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Bidirectional Bending Fibre-Reinforced Soft Actuator Robotic Glove for Finger Rehabilitation

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Abstract: Finger rehabilitation robots are developed to assist therapists in performing rehabilitation processes on patients. The repetitive flexion and extension have shown positive outcome in improving functionality of fingers among post-stroke patients. However, these robots are made of rigid structures and actuators such as pulleys and motors which pose danger to the delicate human fingers. This paper proposes a bidirectional bending fibre-reinforced soft actuator as an alternative actuator for fingers rehabilitation robots. The developed bidirectional bending soft actuator successfully achieved bending angle of 269.5˚ at 70 kPa input air pressure. Shrinking electrical tubes were attached to the bidirectional bending soft actuator to produce bending motion which mimic the motion of finger. The modified bidirectional bending soft actuator was used to construct finger rehabilitation glove and achieved bending angle of 98.5˚ at 90 kPa for flexion motion.

Keywords: Finger rehabilitation, soft actuator, bidirectional bending actuator, robotic glove, fibre-reinforced actuator

1. Introduction

Globally, nearly 6.5 million death, 25.7 million survivors and 113 million suffered disabilities due to stroke [1]. This is an alarming figure where each year in the United States, approximately 795000 people encountered either new or recurrent stroke [2]. Common disabilities suffered by stroke survivors include spasticity and loss of fingers mobility and strength due damages in the region in human brain that controls movements. The loss of mobility of fingers, whether total or partial can greatly inhibits daily living activities thus decreasing the quality of life among stroke survivors [3]. Repeated exercises through rehabilitation process can improve motor control ability and strengthen weaken finger muscles of stroke survivors [4]. Thus, numerous rehabilitation robots using different technologies such as forearm assisting device, pneumatic hip orthosis and power assistive gloves have been invented to assist stroke survivors in recovery processes [5]–[7]. For fingers rehabilitation, Ab Patar, Komeda and Mahmud developed a fingers rehabilitation device which was actuated by using pneumatic cylinders [8]. Meanwhile, Wang *et al.* introduced a portable exoskeleton which utilised motors to move the fingers at the joints [9]. Fingers rehabilitation devices made of rigid actuators can achieve flexion (curling of finger) and extension (straightening of finger) motion but the level of comfort and safety of patients are reduced.

Therefore, soft robotic fingers rehabilitation devices which implement soft actuators are developed and introduced to avoid injuring the delicate human fingers. Soft actuators which are actuated by compressed air such as fibre-reinforced actuator, pneumatic artificial muscle and pneumatic network (PneuNet) actuator are widely used for fingers rehabilitation. Polygerinos, Wang, Galloway, *et al.* developed a fingers rehabilitation glove using fibre-reinforced soft actuators [10]. Al-Fahaam, Davis and Nefti-Meziani implemented pneumatic artificial muscles in their version of wearable rehabilitation device [11] while PneuNets were used by Ariyanto *et al.* in their work [12]. These soft actuators do not require rigid

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mechanical joints to move the fingers as they are in direct contact with fingers. The soft actuators exert bending force onto fingers when they are actuated.

However, limitation such as insufficient strength of the patients to extend their fingers manually once the soft robotic device is deactivated occurred in the design of soft robotic gloves and resulted in inefficient exercise of fingers [13]. Patients who suffer spasticity where their fingers tend to curl are not suitable to use the soft robotic device for fingers rehabilitation as the device cannot assist the fingers of patients with spasticity for extension [14], [15]. Due to the soft nature of soft actuators, the gloves curl with fingers of patients in deactivate state. This paper describes the development of bidirectional bending fibre-reinforced soft actuator to construct finger rehabilitation glove. This paper presents the performance evaluation of the bidirectional bending soft actuator and the finger rehabilitation glove based on the bending angle and the ability to perform flexion and extension motion.

