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EXPERIMENTAL CHARACTERIZATION OF A FLEXIBLE JOINT WITH CONTROLLED STIFFNESS FOR THE DEVELOPMENT OF A REHABILITATION PASSIVE HAND

MOHAMMAD JABARI^[0000-0002-7574-6603], GIOVANNI COLUCCI^[0000-0002-2996-9013],
LUIGI TAGLIAVINI^[0000-0001-8925-0417], LORENZO BAGLIERI^[0000-0002-5022-5326],
CARMEN VISCONTE^[0000-0003-3500-9411]

*Department of Mechanical and Aerospace Engineering (DIMEAS), Politecnico di Torino, Corso
Duca degli Abruzzi, 24, Torino, 10129, Italy, <https://www.polito.it/>*

{mohammad.jabari, giovanni_colucci, luigi.tagliavini, lorenzo.baglieri,
carmen.visconte}@polito.it

ABSTRACT

Passive hand rehabilitation is an effective technique for improving hand range of motion, flexibility, and strength after physical injuries, surgery, or stroke. There are several methods and materials used for passive rehabilitation, with deformable systems being a promising option due to their adaptability and safety. This paper presents a flexible joint called Flexojoint. A compliant rotational joint provided by an embedded inflatable chamber has been specifically designed for active hand rehabilitation therapy. The device is fabricated in thermoplastic elastomer through additive manufacturing techniques. Experimental results show that the Flexojoint can generate various levels of resistive torque during finger rehabilitation exercises.

KEY WORDS: Flexible Joint, Passive Hand Rehabilitation, Joint Stiffness, Inflatable Chamber

1. INTRODUCTION

A person's hands are used for various dexterous manipulations in activities of daily living (ADL). However, more and more individuals are losing the ability to move their hands due to physical injuries, strokes, or other causes. As a result, a hand functional disability can significantly affect one's quality of life. Physical therapy programs can effectively treat movement impairments and restore hand function by involving repetitive task practice (RTP), such as flexing and extending the fingers, in order to regain motor function [1].

While there are different ways to categorize rehabilitation therapy, one common framework is to distinguish between passive, active, and active-assisted therapies. Passive therapy refers to treatments in which the patient is not actively participating in the movement or exercise. Instead, the therapist or a device performs the movement or exercise for the patient. Active therapy, on the other hand, involves the patient actively engaging in exercises or movements to improve their strength, range of motion, or other aspects of their function. Active-assisted therapy is a combination of both passive and active therapies. In this type of therapy, the patient participates in the movement or exercise, but the therapist or device provides assistance as needed. Rehabilitation requires all three phases to return the patient to proper motor function [2].

Rehabilitation therapy program with tradition method is time-consuming and costly, often leading to difficulties with patient compliance, making them inefficient for patients and health care



providers. Due to traditional rehabilitation's drawbacks, robot-assisted rehabilitation has become an increasingly popular method of motivating patients to train at home without clinical supervision [3], [4].

In the passive therapy approach, in order to provide force feedback to the user's fingers or hands, numerous force feedback gloves have been developed. The most common actuators are DC servo motors, linear actuators, and rigid linkages [5–8]. Although rigid mechanisms can exert high forces to accomplish challenging rehabilitation tasks, they can also be bulky and heavy making them difficult for patients to carry. In addition, they are unsuitable to wear for a long duration, and there is a potential risk of injuring fingers in a system failure. Moreover, parasitic force is a common and challenging problem for rigid mechanisms in rehabilitation, leading to pain or at least discomfort [9]. In order to overcome the limitations of hand rehabilitation with rigid mechanisms, alternative approaches, such as cable-driven mechanisms, and soft pneumatic actuators have been developed. A cable-driven rehabilitation system involves electrical motors located away from the fingers' palms and connected to cables which increase wearability due to their lightweight [10], [11]. Furthermore, this mechanism provides independent joint control as well as levels of torque and velocity necessary to achieve a wider range of motion (ROM) [12]. Tendon-driven gloves, however, exhibit unintended behavior changes due to their stretchable structure which can generate an unsafe behavior when the tendon components directly contact users' fingers [13].

In the active therapy approach, therapists encourage the patient to actively participate in their own recovery. This method helps improve hand strength, range of motion, and coordination. In the last sessions of hand rehabilitation active therapy, patients have to do some resistive training on their fingers to strengthen their finger muscles rather than reintroduce proper movement and placement [14]. There are numerous methods and devices that can be used for active therapy, including constraint-induced movement therapy (CIMT) [15], hand therapy balls and putty [16], and robotic devices [17]. A limited numbers of methods mentioned above can provide resistance training during active therapy. For instance, SCRIPT and Saebo orthoses use spring cords to provide resistance training during hand rehabilitation [18], [19].

