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Design and Evaluation of Rheumatoid Arthritis Rehabilitative Device (RARD) for Laterally Bent Fingers*

Matthew Chin Heng Chua, Lim Jeong Hoon, and Raye Chen Hua Yeow, *Member, IEEE*

Abstract— **This paper presents the design and evaluation of a soft-robotic exoskeleton, RARD, for the rehabilitation of arthritis affected individuals with laterally deformed fingers due to Heberden's nodes and Bouchard's nodes. The exoskeleton operates using two 3D-printed soft pneumatic elastomeric actuators that are flexible to conform to the curvature of the deformity when not pressurized. Upon pressurization, the actuators can generate sufficient force to overcome the stiffness of the deformed fingers to realign them straight, allowing for progressive rehabilitation. Experimental study was performed on the designed pneumatic actuators to characterize its maximum bending force output from the pressure input. Additionally, the effectiveness of the exoskeleton was evaluated using a human mannequin hand with the simulated deformity. The soft-robotic exoskeleton has been demonstrated to be a promising rehabilitative device for treating laterally deformed digits on the hands.**

I. Introduction

Laterally bent fingers is a common abnormality in the digits of the hand that can be caused by Heberden's nodes and Bouchard's nodes, which affects up to 300,000 adults in the UK [1]. This usually occurs in adults suffering from Rheumatoid Arthritis or Osteo-arthritis [2]. In severe cases where the angle of bending is more than 10 degrees, the fingers may cross over one another and impair normal hand functions of the affected person. This may also result in social stigma in schools and at the workplace as the patient faces embarrassment [3]. Besides surgical realignment of the fingers, there is a need for a non-invasive method of rehabilitation to reduce the degree of deformity in the fingers. Although multiple wearable robotic devices have been developed for hand rehabilitation, their movements are mostly confined to the normal sagittal plane [4]. There have been results reporting the effectiveness of pneumatic orthotic devices in the correction of finger deformities caused by Dupuytren's contracture[5]; however, from the authors' best knowledge, no pneumatic hand exoskeleton has been developed for rheumatoid arthritis deformities. We have been experimenting on soft actuators to develop rehabilitative gloves [6-9].

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Matthew Chin Heng Chua is with the Department of Biomedical Engineering, National University of Singapore, Singapore 119077 (phone: 65-65161610; e-mail: biecchm@nus.edu.sg).

Lim Jeong Hoon is with the Department of Neurology, National University Hospital, Singapore 119074 (email: jeong_hoon_lim@nuhs.edu.sg).

Raye Chen Hua Yeow is with the Department of Biomedical Engineering, National University of Singapore, Singapore 119077 (e-mail: bieych@nus.edu.sg).

The traditional form of hand exoskeletons comprises of rigid components that are heavy, bulky and limits the degrees of freedom (DOF) of the finger joints [10-12].This may cause safety issues and discomfort to the patient as their motion becomes unnatural. The rigidity also results in the uneven distribution of stress at the skin-device interface and may be unsuitable for extended usage. Compliant materials, such as cables and soft elastomeric actuators, have been utilized in order to develop exoskeletons that are light weight, comfortable and compact [12-15]. These compliant materials allow for better conformation to the different anatomical dimensions of the patients' hands, hence reducing misalignment and discomfort. They are also more robust and can be customized to achieve multiple DOFs with a single input. A number of wearable soft exo-gloves that operates on elastomeric actuators have been developed [16, 17] and are increasingly gaining popularity due to their low cost, streamline design and customizability [18, 19].

In this paper, we present the development and experimental characterization of the world's first soft robotic glove which rehabilitates laterally deformed fingers and aids in their realignment. The 3D printed glove utilizes pneumatically actuated soft elastomeric actuators that are designed to be compact and yet generate sufficient force to overcome the stiffness of the deformed fingers. We also characterize the performance of the aforementioned pneumatic actuators by varying the input pressure and measuring the maximum force it can withstand. Section II presents the design of the hand exoskeleton and describes the experimental characterization of the actuators and glove. Section III presents the results of the experiments while Section IV discusses the work done. The paper finally concludes in Section V.