2. Fabrication of Soft Actuator and Finger Rehabilitation Glove

2.1 Fabrication of Bidirectional Bending Fibre-reinforced Soft Actuator

The bidirectional bending soft actuator was fabricated using Eco-Flex 00-50 (Smooth-On Platinum Cure Silicone Compound) and 3-D printed mould. Eco-Flex 00-50 consists of two parts, A and B which were mixed at a ratio of 1:1 (V/V). A 6.2 mL of part A and B were mixed and stirred gently in a plastic petri dish. Once the mixture was mixed thoroughly, the mixture was degassed in a vacuum chamber. Next, the mixture was poured into the assembled 3-D mould using inner case and left to cure in room temperature for four hours. The cured actuator was demoulded and sewing thread was used to wind the surface of actuator helically in clockwise and anticlockwise manner. A 2.2 mL of part A and B of Eco-Flex were mixed, degassed and poured into assembled 3-D mould with outer case to form an outer coating for the actuator which covered the thread. The mixture of Eco-Flex 00-50 was cured in room temperature and demoulded after cured. Finally, two 4 mm pneumatic tubes were inserted into the fabricated bidirectional bending soft actuator. Zip ties were used to seal the ends of the soft actuator. Fig. 1(a) shows the assembly of 3-D printed mould while Fig. 1(b) shows the fabricated bidirectional bending fibre-reinforced soft actuator.

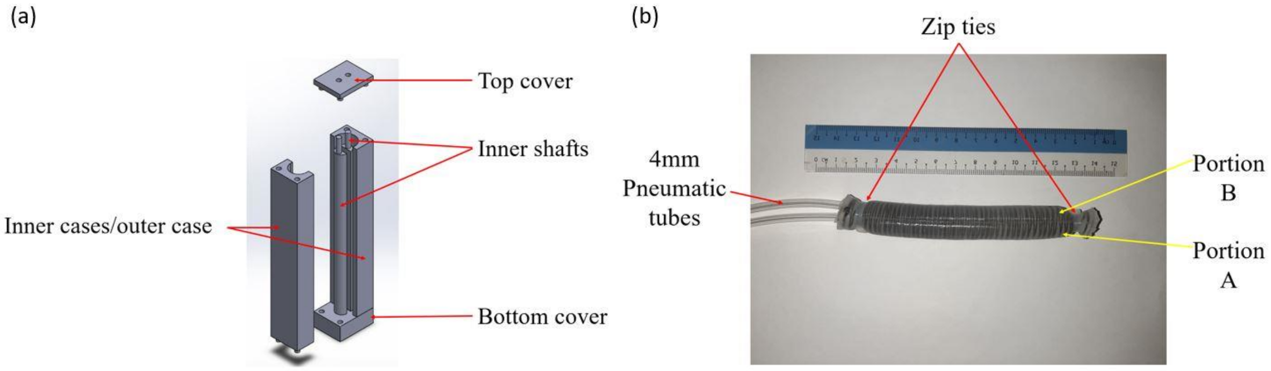


Fig. 1 - (a) Assembly of 3-D printed mould; (b) Fabricated bidirectional bending soft actuator

As shown in Fig. 1(a), the 3-D printed mould of soft actuator consists of top and bottom covers, two inner shafts, a pair of inner case and a pair of outer case. The 3-D mould was built by using 3-D printer (Flsun Delta Kossel, China) with polylactic acid (PLA) filament. The printing temperature was set to 195˚C with the printing speed of 40 mm/s and infill density of 20%. The mould was assembled using inner cases first to construct the body of the bidirectional bending soft actuator. After winding the soft actuator with sewing thread, the mould was assembled using the outer cases which was used to coat the winding thread on the soft actuator. The fabricated bidirectional bending soft actuator in Fig. 1(b) consists of two air chambers labelled Portion A and Portion B. The dimension of the soft actuator is listed in Table 1. As shown in Table 1, the length of the fabricated soft actuator was 110 mm. The geometry of the air chambers was a semi-circle with the radius of 2 mm. The separation gap between the air chambers was 3 mm while the thickness of the outer layer of the air chambers was 3 mm.

Table 1 - Dimension of bidirectional bending fibre-reinforced soft actuator

Parameters	Dimension (mm)
Length	110
Chamber separation	3
Air chamber radius	2
Outer layer	3

