Development of a Bowden-cable-based Exoskeleton Suit for Assisting Passive Stretching Exercises in Patients with Frozen Shoulder

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Abstract
This paper presents the design of a Bowden-cable-based exoskeleton suit specifically developed for assisting with passive stretching exercises for patients with frozen shoulders. Passive stretching exercises are essential in the treatment of frozen shoulders, as they require a higher intensity than what patients can achieve through self-stretching alone. Consequently, the assistance of a therapist is necessary. However, current suits designed for this purpose have drawbacks. Some are too bulky, making it difficult for therapists to interact with patients, while others are too compact to adequately support passive stretching exercises. With this in mind, the objective of this paper is to explore the requirements that a suit must meet to effectively assist patients with frozen shoulder during passive stretching exercises. Based on our findings, we propose an exoskeleton suit that is easy to wear, utilizes a Bowden cable for reduced size, and incorporates a ratchet mechanism to support therapists in the most fatiguing movements, such as forward flexion and abduction. Furthermore, we conducted wearability and functional evaluations to validate the fabricated exoskeleton suit. The results confirmed that the proposed suit is comfortable to wear and effectively assists both the wearer and the therapist in performing forward flexion and abduction movements during stretching exercises.

Keywords Exoskeleton suit · Frozen shoulder · Shoulder rehabilitation · Bowden-cable · Rehabilitation robotics · Therapist assist

1 Introduction

Frozen shoulder is a common disease characterized by inflammation and stiffening in the synovial bursa surrounding the shoulder joint, affecting approximately 2-5% of the global population [1-3]. While it primarily afflicted individuals in their 40 and 50s historically, it has increasingly been diagnosed in younger adults, including those in their 20 and 30s, largely due to excessive use of smartphones and computers, stress, and lack of exercise. The incidence of this condition continues to rise annually among these younger demographics.

A frozen shoulder typically shows a pattern where inflammation subsides, and pain decreases over time. However, this period can be very lengthy, lasting from a minimum of one year to three years. If left untreated, even though the symptoms may improve, the Range of Motion (ROM) in the shoulder joint may not fully recover to normal. Therefore, treatment should be initiated in the early stages when some degree of self-exercise is still possible. Treatment for frozen shoulder is broadly categorized into surgical and conservative approaches. Conservative treatment includes pharmacotherapy, injections, and physical therapy (such as passive stretching, manual therapy, and extracorporeal shock wave therapy) [4]. The primary treatment for frozen shoulder is initially conservative treatment. If symptoms continue or worsen despite 3 to 6 months of conservative treatment, surgical intervention is then considered [5]. In the treatment of frozen shoulder, the most crucial method is passive stretching exercises [6]. Passive stretching exercises are a key component in both surgical and conservative treatments for enhancing ROM and muscle strength recovery in frozen shoulder. They are especially effective in reducing pain and improving shoulder ROM [7,8]. In patients with frozen shoulder, the ROM achievable through active exercise is limited. Therefore, the assistance of a physical therapist is essential to restore normal shoulder ROM. To increase the shoulder ROM for...
patients with frozen shoulder, the physical therapist must gradually increase the range by lifting the patient’s arm. At this time, the physical therapist must support and maintain the weight of the patient’s arm at the boundary of the patient’s active exercise ROM. This requirement can lead to fatigue from the therapist’s perspective, imposing limitations on providing proper stretching exercise assistance [9]. Therefore, to address these issues, recent research has been actively conducting the development of exoskeleton suits designed to help patients perform stretching exercises independently or to assist physical therapists [10-14]. Exoskeleton suits for shoulder rehabilitation can be broadly classified into motor, wire, and pneumatic types based on their actuation mechanisms. In motor-based research, S Buccelli et al. [10] proposed a motor-driven 5-DOF shoulder rehabilitation suit attached to a mobile unit. This setup allows for mobility and prevents the direct transfer of the suit’s weight to the patient. However, the motors are attached to all joints, making the suit very bulky, which constrains the patient’s natural movements due to its attachment to the mobile unit. Additionally, the large size of the suit makes it difficult to wear and limits the therapist to interacting only with the patient from the front. B Kim et al. [11] proposed an adjustable exoskeleton suit composed of parallelogram-shaped links designed to assist all degrees of freedom of the shoulder and adaptable to the user’s body size. However, designed as an active joint system with motors attached to every joint, the suit is notably bulky and heavy. Due to its complex structure, the suit is affixed to a chair, complicating independent wearing by patients and limiting its use to sitting positions, preventing any interaction with the therapist. In the case of pneumatic-based suits, T Proietti et al. [12] proposed a shoulder rehab suit using pneumatic-based soft robotics. As a soft wearable robot, it is adjustable to fit the user and is relatively lighter than motor-based suits, with the advantage of being able to perform a variety of motions through pneumatic control. However, due to the non-linear nature of pneumatic control and the need for an external controller and fluidic supply to generate pneumatic power, there are disadvantages, including reduced durability. In a study by C O’Neill et al. [13], a pneumatic upper extremity rehabilitation suit based on soft robotics was proposed. This wearable vest, designed for easy attachment and detachment, is aimed to reduce therapist fatigue. However, the focus on reducing therapist fatigue resulted in a lack of independent degrees of freedom at the shoulder, preventing the execution of desired movements without human intervention. Additionally, the inherent characteristics of pneumatics did not allow for linear control. Lastly, in the case of wire-based suits, JL Samper-Escudero et al. [14] developed a lightweight, easy-to-wear soft wearable suit based on Bowden cables that can be adjusted to fit the patient’s body. However, this suit lacks independent axes of rotation, requiring patients to manually rotate their arms in the desired lifting direction, and the axes are not intuitive for therapists assisting with exercises. In this way, existing exoskeleton suits for shoulder rehabilitation have limitations such as being bulky and heavy, which reduces mobility, makes wearing them difficult, and restricts interaction with therapists. Conversely, suits that are smaller and lighter often suffer from reduced durability and accuracy in stretching exercises and provide insufficient support for therapists. Therefore, this study proposes a Bowden cable-based suit for shoulder passive stretching exercises that is easy to wear and can assist therapists. The proposed suit uses a composite material called Onyx to achieve lightness and high strength. It features a ratchet gear at the shoulder rotation joint that can secure the patient’s arm, thereby reducing therapist fatigue. Additionally, the actual fabricated suit was tested for wearability and functionality across various genders and age groups, and the results were presented.

