The Wearable Foot Rehabilitation Soft Robot

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***Abstract*— In this paper, a soft robot for foot rehabilitation is proposed. The presented robot is comfortable to wear, and it is designed to be suitable for a wide range of adult foot sizes. It is easy to use either by a physiotherapist or by the patient due to the softness, its lightweight, and a wide range of included programs. Furthermore, the system is suitable for foot exercises. The soft robot is actuated by two contraction pneumatic artificial muscles (PAM) which are controlled by the bang-bang control system. The robot has been tested and validated, and it shows high performance for the rehabilitation process and smooth operation due to the softness of its material and the actuation behaviour.**

Keywords— Foot; Rehabilitation; Soft Robots; Injuries; wearable system.

I. INTRODUCTION

Numerous types of foot and ankle problems happen because of wear and tear, injuries during walking or running, and medical problems or diseases [1][2]. Stroke is considered as the third cause of death [3] and often causes various kinds of disabilities if the patient survives. Most medical problems affect the lower limbs. The difficulties of foot movements and gait issues need physiotherapy treatments by a specialist either at clinics or at the patient's home in some cases [4].

In the last decade, robots have increasingly been used to assist physiotherapists at the clinic [5]. Among these robots, treadmill training is usually used by specialists to improve mobility [6][7]. Several commercial treadmill robots exist in the market including the Lokomat [8], the LokoHelp [9], and the ReoAmbulator [5]. The rehabilitation robots are used to restore the gait patterns [10][11].

Factors such as rigidity, heavy weight, cost, and complexity limit the home utilization of these robotic systems. Furthermore, most of these machines were not developed for home use [2]. Alternatively, the soft robotic system shows a higher force-to-weight ratio, is lower cost, easier to design and implement, friendly to the environment, and safe for individuals [12] [13].

Recently, the pneumatic artificial muscle (PAM) has been used in numerous robotic systems instead of the traditional hydraulic and electrical actuators. The main reasons for that are the simplicity to design and fabricate the PAM, low power consumption, ease of wear, and lower workspace requirement [14] [15] [16].

The main disadvantage of the PAM is the high nonlinearity behaviour, which increases the difficulty to control such types of systems. The contraction and the extension soft muscles are the two early constructed types of PAM, and they provide high tensile and extension forces in comparison with their weight, several hundred newtons per several hundred grams, in most cases [17] [18].

Because of the high demand to utilise the PAM, researchers have developed several innovative actuators, such as the bending actuators, which provide a bending behaviour at actuation [19] [20] [21], and the circular PAM [22] that offers diameter shrinking.

This paper presents the design and fabrication of the foot rehabilitation soft robot using two identical contractions PAM which has been tested to validate its behaviour.

II. FOOT ANATOMY

While the presented robot works on the human foot, the anatomy of the foot and ankle need to describe to understand the main behaviour of the presented device.

A. *Foot and ankle anatomy*

Foot and ankle show complex anatomy and structure due to their function. They provide the body stability during standing and walking, and transfer the forces between the lower limb and the ground [23]. The number of bones in both of them is twenty-six and they perform together with long bones of lower limb thirty-three joints [24]. Fig. 1 shows the human foot and ankle.

Fig. 1. Foot and ankle anatomy [25].

Figure 1 illustrates the leg, ankle, and foot muscles and tendons. After an injury, one or more of these muscles and tendons might be affected. On the other hand, the nerve system also can be suffering after brain problems of strokes. The human ankle consists of three joints: talo-crural (true ankle joint) includes the tibia, fibula, and talus. The main responsibility of this joint is the flexion-extension of the foot. The joint that responsible for the side rotation of the human foot is called the sub-talar and it is shaped by the talus and the calcaneus. The third joint is called syndesmosis and it is laid between the fibula and tibia.

III. SOFT PNEUMATIC ACTUATOR

In the last decades, the pneumatic artificial muscles have been used in numerous applications of robotic systems. Due to its softness, lightweight, and high performance, the PAM is used in medical robots.

A. The contraction of pneumatic artificial muscle

The contraction PAM shows nonlinear contraction behaviour as a function of the applied air pressure [12] [26]. The basic manufacturing strategy of the contraction type is by covering the inner rubber tube with a braided mesh and close both ends with a small inlet from one side. Fig 2. Illustrates the construction of the contractor actuator. The length of the braided mesh is similar to the length of the rubber tube and it represents the length of the PAM too.