This study aims to develop a passive flexible joint with variable stiffness for active therapy during hand rehabilitation. The device consists of an inflatable flexible joint fabricated by fused deposition modeling (FDM) on the palm of the joint. It is made of inexpensive TPU 95A - a thermoplastic elastomer - that can be quickly custom-designed by a 3D printer to fit the anatomy of individual users. This paper presents the design and initial evaluation of a flexible joint for the proximal interphalangeal joint of the index finger in preparation for the development of a more complex hand rehabilitation device as a long-term goal.

This paper is organized as follows. Section 2 examines finger characteristics to determine the Flexojoint requirements, as well as a general overview of the prospective goals. Section 3 describes the fabrication process for the first prototype Flexojoint using the FDM technique. In addition, Section 4 presents a preliminary experimental characterization for measuring the elastic reaction torque of the Flexojoint under flexure due to chamber pressurization. This chapter is followed by a conclusion.

2. DESIGN SPECIFICATIONS

Basic specifications for passive joint rehabilitation may vary depending on individuals' circumstances, but include some general specifications, such as material, size and shape, and range of motion. In order to ensure effective active therapy, the devices should be made of reliable materials that are not dangerous in medical applications. The second feature is that devices for active therapy should fit comfortably and securely on the hand and be customized to the individual's hand

size and shape. In addition, they should provide varying levels of stiffness, depending on the severity of the injury or condition. In order to design a passive joint according to the basic design specifications, it is critical to have a comprehensive understanding of the ROM and size of the fingers.

In the human body, the hand is one of the most complex anatomical structures, containing multiple bones, joints, and muscles that allow it to perform a wide variety of dexterous movements with multiple degrees of freedom. In the human thumb, there is an interphalangeal (IP) joint and a metacarpophalangeal (MCP) joint, while the other fingers have distal interphalangeal joint (DIP), proximal interphalangeal joint (PIP) and metacarpophalangeal joint (MCP). The natural size and ROM of the PIP joint in the index finger were compiled by the Japanese Rehabilitation Society and are presented in Table 1 [20].

Table 1 The natural size and ROM of the PIP joint in the index finger

Parameters	Normal ROM (°) and finger size (mm)
ROM	$0^{\circ} \sim 80^{\circ}$
Length	$35\text{ mm} \sim 60\text{ mm}$
Width	$14.69\text{ mm} \sim 18.89\text{ mm}$
Height	$11.91\text{ mm} \sim 14.30\text{ mm}$

2.1 General description of the device

Fig. 1 shows an overview of the developed device. The device consists of two rigid parts that can be attached to finger phalanges using Velcro straps, with a deformable and inflatable chamber between, which is termed a Flexojoint. Two Flexojoint can be seen in Fig.1 at the MCP and DIP joints. By connecting a joint inflatable chamber with an auxiliary chamber via pipes, the joint inflatable chamber can be put under pressure and then isolated. When the phalanges flex, the deformable chamber is squeezed, causing a reduction in volume followed by an increase in pressure. By varying the auxiliary volume and initial pressure, on the one hand, one can modify the resistance the user feels during the active therapy. As an alternative, it is possible to monitor training activity using pressure sensors. In Fig. 1, the rotational angle of each rigid part relative to the extension state is represented by (θ_1, θ_2) .

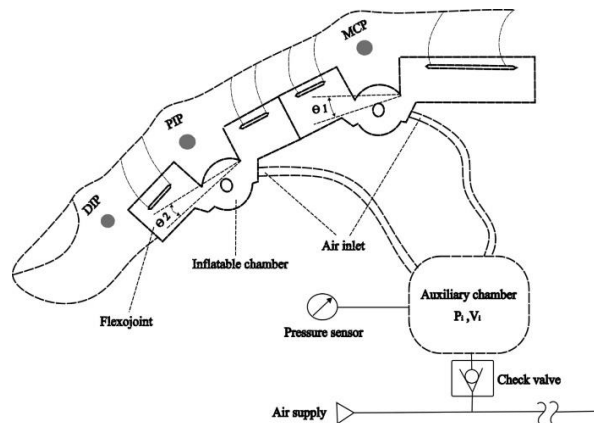


Fig.1 The overview of the Flexojoint for the entire finger

2.2 Concept design of the Flexojoint

In the first step, based on the biological structure of the human hand, a single Flexojoint was designed for the PIP joint. The design parameters can be seen in Table 2. Fig 2 shows in detail the device structure and its main dimensions. Two ribs act as a virtual joint in the Flexojoint. In addition, an attempt was made to place the inflatable chamber located between the two ribs as close as possible (2.5 mm) to the PIP joint to avoid parasitic force effects on the joint itself. The Velcro strap incorporated into the Flexojoint allows the center of the chamber to adapt to finger joints of different shapes and sizes. This feature fulfills the second basic design specification.

