of the rollers and the spring force. Fig. 3 shows the computer-aided design (CAD) model of the proposed design.

III. SOFT ACTUATOR MODELING

A. Design motivation

We propose a device with a single actuator that can perform ALD along the limb length. The primary obstacle while designing such a device is the non-uniformity of limb diameter. For example, the cross-sectional diameter increase from the wrist toward the shoulder and from the ankle toward the thigh. Commercial sequential actuators are based on blood pressure monitor cuff actuators, which are resizable sleeves that can be wrapped around the limb. Since our device does not use a wrapping sleeve mechanism, we address this issue by building a flexible and stretchable silicone-based soft robotic actuator that can work for the varying limb diameters. The selection of silicone is guided by the fact that, in theory, silicone-based soft actuators can be continuously deformed to adapt to infinite degrees of freedom. A common

actuation method for soft robots is soft pneumatic actuators (SPAs) [17]. SPAs are highly compliant actuators that allow safe interaction between the human skin and rehabilitative devices. Thus, we created a soft robotic collar-like actuator that can provide enough actuation to be able to squeeze out the excess lymphatic fluid, as shown (see Fig. 5). For stage 1 lymphedema, a compression of 4 kPa and a lateral traction movement of the skin must be executed. Moreover, as suggested by therapists, the lateral displacement of the skin must be about 3 mm [ref]. The proposed SPA consists of a hollow cylindrical design with four different walls of varying thickness. The inner wall interacts with the limb and has a thickness of 0.5 mm. The outer and sidewalls are of 3 mm thickness. This difference in wall thickness is important because when the SPA is actuated with pneumatic pressure intake, the wall with the lower thickness undergoes higher deformation, and the thicker walls create an opposing stance against pneumatic pressure, resulting in the desired actuation applied on the limb by the inner wall of the actuator.

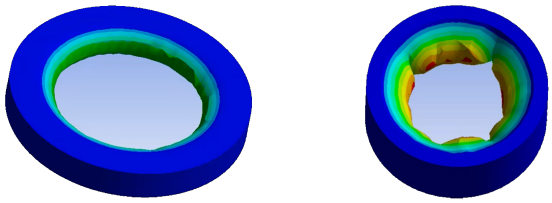
B. Actuator design simulation

Rapid prototyping and testing of SPAs is a time-consuming and laborious task due to a long curing time for silicone and complications that arise from minor defects in the actuator molds. Thus, it is ideal to test the SPA designs in a simulated environment and start the manufacturing once a design yields desirable results in simulation. There have been a few successful attempts in simulating soft actuation and pneumatic or hydraulic inflation [18]. The heart cardiac simulation is an apt example of medical soft actuation [19]. Such simulations, however, are quite complex and require significant computational burden. In recent years, Simulation Open Framework Architecture (SOFA) [18] and Ansys soft robotic simulations [20] have been used in soft robotics research studies. Until recently, finite element analysis (FEA) for soft actuators has been difficult because of the lack of data on the properties of silicone material. However, we successfully simulated the actuation of the proposed SPA using the hyperplastic material analysis (HMA) architecture to increase the efficiency of actuation by using the sample data recently published by Axel Physical Testing Services.

The actuation size of SPA depends on a few physical design parameters of the actuator. These include: inner wall thickness (t_1), sidewall and outer wall thicknesses (t_2, t_3 and t_4), actuator width (T), actuator height (h), applied pneumatic pressure (p), and leakage pressure. We simulate the preliminary design of the SPA that allows us a 12 mm diameter change that is insufficient for our application. However, by tuning the above parameters in HMA we find the most suitable values to carry out ALD. The following parameters were finalized for the hardware design of the SPA: $t_1 = 1$ mm, $t_2 = t_3 = t_4 = 3$ mm, $T = 7$ mm, $h = 26.95$ mm, $p = 0.9$ bar, and Actuation $= 42$ mm = Change in inner diameter of the actuator.

C. Manufacturing of the silicone-based actuator

Based on the design of the actuator, negative designs were created that served as the designs of the molds. To make a closed SPA, fabrication followed a three-step process. In the first step, out of the two molds, one is used to fabricate a part that contains the outer wall and sidewalls. Another mold is used to fabricate the inner wall. These molds are then 3D printed on a PLA printer with 0.6 mm layer height. These molds require a high level of surface finish to prevent any leakage in the final actuator. Furthermore, since the three-wall mold needs to be broken to take out the silicone part, the mold has to be printed at a low infill setting of $7-8\%$. Next, in the second step, the base material for SPA is selected as Dragon SkinTM 30 moldable silicone. Dragon SkinTM 30 is a two-part liquid silicone compound that is mixed in equal amounts before being poured into the molds. The molds are vacuum degassed to remove any trapped air and then left to cure at room temperature for $7-8$ hours. Finally, in the third step, once both silicone parts are taken out of their respective molds, a 3D printed pneumatic connector is placed at the connection hole and the two parts are joined together by adding more silicone material between them and it is left to cure for additional $7-8$ hours.