II. Methods and Materials

A. Design of RARD

The rheumatoid arthritis rehabilitative exoskeleton shown in Fig. 1A comprises of hollow rings lined up in series for the insertion of the user's finger. Each hollow ring has a pair of hollow rectangular supports located at the top and bottom, which enables the rings to be held together by two soft actuators. The actuators are connected to a base grip that has a green Velcro strap that can be tightened when worn on the hand. The rings can be easily removed or added according to the length of the finger (Fig. 1B). A CAD model of the system when dismantled is presented in Fig. 1C where the light blue, grey and orange components are the individual ring segment, soft pneumatic actuator and base grip respectively. The ring series design, coupled with the flexible actuators, enables the exoskeleton to be easily bent laterally to a maximum of around 90 degrees as depicted in Fig. 1D.

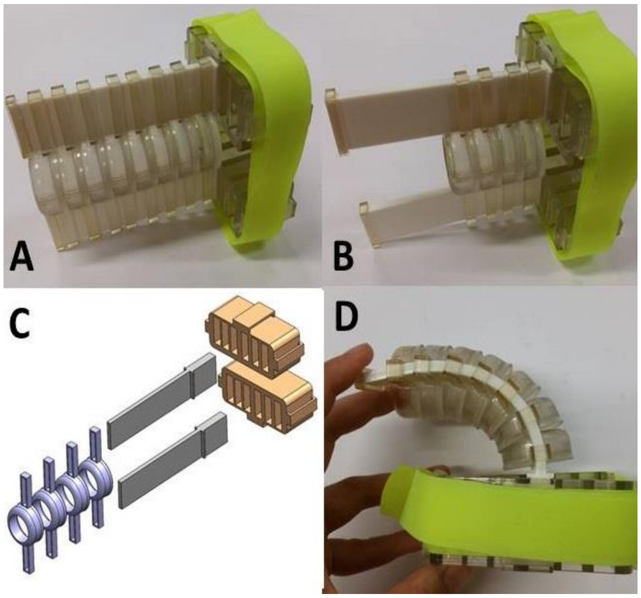

Figure 1. The final prototype of RARD (A) with full set of rings, (B) with partial rings, (C) disassembled and (D) bent to almost perpendicular.

TABLE I. MECHANICAL PROPERTIES OF DIFFERENT 3D PRINTING MATERIALS

Type	Young Modulus (MPa)	Shore Hardness
NinjaFlex®	15.2	85A
SemiFlex®	>15.2	98A
Flex EcoPLA®	95	(3s) 45
Flex® 65	320	65D

Since the entire device is fabricated via rapid prototyping, it allows for patient-specific customization in terms of material type and dimensions. In our prototype, the material of choice for the pneumatic actuator is NinjaFlex® (Fenner Drives Inc., USA) due to its flexibility and low shore hardness compared to other types of silicone rubbers as presented in Table I. The rings and base grip were printed using Veroclear®-RGD810 (Strasys, Singapore). A picture depicting how the device is to be worn is shown in Fig. 2. The design of each pneumatic actuator and its air inlet can be found in Fig. 3. The dimensions of the cavity within the actuator are 110 × 22 × 1 mm, with a wall thickness of 1.5 mm. The minimal thickness of the actuator is required for better bending flexibility and conformation to the finger deformity when worn.

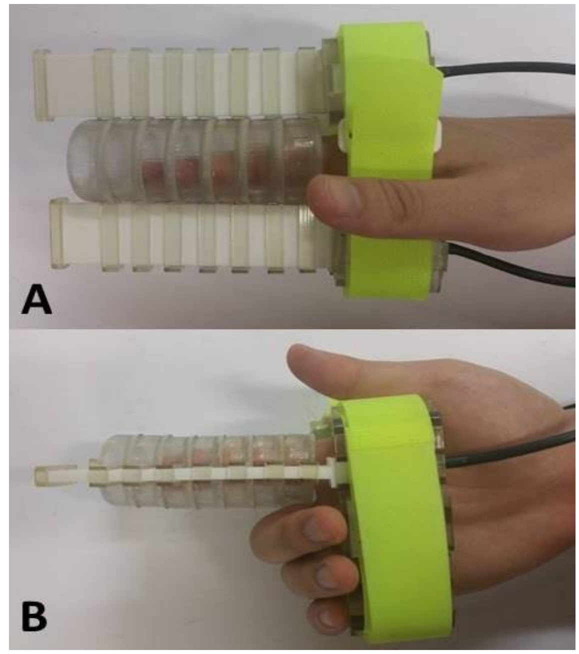

Figure 2. (A)Side view and (B) top view of a person wearing RARD equipped with full set of rings on the index finger.