Table 2 Key parameters of designing of the Flexojoint

Parameters of Size and ROM for PIP joint	Required ROM (°) and finger size (mm)
ROM	0° ~ 60°
Length	50 mm
Width	20 mm
Height	13 mm
Radius of chamber	4 mm
Thickness of chamber shell	0.8 mm
The distance from the chamber to the hand joint	2.5 mm

The chamber design in the Flexojoint must have a suitable thickness and stiffness to reduce as much as possible the structural stiffness, and to be at the same time insulated against air leakage. The thickness of the whole chamber and caps is about 0.8mm allowing them to fulfill the previously specified requirement.

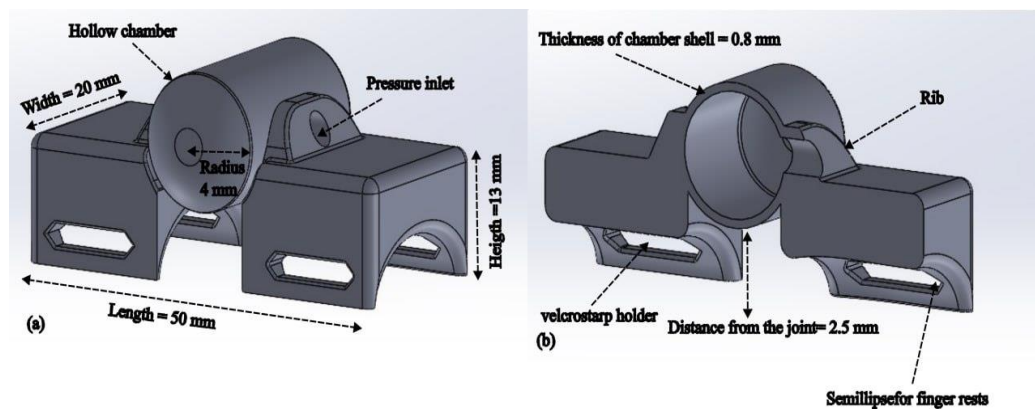


Fig.2 The CAD model of the Flexojoint. (a), (b) Side and cross-section view of the Flexojoint with the design parameters

3. PROTOTYPING

Additive manufacturing and demolding processing methods are highly recommended for producing air pneumatic soft devices. Thanks to the UltiMaker S5 3D printer with a soft material TPU 95A, the flexible joint is created with a chamber, two matching caps, two ribs, and a rigid body that fits around the finger joint. The printing parameters for making the Flexojoint were adjusted as shown in Table 3.

Table 3 Parameters setting for UltiMaker S5

Parameter	Value
Extruding nozzle diameter	0.4 mm
Infill density	100 %
Build plate temperature	60°C
Material flow	106 %

The FDM technique is used for making the chamber. In the first samples of the Flexojoint, the chamber had an air leak and was somewhat stiff. After testing and fabricating various chambers with different dimensions and different materials, the chamber body of the last model had no air leaks and was flexible enough to permit the use of the pneumatic circuit to regulate the joint stiffness. The Flexojoint prototype is shown in Fig 3.