(a) (b)

Fig. 4: Simulation results: (a) first soft actuator with 400 kpa pressure yielding 24 mm of actuation and (b) optimized soft actuator with 30 kpa pressure yielding 32 mm of actuation.

Fig. 5: Actual actuation with 30 kpa pressure yielding 28 mm of actuation.

D. Actuator housing

The housing of the actuator is a PLA casing mounted on the climbing module of the device. The casing has a single degree of freedom to adapt to varying sizes and shapes of the limb being treated. Fig. 3 shows the design of the actuator housing.

IV. ELECTRONICS AND CONTROL

A. Actuation, sensing, control, and program

The climbing action is performed using Dynamixel Servo actuators mounted on the robotic mechanism. Squeezing action for lymphatic stimulation and drainage is accomplished by a SPA operated by a mini air pump. The device's actuators and the sensory system are connected to a control module via hosing and wires. The control module accommodates a microcontroller, 6 V mini air pump, solenoid exhaust valve, hosing connections, L293D motor driver, 12 V power hub, switch, LCD display, 12 V power supply, and other electronic

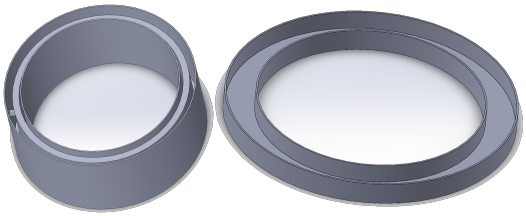


Fig. 6: Mold designs for actuator.

components such as resistors. A force sensitive resistor (FSR) is used to calibrate SPA actuation driven by the mini air pump. The amount of actuation is manipulated by pumps PWM and operational delay values. A threshold FSR value is determined based on the MLD requirement of 4 kPa pressure on the skin of the patient. PWM and delay values are calculated and programmed for distinct stages of ALD at distinct dimensions of the limb. To calibrate SPA actuation pressure values for a specific limb size, LDR uses FSR sensors embedded on the surface of SPA that interacts with the patient's skin. FSR detects the normal reaction between the skin and the SPA. Depending on the type of lymphedema and size of the limb, the SPA pressure value is calibrated using a suitable, constant FSR value. For example, as the limb size gets bigger while climbing, less pressure is required to create the necessary normal reaction on the limb for the ALD effect. The steps of the device operation are as follows. First, LDR is turned on or off using a push button. When turned on, it can perform the entire ALD automatically. Second, at the start of ALD, the robot is supposed to be at the wrist level. As a second step, it pressurizes the SPA to a precalibrated threshold pressure value depending upon the dimensions of the limb being treated. Third, LDR actuates the rollers of the climbing module to shift the robot by a short distance. This creates a draining motion to move the lymphatic fluid from the tissues under the skin towards the lymphatic vessels. Fourth, after pressure squeeze, it exhausts the pressure from SPA and actuates the servo motors of the climbing module to climb a larger step. Fifth, LDR repeats the process from step two to step four for the rest of the limb length.

V. CONCLUSION AND FUTURE DIRECTION

LDR makes the rehabilitation of lymphedema easier, cheaper, and ubiquitous, automating a technique that is usually manually carried out by professional therapists in a medical setting. LDR also succeeds in making the technology-based rehabilitation much more compact than the other commercial solutions. This mechatronic solution can be the next generation low cost, highly mobile, portable, and easy to use at-home rehabilitation device for first and second stage lymphedema patients. The future advancements to this device can be an integration of a mobile application for the control of the robot and the use of sensory data analysis for progress monitoring of the patient. The SPA actuation efficiency can also further be increased if required by the application. We also propose to implement negative pressure therapy using vacuum technology as a side-attachment to the original device for more effective lymphatic drainage.

REFERENCES

[1] A. K. Greene, "Epidemiology and morbidity of lymphedema," *Lymphedema*, A. K. Greene, S. A. Slavin, and H. Brorson Eds., 1st ed.: Springer, Cham., 2015, pp. 33-44.