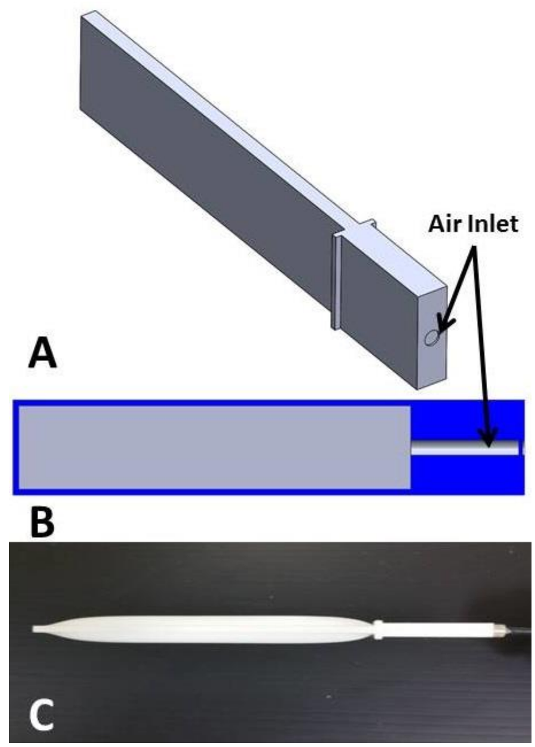

Figure 3. (A) Isometric and (B) sectional view of the soft pneumatic actuator. (C) Inflation of the pneumatic actuator.

B. Characterization of the soft actuators

The setup of the experimental platform for the characterization of the soft bending pneumatic actuator is presented in Fig. 4. Briefly, the soft actuator was mounted at its non-hollow end with its breadth positioned perpendicular to the ground. The tip of a Digital Force Gauge DS2-50N (Imada, Japan) was used to deflect the free end of the actuator through various degrees of bending from its rest position. The actuator was then inflated at input pressures of 1 to 4.5 bars in steps of 0.5 bar and the forces were recorded. Five sets of readings per input pressure at various flexion were taken and the results were computed and shown in the next section.

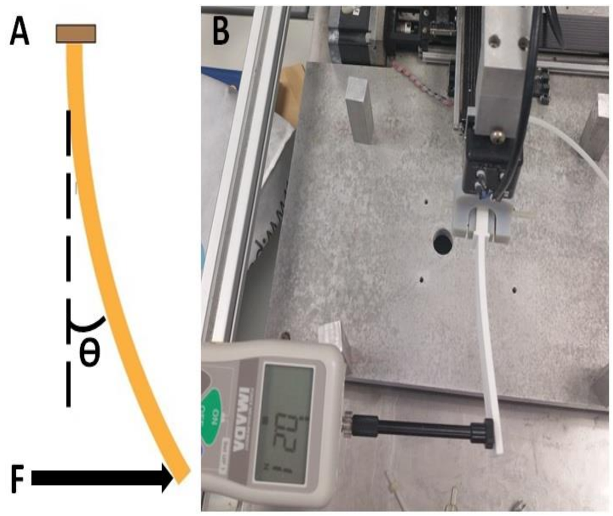

Figure 4. (A) Schematic and (B) photo of the bending characterization platform.

C. Experimental evaluation of RARD with mannequin hand

An experiment to evaluate the effectiveness of RARD using a mannequin hand was performed (Fig. 5). Briefly, the index fingers of the mannequin hands were first bent 60^{o} laterally at the Distal Interphalangeal (DIP) Joint, Proximal Interphalangeal (PIP) Joint and Meta-Carpophalangeal (MCP) Joint as shown in Fig. 6A to C respectively. This is to simulate different various severe lateral deformities caused by rheumatoid arthritis at the joints. For example, lateral deformation of the DIP joint is caused by Heberdon's nodes while the condition affecting the PIP joint is Bouchard's nodes. These nodes are hard bony outgrowth and gelatinous cysts formed at the joints. The hands were then fitted with RARD and a pressure of 3 bars was introduced into the inlet to inflate the actuators to realign the fingers straight. The final finger alignments of photos 6A, 6B and 6C are presented in figures 6D, 6E and 6F respectively. The final angulations and their percentage changes are computed and tabulated in the Results section.

