



Preliminary Evaluation of the Passive Rehabilitation Phase of the REACT System for Tendon Therapy

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Abstract—Tendon injuries, particularly in the hand, require early and controlled rehabilitation to restore joint mobility while preventing adhesion and minimizing the risk of complications, such as suture rupture or gap formation. Robotic tendon therapy systems offer a promising alternative through programmable and repeatable motion delivery, yet many current designs are hindered by bulk and mechanical complexity, limiting their practicality in clinical use. Shape memory alloy (SMA) based actuators represent a promising solution for tendon-driven exoskeletons owing to their lightweight construction, high force-to-weight ratio, and silent operation, features that are particularly advantageous for wearable and portable rehabilitation devices. However, the nonlinear, hysteretic, and thermally dependent nature of SMA behavior poses significant control challenges, necessitating detailed experimental characterization and modelling. This study presents the tendon-driven *Rehabilitation Exoskeleton for Assisted Coordination of Tendon Therapy (REACT)* system, incorporating experimentally derived force–temperature and current–temperature models of SMA units into a current-based position control framework for the passive rehabilitation phase. The controller incorporates these models into the forward dynamics of the finger to achieve accurate torque generation and trajectory tracking within the physiological range of motion. Simulation results indicate high-fidelity reference tracking, with a steady-state error of approximately -8×10^{-3} rad, thereby confirming the feasibility of SMA-based actuation for safe, precise joint positioning in early-stage tendon rehabilitation.

Keywords—Assistive tendon therapy, hand exoskeleton, shape memory alloys, current-based position control

I. INTRODUCTION

Tendon injuries to the fingers significantly impair hand function, restricting mobility and daily activities [1]. Surgical repair is usually required to rejoin the tendon ends and restore joint function [2]. Following surgery, either active or passive, early rehabilitation is strongly recommended to prevent adhesions and promote tendon healing. Effective rehabilitation aims to restore tendon function and joint mobility while avoiding complications such as stiffness, rupture, or gap formation [3]. Conventional rehabilitation, however, relies heavily on therapist supervision, precise movement execution, and repetitive training factors that are difficult to sustain over long recovery periods.

Robotic rehabilitation has therefore emerged as a promising complement to traditional therapy. Robots provide consistent and repeatable motion, enable quantitative progress tracking, and allow therapy to be tailored to the patient's needs [4], [5]. Several robotic hand and finger exoskeletons have been introduced for rehabilitation, with promising outcomes [6], [8], [9]. Yet, most designs remain bulky, noisy, or difficult to personalize, limiting portability and tendon-specific therapy. This underscores the need for lightweight, silent, and wearable solutions.

SMAs have been explored as a promising alternative, combining high force-to-weight ratio and compactness with quiet operation, though they require careful control to address nonlinear behavior [14], [15], [16]. A lack of adaptability in the control of SMAs can either increase the risk of tendon rupture through excessive force or, conversely, restrict recovery by failing to provide adequate mobilization [7], [8], [9]. This makes it important to control SMA actuators in a way that is safe and reliable for tendon rehabilitation. However, SMA actuators also exhibit hysteresis and temperature-dependent characteristics, which pose additional challenges for stable and predictable control. Addressing these issues often requires mathematical modeling and experimental characterization to better understand their behavior and guide controller design [14], [15], [16].

Prior studies on SMA-based actuation robotic systems have explored relatively simple control schemes, such as pulse-width modulation (PWM) with proportional–derivative (PD) feedback and feedforward trajectory planning. These approaches demonstrate that SMAs can achieve reliable motion tracking when combined with sensor feedback. However, their performance is fundamentally constrained by the thermal dynamics of the material, which slow both activation and recovery. This problem has been addressed by integration of active cooling or antagonistic actuator arrangements to improve cycle speed [10], [11].

In addition to controller design, effective control of SMA actuators critically depends on precise thermal and mechanical characterization of the material. The force output of SMA springs depends strongly on temperature through changes

in the shear modulus, meaning that accurate knowledge of transformation temperatures such as austenite finish temperature is essential. Temperature evaluation techniques such as differential scanning calorimetry and dynamic thermal analysis are therefore widely used to identify these properties and enable consistent mapping between electrical input, temperature response, and mechanical force [12], [13]. Together, these studies underline both the promise and the challenge of using SMAs in rehabilitation devices.