2.2 Fabrication of Finger Rehabilitation Glove

A finger rehabilitation glove for right hand was developed using bidirectional bending fibre-reinforced soft actuator. The fabricated bidirectional bending soft actuator tends to curl into circular shape which was not compatible with the bending shape of fingers. The presence of joints on finger resulted in non-circular shape when the finger was bent at 161˚. Therefore, the fabricated actuator was mechanically modified by introducing bending restricted region to mimic the bending of finger. Galloway *et al* used sleeve as strain limiting layer to limit the bending at the region covered by sleeve and allow the non-covered regions to bend [16]. In this work, shrinking electrical tubes were applied onto non-joints region of the fabricated bidirectional bending soft actuator to inhibit bending motion at the non-joints regions as shown in Fig. 2(a). When the soft actuator is pressurized, only the regions not covered by shrinking tube are allowed to bend, resulting in bending motion which mimics the bending shape of finger. The modified bidirectional bending soft actuator was used to construct the finger rehabilitation glove. Velcro tapes were glued onto the modified bidirectional bending soft actuator and the glove. Velcro tapes were used for attachment of modified bidirectional bending soft actuator to the glove to ease replacement in case of defects. The modified bidirectional bending soft actuator was attach on the glove as shown in Fig. 2(b). As shown in Fig. 2(a), the regions not covered by electrical shrinking tubes were the regions with joints on the fingers. As seen in Fig. 2(b), the non-covered region of modified bidirectional bending soft actuator was placed directly on top of the joints of fingers.

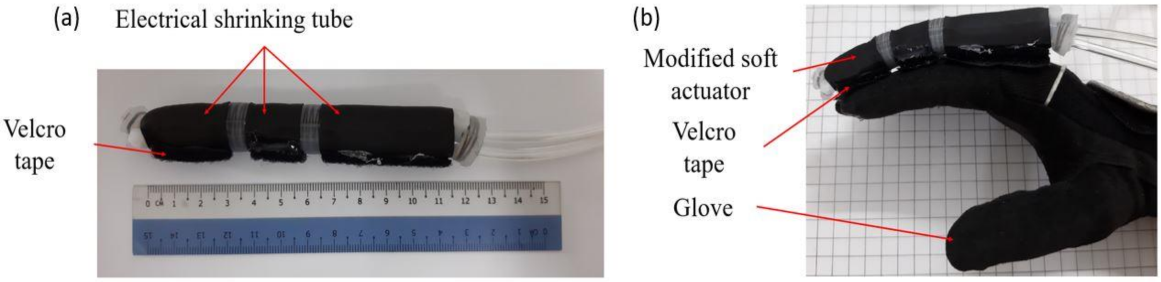


Fig. 2 - (a) Modified bidirectional bending soft actuator; (b) Finger rehabilitation glove

3. Experiment

An experiment was setup to study the bending angle of bidirectional bending fibre-reinforced soft actuator and the required input air pressure as shown in Fig. 3(a). Air compressor was turned on until the air pressure in the air tank reached 200 kPa. By using an air pressure regulator and a digital pressure gauge, the compressed air supplied to the bidirectional bending soft actuator was manipulated and increased at 10 kPa interval until the bending angle of soft actuator was greater than 161˚. The bending angle and input air pressure were recorded. The bending angle for each air pressure input interval was measured based on the photo taken from the top view of the actuator over a grid paper. Fig. 3(b) shows the measurement of bending angle at the intersection of both ends of the soft actuator. The experiment was repeated for finger rehabilitation glove. As shown in Fig. 3(a), the apparatus was set up to study the bending angle of bidirectional bending soft actuator. The photo of bidirectional bending soft actuator was taken on top of 1 cm × 1 cm grid paper. As seen in Fig. 3(b), lines were extended from each end of the bidirectional bending soft actuator until they intersect. The angle between the intersections was taken as the bending angle of bidirectional bending soft actuator.