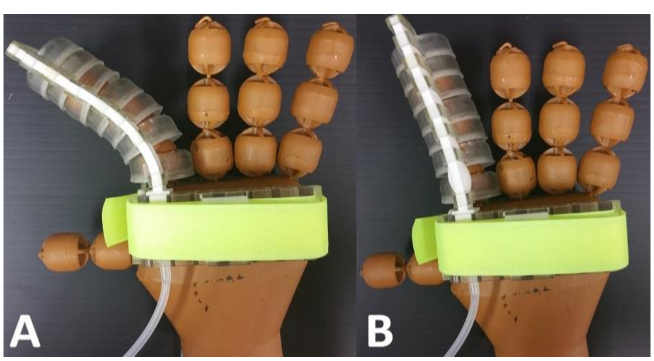

Figure 5. Photos showing the mannequin hand with a laterally bent index finger with the RARD device (A) before and (B) after activation.

III. Results

A. Characterization of the actuators

The relationship between the bending force measured and the input pressure for different degrees of flexion is shown in Fig. 7. At 4.5 bar of input pressure, the flexible pneumatic actuator can achieve close to 2 N of bending force (or 2.24 kg.cm moments) at 40^{o} flexion. Since RARD operates using two actuators, the actual bending force generated by the device would be doubled.

B. Experimental evaluation of RARD

From Fig. 6, we can observe significant realignment of the index fingers after utilizing RARD. The final lateral angulation and the percentage change were tabulated and presented in Table II for comparison.

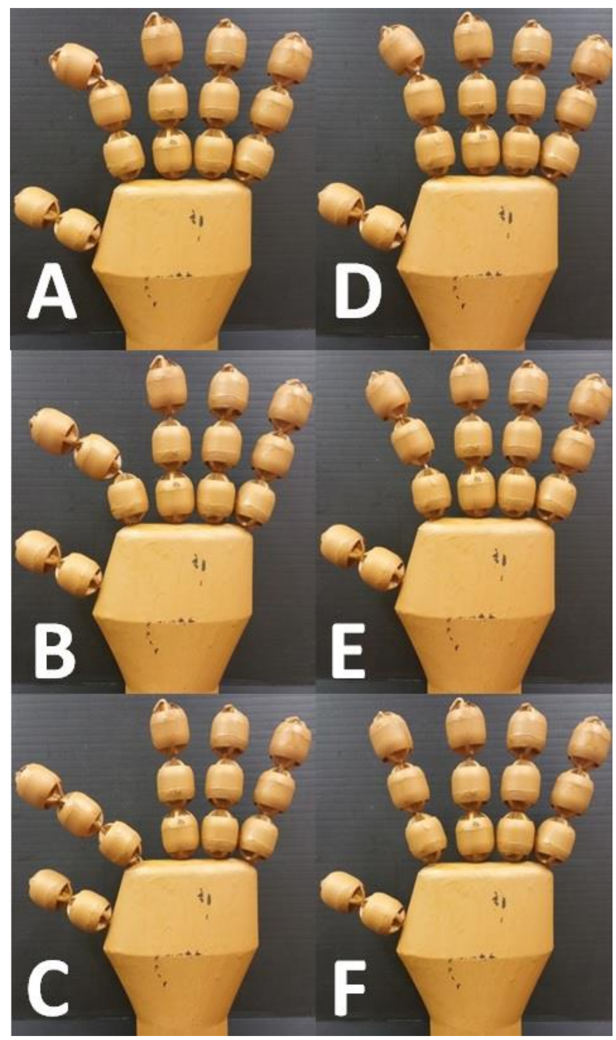

Figure 6. A to C show index fingers with simulated lateral deformity of the DIP, PIP and MCP joints respectively, while D to F are the final shapes after using the RARD.