To explore these challenges, we propose the REACT system, a wearable robotic exoskeleton specifically designed for tendon rehabilitation. The REACT system leverages SMA spring actuators in combination with dynamic system modeling, experimental mechanical characterization, and sensor-based feedback within an adaptive control framework. In this paper, we present simulation results that demonstrate the feasibility of this approach for tendon rehabilitation. These findings provide an initial step toward evaluating adaptive control strategies for safe and responsive assistance, which will require further validation beyond simulation in future work.

The remainder of this paper is structured as follows: Section II introduces the system design, SMA actuator characterization, and control methodology. Section III reports the results and analyzes system performance. Section IV concludes with a summary and outlines directions for future work.

II. METHODOLOGY

The REACT system is a tendon-driven wearable robotic exoskeleton designed for finger tendon rehabilitation. Actuated by SMA springs, it controls the range of motion (ROM) of the metacarpophalangeal (MCP) joint. This paper presents the implementation of a position controller for the passive phase of therapy, where the exoskeleton moves the finger through flexion and extension without patient effort, reducing the risk of tendon re-rupture. The control strategy integrates SMA characterization and forward dynamics modelling to achieve smooth, accurate, and safe joint actuation within the prescribed ROM.

A. System Design

The REACT exoskeleton is a tendon-driven, wearable device designed for finger tendon rehabilitation. As shown in Fig. 1, it features two actuation units responsible for flexion and extension, respectively. Each unit contains antagonistically arranged SMA springs: one contracts to produce the necessary actuation force, while the opposing spring returns the system to its initial position. This arrangement enables precise bidirectional control of finger movement without relying on passive elastic elements.

Force transmission is achieved through a tendon-driven mechanism, where cables connect the SMA actuators to adjustable phalanx rings via Bowden cables. A low-friction slider between the SMA-based actuator unit and tendon cables minimizes force loss, ensuring accurate and efficient motion control. To overcome the SMA's inherent slow cooling and

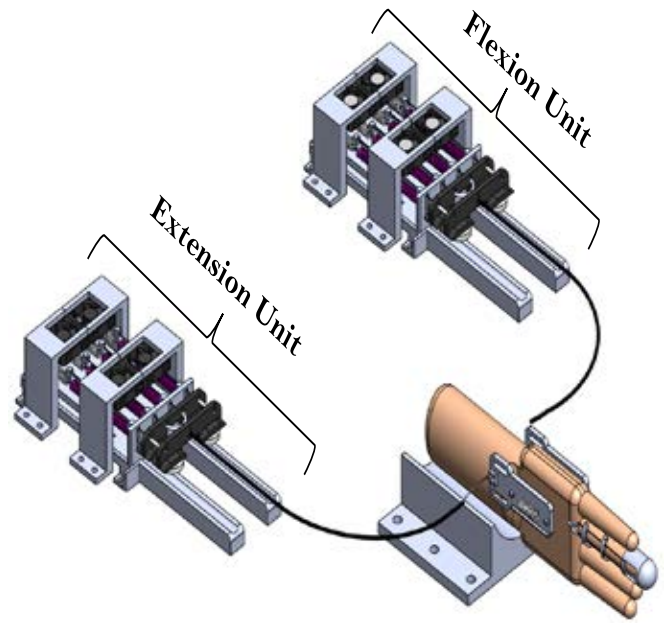


Fig. 1: Solid model of REACT: SMA-based actuation units and wearable module

improve actuation speed, compact cooling fans are integrated to facilitate rapid thermal dissipation.

The system's compact and lightweight design promotes patient comfort and portability. This mechanical configuration optimizes force transmission and establishes the essential foundation for precise position control of the SMA actuators, which is critical for accurate finger joint positioning during rehabilitation.

B. Control Architecture for Passive Therapy

In the REACT system, position control is implemented by modulating the contraction of SMA springs, which actuate the tendon-driven mechanism to achieve the desired finger joint angle. Achieving precise position control requires an understanding of how the finger's motion responds to actuation forces. To this end, a forward dynamics model of the finger is developed, enabling the desired joint position to be expressed as the torque demand for the SMA actuators.