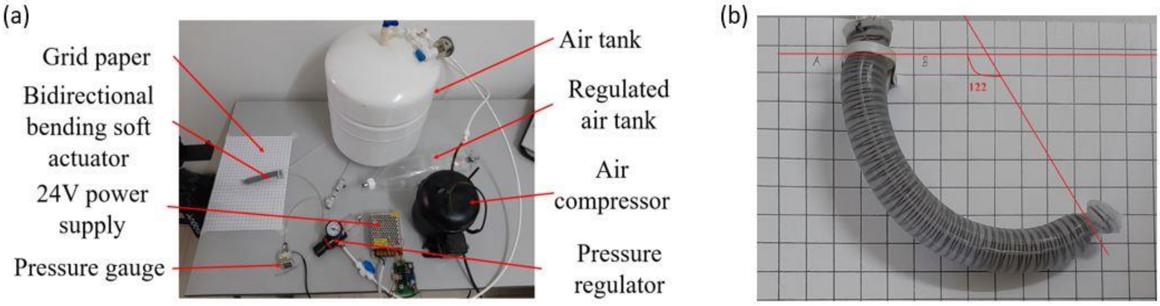


Fig. 3 - (a) Experiment setup; (b) Bending angle measurement

4. Results and Discussion

4.1 Characterisation of Bidirectional Bending Fibre-reinforced Soft Actuator

The bending angle of 211.5˚ and 269.5˚ were obtained for Portion A and Portion B of bidirectional bending soft actuator respectively at 70 kPa input air pressure. The bidirectional bending soft actuator successfully achieved bending angle of 161° required by bending of finger at input air pressure ranging from 40 kPa to 45 kPa for both portions of bidirectional bending soft actuator. Portion B generated greater bending angle as compared to Portion A at the same input air pressure. Greater bending angles were observed on Portion B compared to Portion A because the outer wall of Portion B (3 mm) was thinner than Portion A (4 mm). Thinner outer wall on Portion B enabled greater stretch and expansion when pressurised as compared to Portion A thus resulting in greater bending. Therefore, Portion B was suitable to be implemented for flexion of finger as flexion required more degree of bending compared to extension. Fig. 5 shows the graph of bending angle and input air pressure for the fabricated bidirectional bending soft actuator. As shown in Fig. 5, the mathematical computation plot was obtained from computing the equations proposed by Polygerinos *et al.* and was used as a reference in characterising the fabricated bidirectional bending soft actuator [17]. At 0 kPa to 20 kPa, the bending angle of bidirectional bending soft actuator increased linearly which was identical to the results from mathematical computation. Assumption was made in the result obtained from mathematical computation whereby the expansion of the outer layer of bidirectional bending soft actuator was even when pressurised and the inner layer of actuator was inextensible. Thus, the expansion of outer layer of bidirectional bending soft actuator was uniform when pressurises from 0 kPa to 20 kPa and the inner layer does not extend despite the lack of strain limiting material. Conventionally, the strain limiting material is made up of flexible and inextensible materials [18]. In this paper, the strain limiting material was absence to simplify the fabrication process.

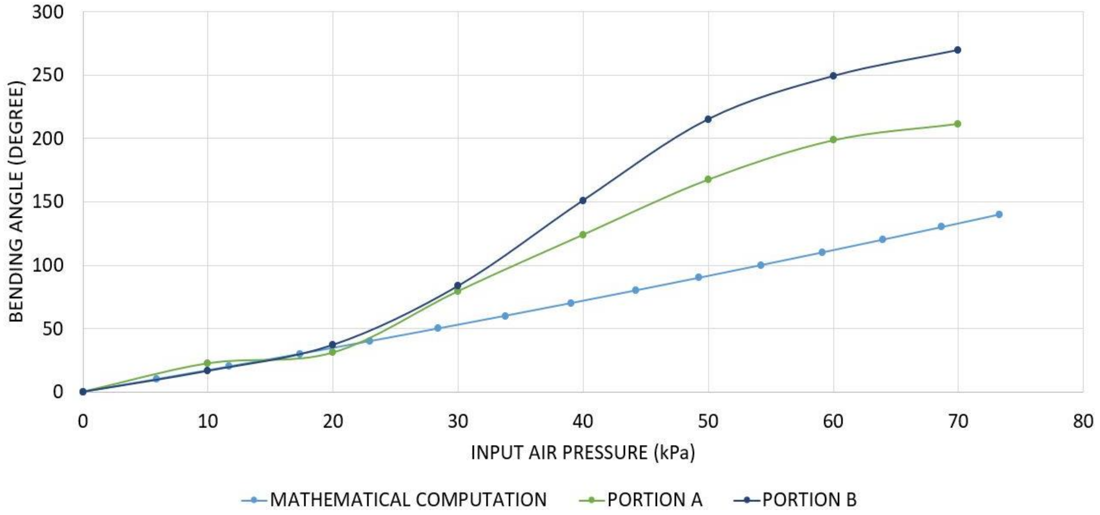


Fig. 5 - Performance of Portion A and Portion B of bidirectional bending fibre-reinforced soft actuator