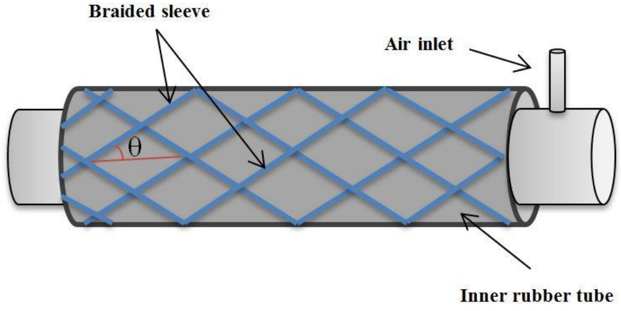


Fig. 2. the construction of the contraction pneumatic artificial muscle

B. The tensile force of the PMA

The contraction PAM develops a tensile force depends on the dimensions of the actuator, the stiffness of the inner tube, the contraction ratio, and the braided angle θ. In "(1)" gives the tensile force in terms of these parameters.

$$\boldsymbol{F = \pi r_0^2\,(P - 0.45)[\alpha(1 - q\varepsilon)^2 - \beta]} \tag{1}$$

$$\boldsymbol{q(P) = 1 + c_1\, e^{-c_2 P}} \tag{2}$$

$$\boldsymbol{\alpha = \frac{3}{tan^2\theta_0}} \tag{3}$$

And

$$\boldsymbol{\beta = \frac{1}{sin^2\theta_0}} \tag{4}$$

Where F is the tensile force, r_0 is the initial radius of the PAM, P is the applied air pressure, θ_0 is the initial braided angle, and c_1, c_2 are positive constants. From "(2)" , the correction factor becomes "1" at the maximum air pressure, where the actuator shape is cylindrical [27].

The actuator dimensions can be any form according to the application, however, typically the length of the PAM starts from several centimetres to one meter, and in most cases between 20 cm and 50 cm [28] [29]. The normal contraction ratio reaches optimally to 30%.

IV. ANKLE REHABILITATION ROBOT

This section proposes a rehabilitation robot for the human foot. For safety and lightweight robot, soft material has been used for the presented robot and the device is actuated by two PAMs.

A. Fabrication of the rehabilitation robot

Fig 3. shows the materials that were used initially to design and to actuate the robot.

Fig. 3. the material and the construction of the proposed rehabilitation robot.

Three stainless steel rings have been used to guide the tendons, the front, and the middle rings for the front tendon, and the rear ring for the back tendon. Two adjustable belts have been sewed to the slipper from the bottom and to the upper fabric from the top to fastening and adjusting the robot. The actuation is accomplished by two 20 cm contraction PAM via two separate tendons. Except the rings and the actuators caps, the proposed robot is fabricated using soft materials. The weight of the robot is about 500 g and the construction cost is about $ 10.

B. Operating the rehabilitation robot

The fabricated robot is shown in Fig 3. It produces two directions of motion, one by pulling the foot from the toes by the front PAM, and the other pulling down the toes by the rear actuator. The two actuators are working alternately during operation. The movements are about 4 cm in each direction. This contraction is about 20% of the initial length of each actuator. Fig 4. Illustrates the behaviour of the robot.

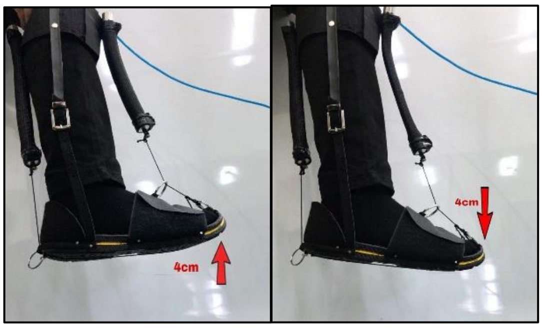


Fig. 4. the motion behaviour of the foot rehabilitation robot.

The operation (the contraction) can be controlled manually or automatically. In this paper, Arduino mega 2560 is used to control the pressure of the actuators by the bang-bang controller for pressure values of 100, 200, 300, 400, and 500 kPa. These values represent five different rehabilitation programmes. The pressure is applied via 3/3 Matrix solenoid valve and it is measured by a pressure sensor to send the feedback value. The maximum contraction occurs at 500 kPa which is considered to be the maximum for safe working conditions. Fig. 5 shows the block diagram for the controller system.