[2] M. Bernas, M. White, B. Kriederman, P. Summers, and C. Witte, "Massage therapy in the treatment of lymphedema," *IEEE Eng. Med. Biol. Mag.*, vol. 24, no. 2, pp. 58-68, 2005.

[3] SA. Szuba and S. G. Rockson, "Lymphedema: Classification, diagnosis and therapy," *Vascular Medicine*, vol. 3, no. 2, pp. 145-156, 1998.

[4] O. Kayiran, C. De La Cruz, K. Tane, and A. Soran, "Lymphedema: From diagnosis to treatment," *Turk. J. Surg.*, vol. 33, no. 2, pp. 51-57, 2017.

[5] A. Williams, "Manual lymphatic drainage: Exploring the history and evidence base," *Br. J. Community Nurs.*, vol. 15, no. Sup3, pp. S18-S24, 2010.

[6] B. Thompson, K. Gaitatzis, X. Janse de Jonge, R. Blackwell, and L. Koelmeyer, "Manual lymphatic drainage treatment for lymphedema: A systematic review of the literature," *J. Cancer Survivorship*, vol. 15, no. 2, pp. 244-258, 2021.

[7] A.-T. Chiang, Q. Chen, Y. Wang, and M. R. Fu, "Kinect-based in-home exercise system for lymphatic health and lymphedema intervention," *IEEE J. Trans. Eng. Health Med.*, vol. 6, pp. 1-13, 2018.

[8] H. K. Wazir, S. R. Bethi, A. R. Kumar, F. Caruso, and V. Kapila, "A wearable pendant sensor to monitor compliance with range of motion lymphatic health exercise," *Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2020, pp. 4588-4591.

[9] H. J. Yoo et al., "Wearable lymphedema massaging modules: Proof of concept using origami-inspired soft fabric pneumatic actuators," *IEEE 16th Int. Conf. Rehabil. Robot.*, 2019, pp. 950-956.

[10] E. Suarez, J. J. Huaroto, A. A. Reymundo, D. Holland, C. Walsh, and E. Vela, "A soft pneumatic fabric-polymer actuator for wearable biomedical devices: Proof of concept for lymphedema treatment," *IEEE Int. Conf. Robot. Auto.*, 2018, pp. 5452-5458.

[11] V.-P. Vuorinen, J. Iivarinen, J. Jurvelin, and O. Airaksinen, "Lymphatic therapy using negative pressure," *Innovation*, vol. 5320003, pp. 221-233, 2013.

[12] H. Bae and H. J. Kim, "Clinical outcomes of extracorporeal shock wave therapy in patients with secondary lymphedema: A pilot study," *Ann. Rehabil. Med.*, vol. 37, no. 2, pp. 229-234, 2013.

[13] M. Li et al., "A soft robotic glove for hand rehabilitation training controlled by movements of the healthy hand," *17th Int. Conf. Ubiq. Robots*, 2020, pp. 62-67.

[14] M. Haghshenas-Jaryani, C. Pande, and B. M. Wijesundara, "Soft robotic bilateral hand rehabilitation system for fine motor learning," *IEEE 16th Int. Conf. Rehabil. Robot.*, 2019, pp. 337-342.

[15] I. Galiana, F. L. Hammond, R. D. Howe, and M. B. Popovic, "Wearable soft robotic device for post-stroke shoulder rehabilitation: Identifying misalignments," *IEEE/RSJ Int. Conf. Intel. Robot. Sys.*, 2012, pp. 317-322.

[16] M. V. Pawar, "Experimental modelling of pneumatic artificial muscle systems designing of prosthetic robotic arm," *3rd Int. Conf. Converge. Tech.*, 2018, pp. 1-6.

[17] D. G. Caldwell, N. Tsagarakis, D. Badihi, and G. A. Medrano-Cerda, "Pneumatic muscle actuator technology: A light weight power system for a humanoid robot," *Proc. IEEE Int. Conf. Robot. Autom.*, 1998, vol. 4, pp. 3053-3058.

[18] F. Largilliere, V. Verona, E. Coevoet, M. Sanz-Lopez, J. Dequidt, and C. Duriez, "Real-time control of soft-robots using asynchronous finite element modeling," *IEEE Int. Conf. Robot. Autom.*, 2015, pp. 2550-2555.

[19] Allard et al., "Sofa – an open source framework for medical simulation," *Med. Meets Virt. Real.*, 2007, vol. 125, pp. 13-18.

[20] K.-H. Lee et al., "FEM-based soft robotic control framework for intracavitary navigation," *IEEE Int. Conf. Real-time Comp. Robot.*, 2017, pp. 11-16.