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Human force observation and assistance for lower limb rehabilitation using wire-driven series elastic actuator[☆,☆☆]

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ABSTRACT

This study involves proposing an assistive device using a wire-driven Series Elastic Actuator (SEA) for leg rehabilitation that can design and provide assistive force for exercises based on the physical ability of a patient. The proposed assistive device possesses a force estimation ability to measure the mass of the leg along with the force exerted by a user in real-time. In order to achieve precise human force estimation and assistive force generation, a compact Planetary-geared Elastic Actuator, which is a type of Series Elastic Actuator is applied in the proposed device. Various algorithms to provide robust assistive force and to estimate force and work performed by the user are proposed in the study. Pilot tests were conducted with an exercise scenario that fully utilizes the functions and algorithms proposed in this study, and the effectiveness of the proposed system was validated based on two types of experiments: a healthy subject case and a patient case. The results of pilot test approve that the proposed device and algorithm enable patients to perform the exercise with ease, and increase their physical capabilities effectively.

1. Introduction

The ultimate aim in the field of mechatronics extends beyond the pursuit of an industrial society. Specifically, extant studies examine environmental systems involving active cooperation or contact between a human and robots [1,2]. Thus, the trend involves increased focus on the reaction of a compliant force control or impedance control to the contacted environment in an interactive situation with a human or a subject as opposed to studies that examine precise positioning [3,4].

Significant research was conducted in the rehabilitation robotics field to apply compliance force control technology to effectively interact with humans [5,6]. Several studies used a force sensor to realize compliant force control. However, force sensors involve several issues such as excess size, cost, and fragility, and even force measurement bandwidth [7]. Several studies focused on a Series Elastic Actuator (SEA) as a potential actuator system that achieves safe and compliant force generation [8].

SEAs exhibit significant advantages in terms of response to force measurement because they measure spring deformation from the encoder and estimate the force based on it for feedback control. Therefore, recent studies and projects involved diversifying and generalizing SEAs, and thus various SEA mechanisms were suggested [9,10]. Advances in the SEAs increased the accuracy of interaction and assured safety in the field of service robots [11,12]. On the other hand, several attempts focused on combining mechatronic technology with rehabilitation. The two main aims of these attempts involved ‘measuring’ and ‘assisting’ in a patient’s rehabilitation, which can exploit the advantages of SEA [13].

A rehabilitation of the lower limb while confined to bed involves Straight Leg Raise (SLR) exercise that is considered as one of the most effective ways to develop essential lower limb muscles [14]. It is a training method to reinforce muscles related to walking to prevent difficulties encountered by a patient while returning to normal life due to the degeneracy of muscles after lower limb or back surgery. Several existing studies attempted to analyze the effect of this exercise and enhance it by either measuring or assisting force or position during the exercise as shown in Fig. 1 [15–18].

Extant studies including [15,16] (Fig. 1 (a) and (b)) mainly focused on measuring the intensity of the exercise as follows: the study in [15] measured the elevated angle and voluntary force of a leg to examine the effectiveness of SLR exercises. However, this approach involves the risk of constraint force as it interferes with the exercises

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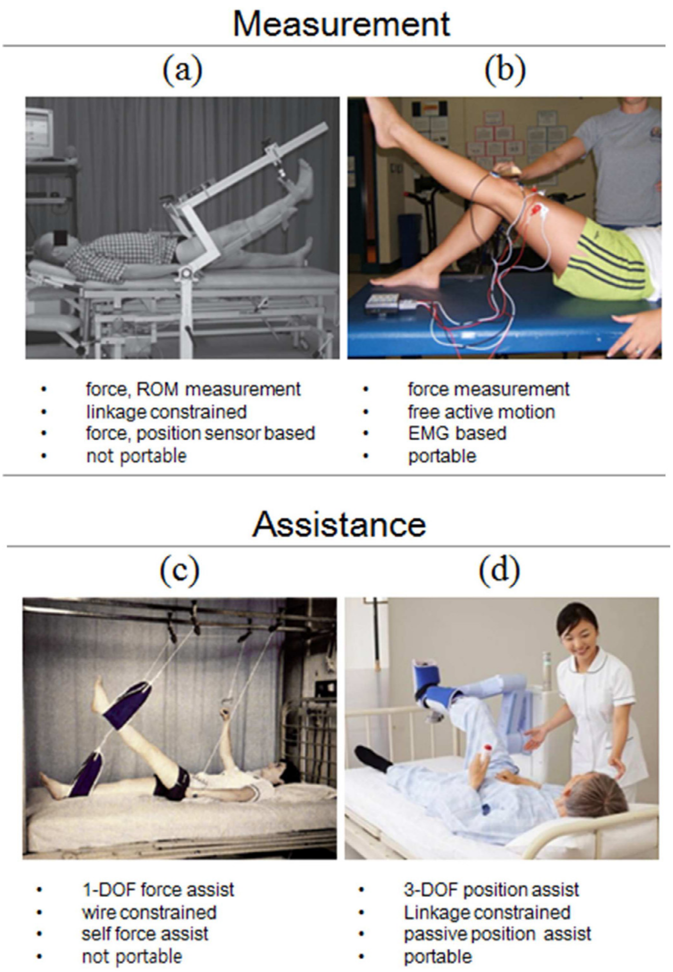

Fig. 1. Various techniques of measurement and assistance for straight leg raise exercise.

due to the use of stiff linkages. Conversely, the study by Kushion et al. [16] attempted to directly measure muscle activation during SLR exercises through EMG. This method cannot measure motions, and thus requires an individual to verify whether proper SLR exercises were performed.