Accurate torque generation requires a detailed understanding of SMA actuator behavior. For this purpose, experimentally derived models of the SMA springs are developed to characterize their actuation response under different operating conditions. These models are integrated into the control block to predict and regulate actuator output during position control.

The overall control process, illustrated in Fig. 2, begins with the desired MCP joint position (q_{ref}) as input. The position error (e), calculated from the difference between the target and measured angles (q_{actual}) via an IMU sensor, is processed by a PID controller. The controller output is passed through the finger's forward dynamics model, which computes the torque required to achieve the commanded motion. The equations

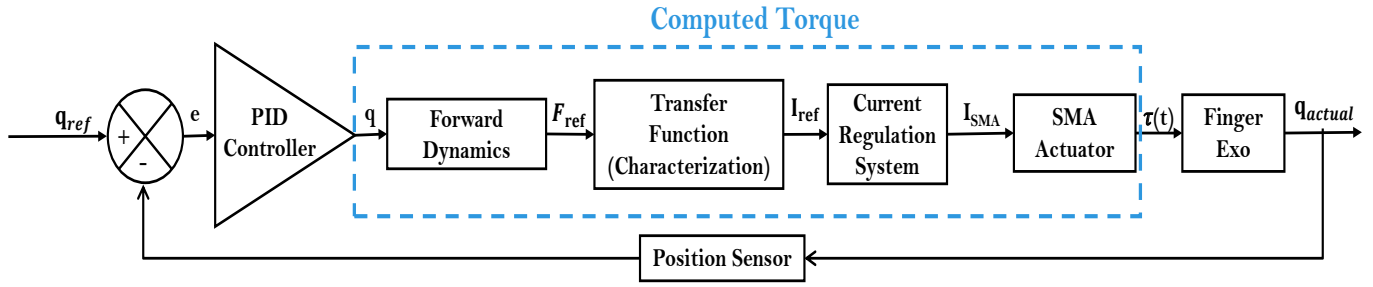


Fig. 2: Representation of the control block diagram of the REACT system for the passive therapy of the patients

governing this model follow the standard manipulator dynamics formulation given in Eq. 1.

$$\tau = M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + G(\theta), \quad (1)$$

, where symbol $M(\theta)$ represents the inertia matrix, $C(\theta, \dot{\theta})$ captures Coriolis and centrifugal effects, and $G(\theta)$ accounts for gravitational torques. For integration with the SMA characterization model, this torque is represented as an equivalent linear tendon force using the relationship given in Eq.2.

$$\tau = F_{\text{ref}} \cdot R \quad (2)$$

, where symbols R and F_{ref} are the joint moment arm and force, respectively. Here, the force acquired from the SMA actuator is employed to generate the desired joint torque to actuate the finger.

The required torque is then mapped to an SMA force and converted into a target temperature using the experimentally obtained force–temperature curve. The Joule heating model subsequently determines the necessary electrical current (I_{ref}), which is regulated by a dedicated current control loop. The actuated SMA contracts to generate the desired tendon force, rotating the MCP joint to the reference position. Continuous sensor feedback ensures accurate tracking and compensates for any discrepancies due to actuator nonlinearities or external disturbances.

C. SMA Characterization

Accurate control of the REACT system relies on the mathematical modelling of SMA actuator behavior. Since the performance of SMA actuator units is highly dependent on both temperature and electrical current, an experimental characterization is carried out to systematically establish the relationships among input current, actuator temperature, and the resulting force output.

The characterization involved measuring SMA spring force output over a range of temperatures while ensuring operation within the identified elastic limits to avoid plastic deformation. A fourth-order polynomial model is obtained to represent the force–temperature relationship:

$$F(T) = 1.06 \times 10^{-5}T^4 - 1.96 \times 10^{-3}T^3 + 1.30 \times 10^{-1}T^2 - 3.36T + 29.7 \quad (3)$$

, where $F(T)$ is the output force [N], and T is the SMA temperature [°C].

To link electrical input to thermal response, the SMA heating rate is measured for various applied currents. The resulting temperature–current relationship follows the Joule heating principle and is fitted to a linear model:

$$\frac{\Delta T}{\Delta t} = 0.1986 I^2 - 0.3515 \quad (4)$$

where $\frac{\Delta T}{\Delta t}$ is the average temperature rise rate [°C/s], and I is the applied current [A].