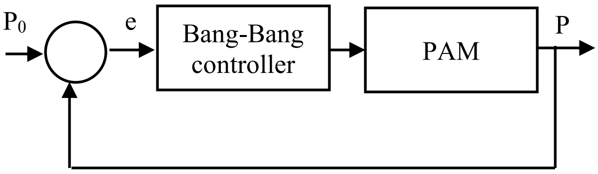
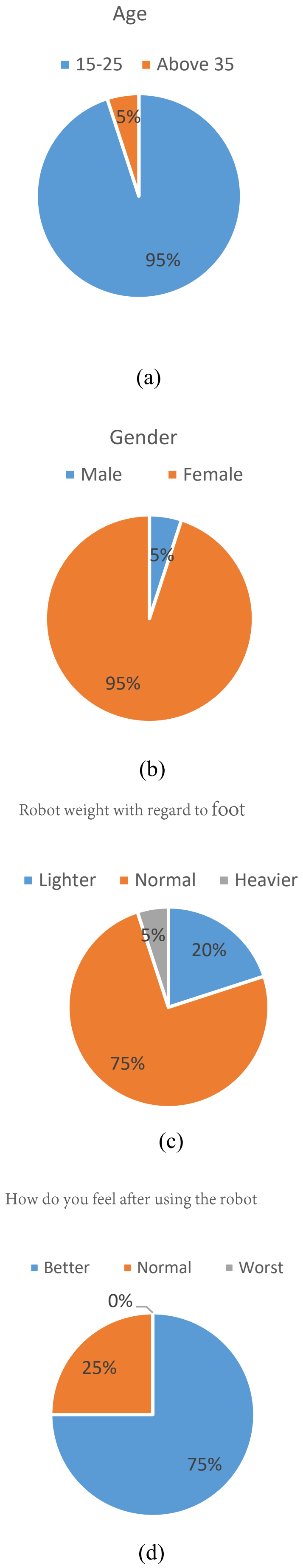


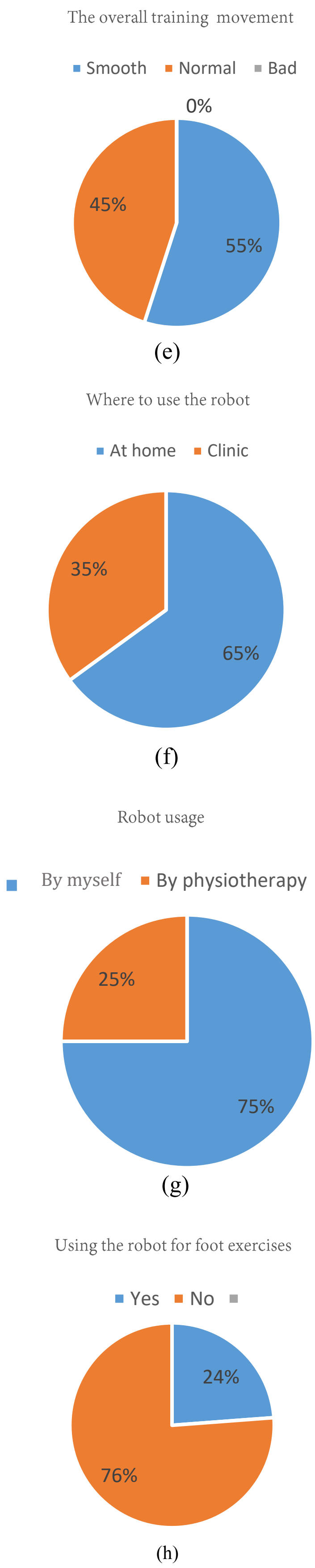
Fig. 5. The Bang-Bang control system.

P_0, e, and P represent the required air pressure, error, and the output pressure, respectively. For each actuator, two controllers have been used, one for the filling process and one for the venting operation.

V. TESTING THE PRESENTED ROBOT

The presented device has been tested by a group of forty people. After the trials, the volunteers have answered several questions and the results are illustrated in Fig 6.





(e)

(f)

(g)

(h)

Fig. 6. The test results for the presented robot.

The results in Fig 6. a-g, show that the volunteers recommend using the device for its lightweight, smooth movements, and ease of use even by themselves and without the need for the physiotherapist. On the other hand, Fig 6.h illustrates that the volunteers did not prefer to use the robot for just exercise for a healthy foot. 76 % of participated volunteers argue that they will not use the robot for foot exercise if they did not suffer from any injury.

The hysteresis in the PAM is considered as a disadvantage for such types of actuators. This behaviour provides an advantage for the presented rehabilitation robot because it avoids sudden movements. Fig. 6-e illustrates that the participates are voted for smooth and normal operation by 100 %.

VI. CONCLUSION

The foot and ankle, like any other part of the human body, need exercises after injury, accident or strokes. The rehabilitation can be done by physiotherapists or by devices, or both. This paper presents a soft, lightweight, cheap, easy-to-use foot rehabilitation robot that can be used by patients without the need for help by specialists. Since the presented robot is actuated by pneumatic artificial muscle, it is considered to be safe for human-robot interaction and friendly to the environment. The robot can be manufactured and used either in clinics or at homes. As A future work, more actuators can be added to the proposed robot to develop all possible movements of the human foot.

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