There are two examples that use equipments to assist SLR exercise (Fig. 1 (c) and (d)). The study in [17] proposed a device that supports the force necessary for a patient who is unable to properly perform an SLR exercise. It utilized wires to remove the unnecessary constraint force on the leg although the results were limited since the force to assist leg exercises must come from the patient him/herself. Moreover, it is necessary to install the equipment to constrain wire movements on the bed, and therefore it is difficult to apply the same to various patients. YASKAWA has developed a three degree-of-freedom supportive equipment for pelvic limb exercises that is available in the market [18]. The robot helps a patient to move by using motion profiles and corresponds to a position-control-based device. In this case, the robot performs the leg movement irrespective of the patient's force, and the exercises do not occur due to the patient's active intention. This limits the effectiveness of the exercise.

This study proposes an assistive device that is developed for lower limb rehabilitation to overcome the fore-mentioned disadvantages. The proposed device is also capable of simultaneously performing force measurement and assistance by using a wire-driven SEA. Thus, it assists the force of the patient without kinematic constraints and also enables monitoring of the patient including the force generated by the patient, which

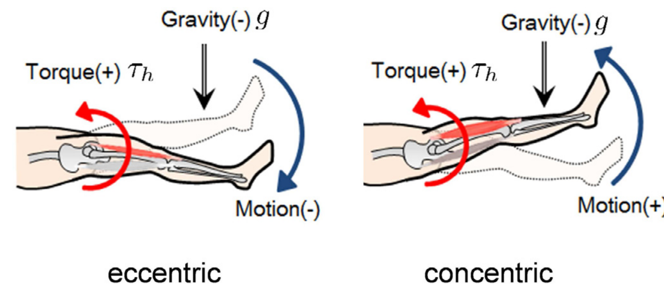

Fig. 2. Illustration of a straight leg raise exercise [20]: eccentric (left) and concentric (right) muscle contractions.

can be utilized by a therapist to precisely diagnose the condition of the patient such as the ability to generate force or a rehabilitation progress.

This study includes the following contributions:

- A single degree of freedom robotic device, based on a wire-driven SEA, is developed and its design process is explored.
- Various control modes of SEA are designed to enable both 'assistance' and 'measurement' for rehabilitation.
- Human Force Observer (HFO), an algorithm that estimates the force generated by human, is newly proposed.
- A pilot test of rehabilitation scenario of SLR exercise using the proposed device is conducted.
- The performance of the mechatronic system including the proposed device and algorithm for the scenario is demonstrated through experiment.

This paper is organized as three parts: Section 2 is mechanical design part (hardware), Section 3 is operating algorithm part (software), and Section 4 is experimental verification.

2. Mechanical design of straight leg raise assistive robotic device

2.1. Mechanical analysis of target rehabilitation

In order to design a robotic device to assist the exercise, the Straight Leg Raise (SLR) exercise is inspected in terms of the following dynamics; SLR is a movement that keeps the leg straight and lifts around the hip joint, and thus it is modeled as one degree-of-freedom motion as follows [19]:

$$J_h \ddot{\theta}_h = \tau_h + \tau_g(\theta_h), \tag{1}$$

where J_h denotes the moment of inertia of the whole leg (lower extremity), θ_h denotes the hip joint angle of the leg, τ_h denotes the hip joint torque generated by an individual, and $\tau_g(\theta_h)$ denotes the load caused by the gravity force of leg mass. It should be noted that the leg is assumed as a pure mass for simple analysis in the study although it is modeled by including passive damping and stiffness characteristics of muscles [19]. Essentially, the leg is loaded in the gravity direction by its own weight during the SLR exercise as shown in Fig. 2. The significant load on the muscles during the exercise is mostly due to gravity $\tau_g(\theta_h)$, and it is modeled as follows:

$$\begin{aligned} \tau_g(\theta_h) &= M_h g l_{leg} \cos\theta_h && (\text{when, } \theta_h > 0), \\ \tau_g(\theta_h) &= 0 && (\text{when, } \theta_h = 0), \end{aligned} \tag{2}$$

where l_{leg} denotes the distance between the hip joint and the mass while modeling the leg as a point mass M_h as shown in Fig. 3. g denotes the gravitational constant.

2.2. Assistive device for SLR exercise

The above results suggests that the torque generated by an individual τ_h must exceed $\tau_g(\theta_h)$ to lift the leg in the starting phase of SLR exercise.