2 Shoulder Passive Stretching Exercises Assist Suit Requirements

Motion of the shoulder joint includes flexion and extension, abduction and adduction, as well as external rotation and internal rotation. The active range of motion (ROM) of a normal shoulder is detailed in Table 1. A diagnosis of frozen shoulder is made when the shoulder’s range of motion decreases by more than 25% from this normal range [15].

Passive stretching exercises for treating frozen shoulder involve exercises aimed at restoring shoulder range of motion (ROM) in all directions, as depicted in Fig. 1. These exercises, assisted by a physical therapist, are performed to the point of slight stiffness and held for 10 to 15 seconds. It is recommended to repeat these holds for approximately 10 seconds at least three times a day [16].

Physical therapists assist patients in performing passive stretching exercises with the goal of gradually increasing the range of motion. The exercises are performed three times a day [16].

Table 1 Normal shoulder active ROM

<table>
<thead>
<tr>
<th>Exercise</th>
<th>ROM (°)</th>
<th>Exercise</th>
<th>ROM (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>170-180</td>
<td>Extension</td>
<td>60</td>
</tr>
<tr>
<td>Abduction</td>
<td>170-180</td>
<td>Adduction</td>
<td>45-60</td>
</tr>
<tr>
<td>External rotation</td>
<td>60</td>
<td>Internal rotation</td>
<td>70</td>
</tr>
</tbody>
</table>

Fig. 1 Stretching exercises protocol for frozen shoulder rehabilitation
stretching exercises by correcting their posture and helping them achieve and maintain the maximum range of motion for the shoulder. This is particularly important during exercises involving forward flexion and abduction, where the therapist adjusts the patient’s shoulder to prevent it from rising. This responsibility places a significant burden on the therapist, who must support the weight of the patient’s arm while applying pressure. Accordingly, based on the previously discussed points, an exoskeleton suit designed to help therapists and allow patients to engage in shoulder passive stretching exercises needs to fulfill the following conditions.

1) ROM: The suit’s shoulder range of motion (ROM) must be capable of achieving the normal ROM required for the specific stretching exercises intended.

2) Lightweight: The suit must be lightweight and easy to wear, designed to conform to the patient’s body without causing any burden.

3) Small Volume: The suit should be non-bulky to avoid hindering the therapist’s interaction with the patient.

4) Therapist Assistance: The therapist must be able to assist the patient in such a way that the patient does not bear the full weight of their arm.