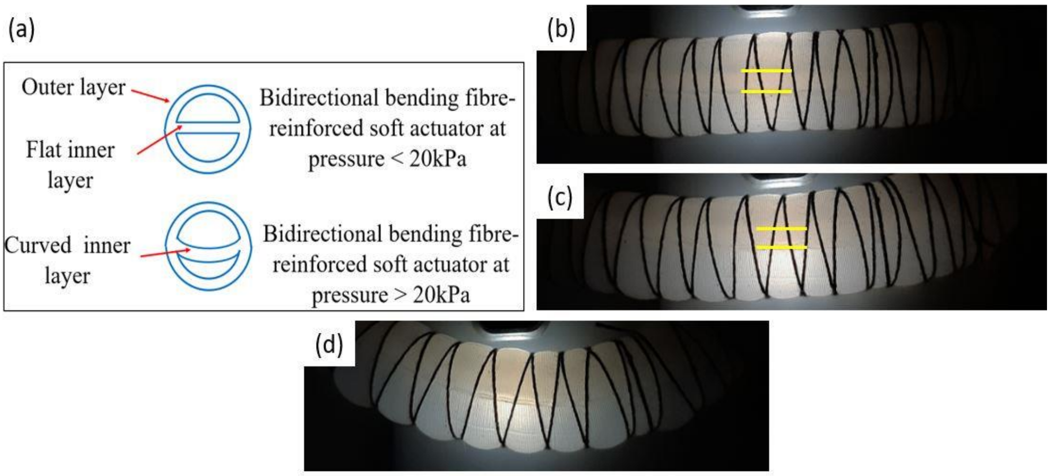


Fig. 6 - (a) Visualised cross-sectional view bidirectional bending soft actuator; (b) Inner layer (bounded by two yellow lines) at 10 kPa; (c) Inner layer (bounded by two yellow lines) at 20 kPa; (d) Inner layer at input air pressure greater than 20 kPa

Beyond 20 kPa input air pressure, both Portion A and Portion B showed an increase of bending angles that were larger than the results from mathematical computation. It was observed that at input air pressure greater than 20 kPa, the inner layer of bidirectional bending soft actuator was curved instead of remaining flat. The absence of strain limiting material in the inner layer caused the inner layer to curve and extend in length simultaneously. The curving of inner layer explained the deviation of bending angle at input air pressure greater than 20 kPa for Portion A and Portion B from mathematical computation. Fig. 6 shows the visualised cross-sectional view and side view of curving inner layer of bidirectional bending soft actuator at air pressure below and above 20 kPa.

As shown in Fig. 6(a), the inner layer of bidirectional bending soft actuator was curved at input air pressure greater than 20 kPa but remained flat at input air pressure below 20 kPa. The inner layer of bidirectional bending soft actuator was visible for input air pressure of 10 kPa and 20 kPa, which was indicated by the two yellow lines as shown in Fig. 6(b) and (c). At input air pressure greater than 20 kPa, the inner layer was not visible as it curved away from the pressurised portion of the bidirectional bending soft actuator shown in Fig. 6(d). The extension in length of bidirectional bending soft actuator occurred due to the lack of strain limiting material in the inner layer which is used to inhibit the extension of inner layer of actuator during bending motion. Fig. 7 shows the extension in length of bidirectional bending soft actuator which is observed by comparing the number of grids covered the bending actuator at input air pressure lower than 20 kPa and the number of grids at input air pressure above 20 kPa. As shown in Fig. 7(a) and (b), the length of bidirectional bending soft actuator remained the same as the initial length of 22 units when Portion A and B were pressurised with air pressure of 20 kPa. In Fig. 7(c) and (d), the length of bidirectional bending soft actuator increased from 22 units to 32 units for Portion A and 31 units for Portion B at 70 kPa of input air pressure which showed that extension in length occurs at input air pressure above 20 kPa.