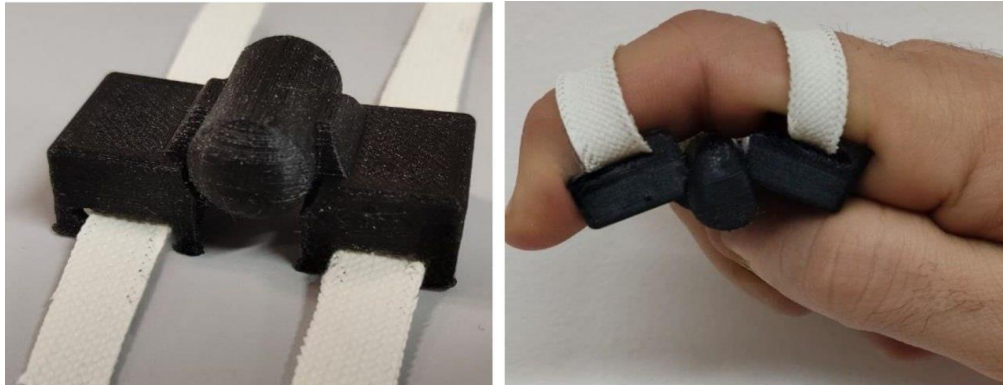


Fig.3 The prototype of the Flexojoint made with the 3D printer

4. EXPERIMENTAL CHARACTERISATION

The elastic reaction torque of the compliant joint is one of the most critical indicators for measuring the function of the rehabilitation device. Moreover, it is important to find the relationship between antagonistic torque and the flexible joint's characteristic parameters (pressure and volume). To validate the proposed flexible joint structure, the test platform is designed in two parts. The first part is a flat aluminum plate that is graduated from 0° to 90° indicating the degree of rotation of the virtual joint. The other part is a movable plate made by the FDM technique, on which the dynamometer is mounted Fig.4. One side of the Flexojoint is fixed to the aluminum plate, while the other side keeps in touch with the dynamometer.

In each angular configuration, the rotational force transmitted by the virtual joint at a certain level between 0 kPa to 120 kPa (gauge pressure) is measured and recorded. Once the force F is measured, the relative elastic torque T can be easily calculated. Fig.5 illustrates the torsional stiffness of the Flexojoint in different angular configurations.

Tests were repeated by inflating the joint chamber and setting different values of pressure, to evaluate the increase in torsional stiffness due to chamber pressurization.



Fig.4 The overview of the experimental setup

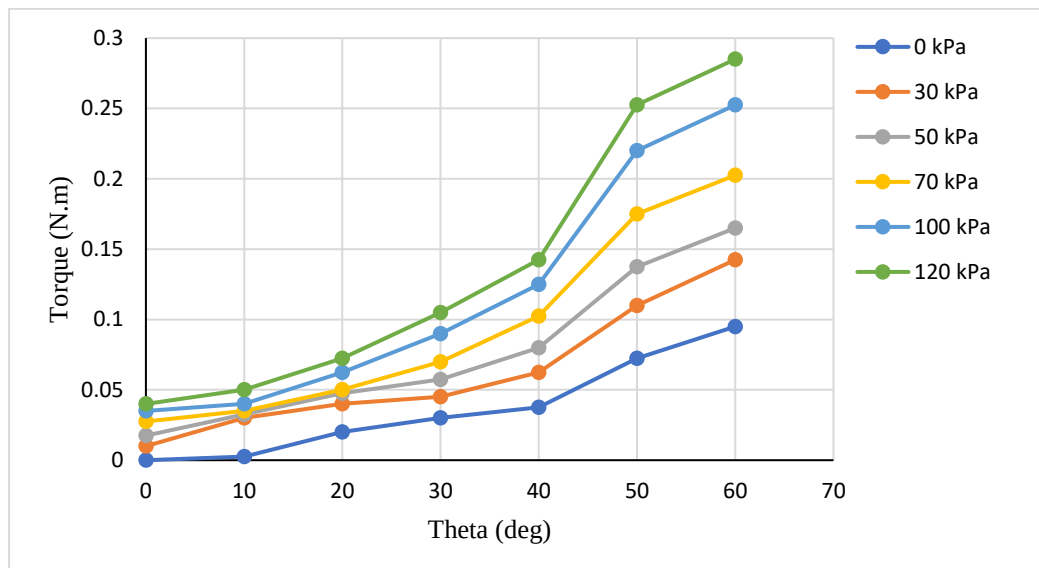


Fig.5 Various torques provided by the Flexojoint at different pressures during imposed various angles

5. CONCLUSION

In this study, a novel compliant joint called Flexojoint for the PIP joint is investigated. The goal is to develop a passive flexible joint that would be simple, light, and close to the joint's finger as much as possible which can be used for active therapy in hand rehabilitation. To design an entire glove with compliant joints for hand rehabilitation, a preliminary model of the flexible joint is designed and fabricated using the FDM process. The structural stiffness of the Flexojoint and its variation as an effect of inflatable chamber pressurization were measured experimentally.

In the case of finger joints, certain problems remain to be optimized or solved. First, using different materials with better flexibility affects the stiffness of the Flexojoint. To optimize the Flexojoint, it may be useful to use a thermoplastic elastomer with higher flexibility to achieve greater flexure and reduce the structural stiffness of the Flexojoint. The broader bend helps the Flexojoint to better adapt to the ROM of the fingers. Second, an optimization of the pneumatic circuit of the flexible joint is needed to define the auxiliary chamber volume and the level of pressure needed to obtain a torsional stiffness varying in a range useful for strengthening the muscle.

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