This study meets these requirements and introduces a Bowden cable-based wearable suit designed to assist with shoulder passive stretching exercises, specifically targeting forward flexion and abduction—movements that are most burdensome for therapists.

### 3 Shoulder Passive Stretching Exercises Assist Suit Design

#### 3.1 Shoulder Joint Mechanism

The glenohumeral joint (GH joint), responsible for shoulder rotation, is anatomically characterized within the human body’s planes. It supports flexion and extension along the frontal axis, abduction and adduction along the sagittal axis, and external and internal rotation along the longitudinal axis, as depicted in Fig. 2. In this study, we developed a wearable suit designed to assist with passive shoulder stretching exercises, specifically targeting forward flexion and abduction. Accordingly, only the frontal axis, where flexion and extension occur, and the sagittal axis, where abduction and adduction take place, are considered, resulting in a total of 2 degrees of freedom (2-DOF).

Fig. 3 illustrates the 2-DOF shoulder joint mechanism proposed in this study. The position of the glenohumeral (GH) joint, which facilitates shoulder rotation, varies along the frontal axis due to individual differences in the size of the shoulder skeleton and muscles. Given that the GH joint is a spherical joint, the centers of the two revolute joints in the suit must be precisely aligned with the center of the GH joint, which varies among individuals, to achieve the targeted motion. To ensure precise alignment between the variable positions of the glenohumeral (GH) joint and the two revolute joints on the suit, the suit consists of two separate links that connect the joint along the sagittal axis to the joint along the frontal axis. Furthermore, the suit utilizes linear motion (LM) guides and LM guide stoppers, enabling adjustments to be made according to the specific position of each wearer’s GH joint.

#### 3.2 Therapist Assistance Mechanism

Typically, exercises prescribed for the treatment of frozen shoulder are performed with the therapist positioned laterally and posteriorly relative to the patient. In particular, for the flexion and abduction movements primarily addressed in this study, it is crucial to minimize the elevation of the patient’s
shoulder, necessitating that the therapist apply downward pressure with one hand while simultaneously assisting with the flexion and abduction movements with the other hand. Therefore, the optimal position for a therapist assisting with exercises is behind the patient, enabling effective interaction during the treatment. In this study, we accounted for these considerations and designed the suit to enable both flexion and abduction movements via a handle and knob attached to the back, as illustrated in Fig. 4.

The rotation lever, mounted on the back of the suit, controls movement along the sagittal and frontal axis joints and incorporates a ratchet gear to restrict motion to only the abduction and flexion directions, as illustrated in Fig. 5. This gear, consisting of 46 teeth, enables the lever to achieve a resolution of approximately 8 degrees per click. This movement causes significant fatigue to therapists, as abduction and flexion movements require supporting the weight of the arm and maintaining its position for 10 to 15 seconds. To reduce this fatigue, a ratchet gear is utilized to lower the arm to the desired angle and securely fix it in place, preventing any slippage. To perform extension and adduction, which are the opposite actions of flexion and abduction, respectively, use the frontal axis angle adjustment lever located at the top of the link shown in Fig. 5 and the sagittal axis angle adjustment lever located below it. By releasing the fixed pole through these levers, the ratchet gear can be rotated in the reverse direction, enabling the execution of adduction and extension movements.

3.3 Bowden Cable-based Power Transmission Mechanism

Abduction and adduction movements are directly facilitated by a joint in the sagittal axis connected to the back plate of the suit. However, for flexion and extension movements, power is transmitted via a rotation lever attached to the back plate to a joint on the side of the suit, oriented along the frontal axis. Typically, rehabilitation suits employ cable-driven methods to transmit power to locations distant from the power source. In exoskeleton suits for rehabilitation, power transmission mechanisms based on cables are classified into two types: general and Bowden cables. Additionally, these mechanisms are further categorized by their pulley system arrangement into either open-pulley or closed-loop pulley transmissions [17]. Lacking an external sheath reduces the volume of the cable and power loss due to decreased friction; however, they require a complex routing system to maintain constant tension as the joint moves [18]. To address this, our study utilizes a Bowden cable, which simplifies the mechanical design by reducing the need for a complicated pulley and wire arrangement. Open pulley transmissions, which only allow unidirectional force transmission, necessitate numerous pulleys and wires for bidirectional operation. Consequently, we adopted a closed-loop pulley transmission, which allows for bidirectional force transmission and overcomes the limitations of a single-wire system. Fig. 6 illustrates the Bowden cable-based power transmission mechanism developed for this study. The system, consisting of just a driving and a rotating part pulley, uses a pretension device at the front of the pulley to prevent sheath movement and maintain tension. Due to the characteristics of Bowden cables, a closed-loop pulley transmission with a single wire is unfeasible; therefore, we designed the transmission with two Bowden cables wound in opposite directions around each pulley to ensure smooth, bidirectional operation. For this pulley system, the ratio between the driving part pulley and the rotating part pulley is set at 1 : 2. This setup allows the
therapist to support and lift 4 kg, the average weight of an adult male or female arm, by 90 degrees, which is about half the required torque (13.7 N/m). Consequently, a torque of 6.85 N/m is necessary.

