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Fuzzy logic based adaptive admittance control of a redundantly actuated ankle rehabilitation robot

Mustafa Sinasi AYAS*, Ismail Hakki ALTAS

Department of Electrical and Electronics Engineering, Karadeniz Technical University, 61080 Trabzon, Turkey

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ABSTRACT

Ankle rehabilitation robots have recently attracted great attention since they provide various advantages in terms of rehabilitation process from the viewpoints of patients and therapists. This paper presents development and evaluation of a fuzzy logic based adaptive admittance control scheme for a developed 2-DOF redundantly actuated parallel ankle rehabilitation robot. The proposed adaptive admittance control scheme provides the robot to adapt resistance/assistance level according to patients' disability level. In addition, a fuzzy logic controller (FLC) is developed to improve the trajectory tracking ability of the rehabilitation robot subject to external disturbances which possibly occur due to human-robot interaction. The boundary scales of membership functions of the FLC are tuned using cuckoo search algorithm (CSA). A classical proportional-integral-derivative (PID) controller is also tuned using the CSA to examine the performance of the FLC. The effectiveness of the adaptive admittance control scheme is observed in the experimental results. Furthermore, the experimental results demonstrate that the optimized FLC significantly improves the tracking performance of the ankle rehabilitation robot and decreases the steady-state tracking errors about 50% compared to the optimized PID controller. The performances of the developed controllers are evaluated using common error based performance indices indicating that the FLC has roughly 50% better performance than the PID controller.

1. Introduction

Attempts have been made to improve rehabilitation process which is a significant issue in the 21st century (Zhang, Davies, & Xie, 2013). In addition to novel methods, smart devices have also been developed to contribute to the quality of life in society. Ankle rehabilitation robots are one of such devices used in clinical rehabilitation of sprained ankle which is one of the most common orthopedic injuries occurred in daily life (Kemler, Port, Valkenberg, Hoes, & Backx, 2015; Mittlmeier & Wichelhaus, 2015). Conventional rehabilitation methods require physical therapists to rehabilitate patients one-to-one. The effectiveness of this rehabilitation process relies heavily on the experience of a therapist. Since the rehabilitation process contains repetitive and intensive exercises, it can take a long time which affects the therapist in a negative way. Hence, the same therapist cannot ensure repeatability and correctness of the rehabilitation process. When the number of patients is considered too many, receiving support from auxiliary robots while performing treatments is a great advantage. The importance and requirement of robotic-based rehabilitation has been emphasized by many studies and regarded to be essential in rehabilitation processes from the viewpoints of patients and therapists (Jamwal, Xie, Hussain, & Parsons, 2014; Saglia, Tsagarakis, Dai, & Caldwell, 2009b; Wang et al., 2015). Fatigue in patients and therapists, long clinical sessions, inconsistency in treatments and slow recuperation are some of the drawbacks in conventional treatments which have been resolved in the robotic-based rehabilitation. Furthermore, providing a rich stream of measurement data to therapists to record and observe every detail of a rehabilitation process is another important advantage of these robots.

Ankle rehabilitation robots can be classified into two main categories as exoskeletons (Gordon, Sawicki, & Ferris, 2006; Jamwal et al., 2014; Roy et al., 2009), i.e. wearable robots, and platform robots (Dai, Zhao, & Nester, 2004; Girone, Burdea, & Bouzit, 1999; Liu, Gao, Yue, Zhang, & Lu, 2006; Saglia, Tsagarakis, Dai, & Caldwell, 2009a Saglia, Tsagarakis, Dai, & Caldwell, 2013; Yoon, Ryu, & Lim, 2006; Zhang et al., 2002), although several design approaches have been proposed. Exoskeletons are used to correct patients' gait patterns, while platform robots are used to manipulate patients' ankles and facilitate the treatment of ankle sprains. In this study, exoskeletons are not discussed, since only devices used to manipulate ankles in the sprained ankle treatment process are considered.

Girone et al. (1999) developed a 6 degrees-of-freedom (DOF) ankle

* Corresponding author.
E-mail addresses: msayas@ktu.edu.tr (M.S. AYAS), ihaltas@ktu.edu.tr (I.H. ALTAS).

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rehabilitation system based on Stewart platform. It is the most popular and earliest ankle rehabilitation system that could perform both passive and active training of the sprained ankle. A position controller for trajectory tracking control (passive training) and a force controller for resistive exercises (active training) are utilized in the study. The results of clinical tests performed using the Rutgers ankle show that the device has the potential of supporting the rehabilitation process (Deutsch, Latonio, Burdea, & Boian, 2001). Zhang et al. (2002) developed a 1-DOF rehabilitation device to only perform the passive range of motion (ROM) exercises with a velocity control scheme and observed the resistive torque derived from patients through a torque sensor. A parallel mechanism that could be used as a ROM exercise device and a balance/proprioception device was developed by Yoon, Ryu, and Lim (2006). Position and impedance control schemes required for rehabilitation protocols were also presented. Lin, Ju, Chen, and Pan (2008) developed a 1-DOF device in order to perform both resistive and assistive exercises. The active exercises were carried out using constant resistive and assistive torques. A passive device only capable of performing passive ROM exercises was proposed by Bucca, Bezzolato, Bruni, and Molteni (2009). Although a position control scheme was presented, no control scheme was provided for active exercises. A redundantly actuated parallel robot with a central strut was proposed by Saglia, Tsagarakis, Dai, and Caldwell (2009), who performed trajectory tracking control of the mechanism using the traditional proportional-derivative (PD) controller and also analyzed the effects of the controller parameters which were changed manually in order to find optimum tracking performance. Another article proposing control strategies for patient-assisted training of sprained ankle was published by Saglia, Tsagarakis, Dai, and Caldwell (2013). They described the general control structure of a developed parallel mechanism. Jamwal et al. (2014) proposed a 4-DOF adaptive wearable parallel robot for sprained ankle. Flexion, inversion, and adduction trajectories were followed using a fuzzy logic controller (FLC) with a healthy subject in the passive mode. The authors emphasized to improve the controller performance, since the results obtained from a healthy subject clearly showed the disturbance effect, which could not be eliminated by the controller.