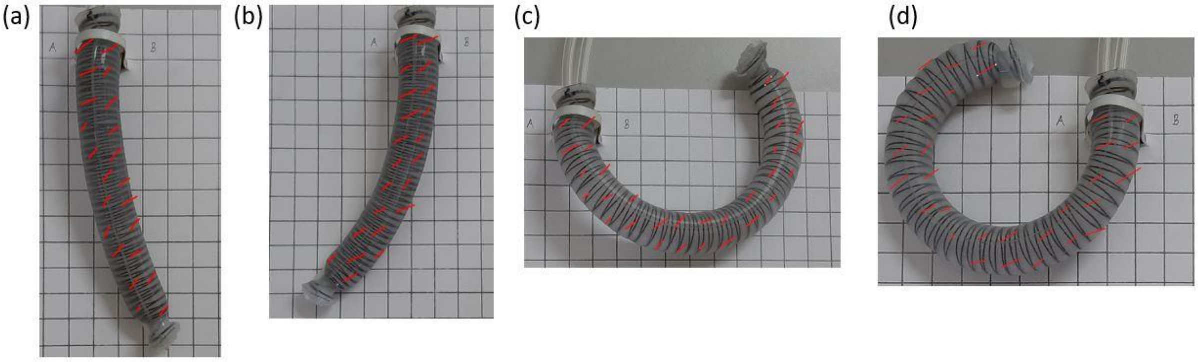
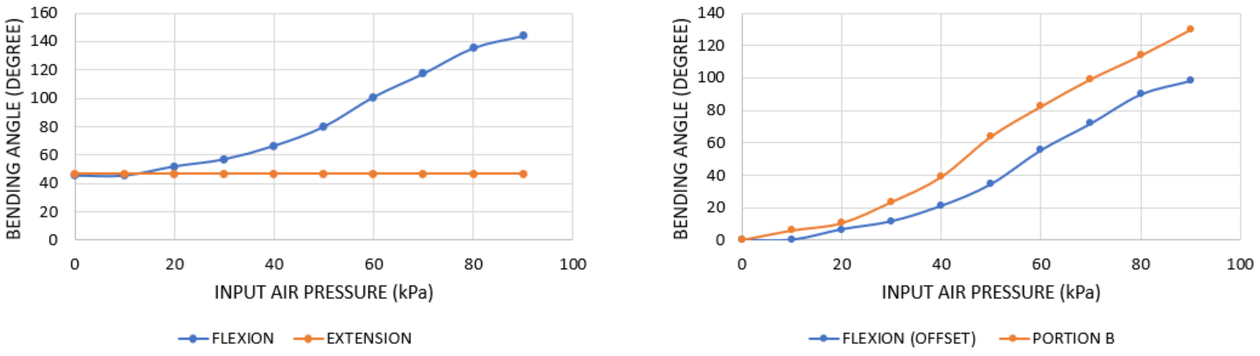


Fig. 7 - (a) 22 units at 20 kPa for Portion A; (b) 22 units at 20 kPa for Portion B; (c) 32 units at 70 kPa for Portion A; (d) 31 units at 70 kPa for Portion B

4.2 Characterisation of Finger Rehabilitation Glove

Based on the Fig. 5, Portion B which had greater bending angle was used for flexion motion on finger rehabilitation glove. Flexion motion refers to the motion produced when curling the fingers while extension refers to the opposite motion of flexion. Fig. 8(a) shows the bending angle of finger rehabilitation glove with different input air pressure. As shown in Fig. 8(a), at input air pressure of 0 kPa, the bending angle of the finger was 45.5˚ due to the minor bending of finger at rest. As the input air pressure increases, the bending angle increases. A 144˚ bending angle was achieved at 90 kPa of input air pressure for flexion motion, which lacked 17˚ from the expected finger bending angle of 161˚. The initial bending angle of finger at rest was included in the bending angle measurement. There was no change in bending angle of finger at 10 kPa because the force generated by actuator was not enough to bend the finger. As for extension of finger, the bending angle remained at 47˚, which was the same as the bending angle of finger at rest. The finger rehabilitation glove could not perform extension on human finger due to the absence of bending region at metacarpophalangeal (MCP) joint. The modified bidirectional bending soft actuator used for finger rehabilitation glove covered distal interphalangeal (DIP) and proximal interphalangeal (PIP) joints only as shown in Fig. 9.

As shown in Fig. 9, the bending region of modified bidirectional bending soft actuator was not placed onto the MCP joint thus resulting in the inability to perform extension motion. Despite the inability to perform extension motion when pressurised, passive extension was achieved when the actuated region was depressurised. By offsetting the initial bending angle of finger rehabilitation glove, the subsequent increase in bending angle can be compared to the performance of modified bidirectional bending soft actuator in free space as shown in Fig. 8(b). The bending angle was reduced with the presence of finger. The maximum bending angle of 98.5˚ was achieved at 90 kPa during flexion motion compared to 130˚ at 90 kPa in free space. The reduction in bending angle was due to the resistant imposed by the finger in glove. Similar trend of reduction in bending angle was also reported by Chatterjee, Hore and Arora where 33˚ was achieved at 30 kPa when tested on human finger compared to 68˚ at 30 kPa in free space [13]. Fig. 10 shows the bending of finger rehabilitation glove at different input air pressures during flexion process. The bending angles shown in Fig. 10 were offset values.