These experimentally derived models are integrated into the control architecture (Fig. 2) to determine the required temperature and corresponding current needed to generate the torque demanded by the forward dynamics model, ensuring accurate and repeatable finger positioning during rehabilitation.

III. IMPLEMENTATION AND SIMULATION RESULTS

The position control scheme for the passive therapy phase is implemented in the MATLAB/Simulink environment, integrating the experimentally derived SMA characterization models with the forward dynamics of the finger exoskeleton to assess control accuracy. A sinusoidal reference trajectory, ranging from 0° to 90°, is used to represent the physiological ROM of the finger joint, simulating the target movement pattern for rehabilitation.

Figure 3 presents the simulation results for reference tracking, tracking error, and a zoomed-in view of the steady-state error. The top plot shows that the controller accurately follows the desired joint position, with the actual trajectory (solid line) closely overlapping the reference (dashed line) throughout the motion cycle. The middle plot depicts the tracking error over time, revealing a rapid initial transient followed by a small and stable error profile. The bottom plot highlights the steady-state error, which remains approximately -8×10^{-3} rad (about -0.46°), confirming the controller's high tracking accuracy in the passive phase.

The simulation demonstrates that the integration of the SMA actuator model within the control loop enables accurate torque generation for position regulation, despite the nonlinear and temperature-dependent nature of SMA behavior. The use of the forward dynamics model ensures that the control law accounts for the mechanical dynamics of the finger exoskeleton, while

ACKNOWLEDGMENT

This project has been supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) 2209B Industry-Oriented Research Project Support Programme.

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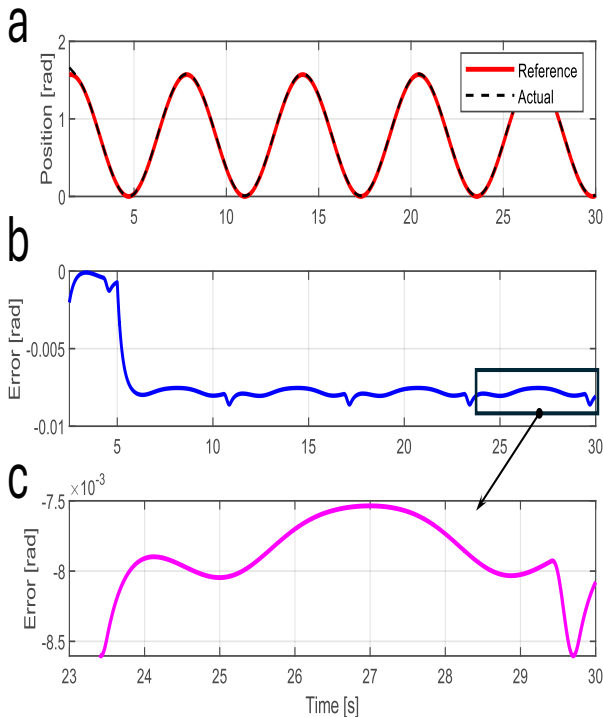


Fig. 3: Simulation results of the passive phase position controller. (a) Reference and actual MCP joint position tracking. (b) Tracking error over the full simulation time. (c) Zoomed-in view of the steady-state error, showing a consistent offset of approximately -8×10^{-3} rad.

the characterization-based transfer functions translate desired forces into appropriate current inputs for each SMA actuator.

IV. CONCLUSION

This study successfully demonstrates the implementation of a current-based position control strategy for the REACT tendon-driven finger exoskeleton for the purpose of the passive rehabilitation phase. The SMA characterization model derived experimentally is used in the forward dynamics of the finger; the control of the physical system effectively compensates for the nonlinear and temperature-dependent behavior of SMA actuator units. Simulation results demonstrate precise tracking performance within the physiological range of motion, with steady-state errors maintained in the milliradian range. These findings validate the feasibility of SMA-based actuation for delivering precise, reliable, and safe joint movements in tendon rehabilitation. Future work will involve implementing position control based on the dynamic model in the physical prototype of the REACT system, followed by experimental evaluations with healthy participants and patients. These trials will assess the system's performance under clinical rehabilitation conditions during the passive rehabilitation phase, ensuring its safety, accuracy, and suitability for early-stage tendon therapy.