Although the aforementioned studies showed pleasant results, none of them met the necessities considered in this study such as providing an adaptive admittance control scheme required for active exercises, improving the trajectory tracking performance of the mechanism subject to external disturbance by optimizing the parameters of the controller and measuring the performance of the controller using common performance measurement methods. The rehabilitation robot presented by Saglia et al. (2013) can be considered the most successful device so far. However, the impedance control scheme used in their study is not an adaptive one which can consider patients' disability level and adapt the resistance/assistance level accordingly, and the authors have neither revealed their controller performances using any specified performance index, nor used any optimization methods to tune the controller parameters.

Ankle rehabilitation exercises can be classified into three main categories as range of motion (ROM) exercises, strengthening exercises, and proprioceptive exercises. In addition to a position control scheme required in these exercises, an admittance control scheme is also needed for some types of exercises, i.e. active ROM and isotonic exercises mentioned in Section 2. Moreover, such an admittance control scheme should adapt the resistance/assistance level according to the individuals' disability level as patients' disability level varies from person to person and also for the same person during the rehabilitation exercise. Since fuzzy logic provides a human reasoning and decision making in the format of fuzzy rules, it can be used to adapt the admittance control scheme (Prabhu & Garg, 1998).

It should be noted that the main purpose of this study is not to make improvements in structural design of the rehabilitation robot and its kinematic analysis. This paper focuses more on control aspect of the ankle rehabilitation robot. The main contribution of this study is to developed a fuzzy logic based adaptive admittance control scheme which provides the robot to adapt resistance/assistance level according to patients' disability level instead of providing a certain level of resistance/assistance, and thereby results in more appropriate and effective exercises. There are studies indicating that traditional rehabilitation slows down the recovery process since they don't consider the patient actively, i.e. they don't take into account the patient condition in the exercises (Krebs et al., 2003; Vallery, Duschau-Wicke, & Riener, 2009). Because the patient can be tired during intensively repetitive exercises and required more assistance, or the patient's muscles are very strong for the exercise and need more resistance to strengthen the muscles. This emphasized result can shed light on the importance of adaptiveness of the generated admittance level. In other words, if the static admittance control scheme is used, the patient condition isn't taken into account and thereby the exercises required assistance cannot be completed, or the patient cannot strengthen the muscles if the patient's muscles are quite strong for the strengthening exercise. Therefore, the adaptive admittance control scheme might improve the patient outcomes. The resistance/assistance level not only depends on the force applied by the patient, but also depends on the fuzzy support level decided by the therapist. The adaptive admittance control scheme contains a fuzzy logic based gain regulator (FGR), which is explained in Section 3 in detail. The FGR regulates the gain of admittance filter by taking into account both the applied force and the fuzzy support level, and thereby instead of a level which only depends on the applied force, a variable resistance/assistance level is provided to patients. The advantage of the FGR can be reword as: if patients can not apply sufficient force or patients are quite strong for the decided assistance/resistance level, the robot provides the patient to perform the required exercise more appropriate by assisting or resisting patients, respectively. According to the authors' best knowledge, a fuzzy logic based adaptive admittance control of such a robotic rehabilitation device has not been stated in the literature.

Another contribution of this study is that an FLC whose boundary scales of membership functions are tuned using CSA is designed to improve the trajectory tracking performance of the developed ankle rehabilitation robot subject to external disturbance. An optimized FLC for trajectory tracking control of a parallel ankle rehabilitation robot has not been reported in the literature. A PID controller, the parameters of which are optimally tuned using CSA, is also developed to compare the performance of the optimized FLC since many ankle rehabilitation studies in the literature used PID controller even without tuning its parameters. In order to estimate the controller performances, error-based performance measurement methods, i.e. integral of absolute error (IAE), integral of time-weighted absolute error (ITAE), and integral of squared error (ISE), are utilized. The controller performances are observed when the ankle rehabilitation robot is subject to external disturbance, since the interaction between patient and robot results in disturbance effect.

This paper is organized as follows. Section 2 presents the developed 2-DOF redundantly actuated parallel ankle rehabilitation robot, its inverse kinematic analysis and the control strategies for rehabilitation exercises. Section 3 introduces a fuzzy logic based admittance control. The FLC design for trajectory tracking control is presented in Section 4. Section 5 explains the experimental setup used in this study and gives the experimental results. Finally, the conclusions are drawn.

2. Designed ankle rehabilitation robot

Anatomic structure of the human ankle is required in addition to the knowledge of the common ankle rehabilitation protocols in order to develop an ankle rehabilitation robot. The human ankle is capable of performing three kinds of movements, i.e. plantar flexion/dorsiflexion, inversion/eversion, and adduction/abduction movements, through the ankle and subtalar joints in sagittal, frontal and transverse planes,