(a) (b)

Fig. 8 - (a) Bending angle for flexion and extension motion; (b) Effect of resistant of finger on bending angle of finger rehabilitation glove

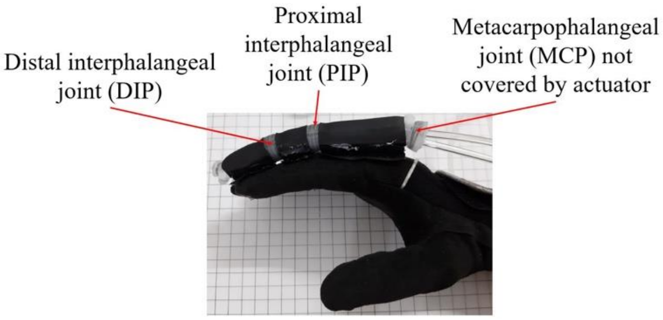


Fig. 9 - Joints covered by finger rehabilitation glove

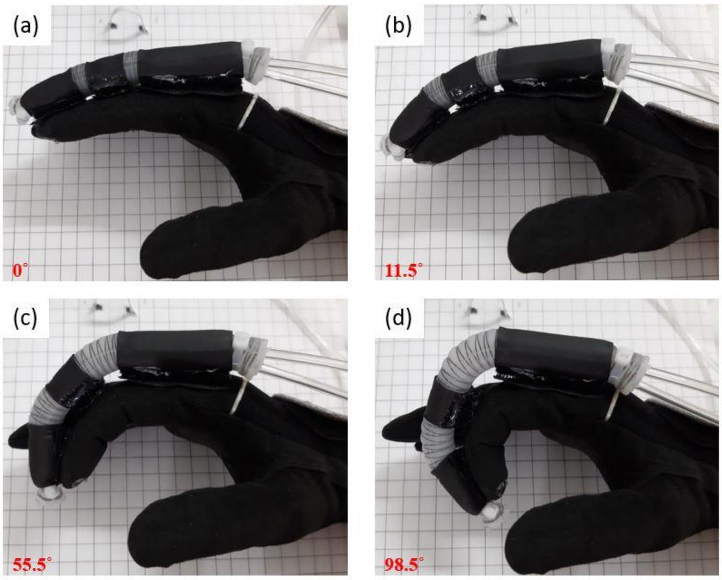


Fig. 10 - (a) 0 kPa; (b) 30 kPa; (c) 60 kPa; (d) 90 kPa

As shown in Fig. 10, the bending angle of finger increased as the input air pressure increased. At 90 kPa, a bending angle of 98.5˚ was achieved, which was lower than the expected bending angle of finger (161˚). Future improvement on modified bidirectional bending soft actuator is needed to improve the bending angle of finger rehabilitation glove. The limitation of the developed bidirectional bending soft actuator is the extension in length occurred during the pressurisation of the actuator which results in the non-linear bending angle produced by the actuator. Besides, the developed finger rehabilitation glove is limited to performing flexion motion only since the actuator did not cover the MCP joint.

5. Conclusion

As a conclusion, the bidirectional bending fibre-reinforced soft actuator is successfully fabricated using 3-D printed mould and Eco-Flex 00-50. The fabricated bidirectional bending soft actuator consists of two air chamber which are pressurised alternately to produce bending motion. Due to the difference in thickness of outer wall and inner wall, the bidirectional bending soft actuator is able to produce bending motion whereby the bending direction was towards thicker wall. The bidirectional bending soft actuator achieves bending angle of 211.5˚ and 269.5˚ for Portion A and Portion B at 70 kPa input air pressure, which are greater than required for bending angle of human finger which was 161˚.

To construct finger rehabilitation glove, the fabricated bidirectional bending soft actuator is modified by adding electrical shrinking tubes onto non-joints regions. The addition of electrical shrinking tubes allows only the joints region to bend which produce bending motion that mimics the bending of human finger during flexion. The modified bidirectional bending soft actuator is used to construct finger rehabilitation glove. A bending angle of 98.5˚ is achieved by the finger rehabilitation glove at 90 kPa during flexion motion. The limitations of this finger rehabilitation glove design are the lack of MCP joint on the modified bidirectional soft actuator which hinder the finger extension motion and the non-linear characteristic caused by the extension in total length of the actuator during pressurisation. Despite the inability to perform extension by pressurising glove, passive extension is achieved by depressurising the actuated portion of modified bidirectional bending soft actuator on the glove.

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