3.4 Design for Patient Convenience

The suit designed for frozen shoulder rehabilitation must be anchored to the back, where movement is typically limited, resulting in most wearable designs being configured to encompass the back and shoulders. In other words, since the weight of the suit is borne directly by the patient’s shoulders and back, a heavier suit increases the burden on the patient, potentially exerting a detrimental effect on the shoulders. Therefore, the suit must be lightweight yet highly durable, ensuring the patient experiences no discomfort while wearing it. To meet the design requirements in this study, we opted for onyx, a nylon material reinforced with microcarbon fibers, as depicted in Fig. 7. This material choice achieved a balance of high strength and lightweight, with the suit weighing approximately 1.9 kg. This is about 75% lighter compared to the traditional bowden-cable driven upper-limb exoskeleton suits, which weigh 7.7 kg [19]. In addition, to enhance wearability and comfort for patients, we utilized elastic polyurethane straps and buckles for the suit’s fixing straps, which directly contact the patient. We also incorporated memory foam on the back of the suit, which has the largest contact area with the human body. To minimize discomfort, cushions made of foam and suede were attached to these areas. At this time, we used high-friction suede fabric for the suit material to ensure it adhered closely to the wearer’s back. Consequently, the alignment of the suit’s rotation joint and the glenohumeral (GH) joint shifted due to the scapula’s upward and downward rotation during adduction and abduction motions. However, this design minimized the warping phenomenon to some extent, as the suit moved up and down in sync with the wearer’s back.

4 Experiments

In this study, the functionality and wearability of the manufactured suit were evaluated through practical use tests involving participants of diverse ages and genders, as depicted in Fig. 8.

In this study, evaluations focused on the wearer’s ease of putting on and taking off the suit, the comfort and fit of the suit, and any pain or discomfort during active and passive stretching exercises. Additionally, from the therapist’s perspective, the suit’s range of motion and the ease of using its mechanisms to assist with passive stretches were assessed. To assess usability, participants were asked to wear the suit unassisted, thus verifying their ability to independently put on and remove the suit. Subsequently, they engaged in active stretching exercises, as depicted in Fig. 8, to evaluate their capacity to exercise independently. Surveys were conducted to gather insights on the suit’s fit and any discomfort encountered. The data from these assessments were systematically quantified and are detailed in Table 2. Additionally, we collaborated directly with therapists to assess any discomfort and verify whether assistance was provided during the performance of passive stretching exercises.
The overall average score from the survey evaluation was approximately 7 points, suggesting that the suit was effective in facilitating passive stretching exercises. Specifically, male participants reported the pain due to the weight of the suit was almost negligible, with scores of 10 and 7, indicating that discomfort was largely absent. Regarding the ease of wearing and removing the suit, participants found it relatively straightforward, with scores of 8 and 6. Furthermore, participants experienced no significant discomfort during active and passive stretching exercises while wearing the suit, receiving scores of 7 and 6, respectively. It was also noted that the mechanism designed to assist with flexion and abduction movements provided adequate support for the arm. However, some patients reported experiencing pain in the area where the suit fixes the arm, as the part produced by the 3D printer comes into direct contact with the skin. For a female participant, there were no significant challenges in wearing the suit, as indicated by a score of 7. However, like their male counterparts, they reported discomfort due to the rigidity of the arm-securing component. Additionally, because the suit is constructed exclusively for the right shoulder, the weight is unevenly distributed, leading to discomfort for the wearer. Additionally, the rigid 3D-printed part that secures the arm, being in direct contact with the skin, also contributes to discomfort. Since the proposed suit focuses on assisting with forward flexion and extension, as well as abduction and adduction, it has a limitation in that it does not support external and internal rotation from the perspective of passive stretching exercises. To address these issues, future development will aim to enhance the arm fixation component to ensure a better fit and support all passive stretching exercises for both shoulders.

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References


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