TABLE II. TABULATED RESTORATION OF THE LATERAL DEFORMITY OF THE MANNEQUIN HAND

Location of Deformity	Initial Angulation (°)	Final Angulation (°)	Percentage Change
DIP Joint	60	25	58.3
PIP Joint	60	18	70
MCP Joint	60	15	75

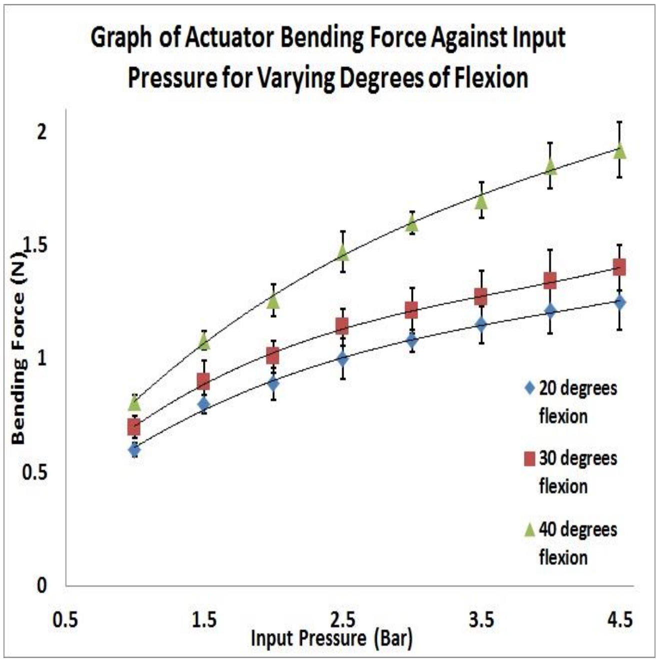

Figure 7. Graph of mean measured force against input pressure for various degree of flexion.

IV. DISCUSSION

From the characterization of the soft actuator, we can observe that the bending force increases more as the degree of flexion increases. At 4.5 bar input pressure, the bending force reaches to almost 2N. This translates to around 4 N of bending force in the device that totals to 4.48 kg.cm moments, which is within the measured lateral abduction range of fingers [20]. The second experiment involving the use of RARD on a mannequin hand has demonstrated the feasibility and effectiveness of the device for rehabilitation of rheumatoid arthritis afflicted fingers. It is noticed that the MCP joint, which is the finger joint nearest to the palm experienced the most reduction of lateral deformity. This could be due to the increased stiffness of the actuator at the base grip, which resulted in a greater restoring moment on the finger.

Due to the limitations of the pump, we were not able to characterize the soft actuator for pressures greater than 4.5 bars. This will be carried out in the future to fully evaluate the limits of this actuator design. Further studies on the durability of the material will be needed as well as it is not known how significant the hysteresis effect would be after many cycles. Another concern that needs to be addressed is user safety. Future designs would incorporate a mechanism to detect failure and to allow the device to fail safely. This is to prevent an accidental failure of the pressure regulator, which would result in an explosion of the pneumatic actuator. Lastly, the force characterization at the tip of the actuator might be insufficient to fully understand the force distribution levels along the length of the actuators. Additional work in future would include covering the mannequin hands and human test subjects' hands with force sensors to measure the exact force distribution along the finger for evaluation purposes. Human trials would also serve to validate the efficacy and reliability of the device when used at the targeted patient population.

The RARD can be extended to other rehabilitative applications by modifying the actuator design. For example, the actuators design can be repositioned horizontally instead of vertically to allow for flexibility in the plane perpendicular to the palm. This can be used to help patients suffering from weak hand muscles and have difficulties straightening their fingers from a curled position.

V. CONCLUSION

This paper has presented the development and experimentation of a new Rheumatoid Arthritis Rehabilitative Device (RARD) for the potential robot-assisted treatment of and realignment of laterally bent fingers in patients. The soft elastomeric actuator used in the device is highly compliant and flexible to conform to the curvature of the deformed finger. The bending force output of the actuator was also characterized at different degrees of bending and at different pressure input. Lastly, the device was tested on a mannequin hand simulating different levels of laterally deformities caused by rheumatoid arthritis and has been evaluated to be effective in the realignment of the finger. In conclusion, the design and characterization of the soft pneumatic actuator in this paper may be useful for developing other wearable robotic devices in the future.

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