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# Mechanical design and evaluation of a compact portable knee–ankle–foot robot for gait rehabilitation

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ABSTRACT

This paper presents the mechanical design and evaluation of a knee–ankle–foot robot, which is compact, modular and portable for stroke patients to carry out overground gait training at outpatient and home settings. A novel compact series elastic actuator (SEA) is developed for safe human–robot interactions. As a solution to the limitation of conventional SEA designs, one low-stiffness translational spring and a high-stiffness torsion spring are placed in series for force transmission. The springs are selected based on gait biomechanics to maintain a high intrinsic compliance for most period of a gait cycle, while retaining the capacity to provide the peak force. To achieve portability, the robotic joint mechanism is optimized based on gait biomechanics, and the mechanical structure is built with lightweight materials. This robot demonstrates stable and accurate force control in experiments conducted on healthy subjects with overground walking. The activation level of the major leg muscles of subjects is reduced as indicated by the EMG signals and the normal gait pattern is maintained during the test, which demonstrates that the robot can provide effective assistive force to the subjects during overground walking.

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## 1. Introduction

Stroke has become one of the leading causes of adult disability with the growing aging population [1]. Impairment to neurological systems due to stroke frequently leads to a range of symptoms, including paralysis, muscle weakness, gait disorder and pain, which affect the patients' ability to perform activities of daily living (ADL) [2]. Physical therapy aiming to evoke brain plasticity to regain the lost functions of the brain proves to the main effective treatment for stroke patients [3]. However, conventional manually assisted gait training is labor intensive and physically demanding for therapists [4]. The availability, consistency, duration, and the frequency of training sessions are often limited, leaving many stroke patients with permanent disabilities untreated.

Rehabilitation robots have been introduced into the earlier phases of recovery after stroke to overcome the major limitations of traditional manual therapy [5]. High-quality rehabilitation therapies can be delivered by robots with good quantitative measurements and consistency. Over the years, various gait rehabilitation robotic devices have been developed based on different concepts [6,7]. However, most of existing robotic gait training systems, such as Lokomat [4], ReoAmbulator [8], LOPES [9], ALEX [10] and Auckland University's system [11], integrate treadmills and fixed platforms [12]. They are meant for acute patients at big rehabilitation centers or hospitals; and rehabilitation progress of which is inferior to overground gait training [13,14].

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Therefore, there is a great need for portable wearable robotic systems for chronic stroke patients at community rehabilitation centers or home settings. Such portable devices should be lightweight, safe, and easy to don and doff.

A number of gait rehabilitation devices targeted at specifically either the ankle joint [15–18] or the knee joint [19–23] have been developed. However, the weight remains to be the main challenge to achieve portability. The ankle robot developed at MIT [16] weighs 3.1 kg for just the ankle joint. The commercialized knee assistive device developed by Tibion [20] weighs more than 4.5 kg for just the knee joint. A quasi-passive compliant stance control orthosis (CSCO) for knee joint assistance recently developed by Shamaei et al. weighs 3 kg [23]. Besides, portable devices aimed at providing active assistive torque to both the knee and ankle joints are very rare due to ineffective and bulky actuation design. The lightweight knee–ankle–foot orthosis (KAFO) is recently attempted at University of Michigan [24], but it is designed with pneumatic actuators tethered to a stationary compressor and so the system cannot be truly portable and used at home.

In this paper, we present a compact and modular knee–ankle–foot robot aiming for sub-acute and chronic stroke patients to conduct gait rehabilitation at outpatient rehabilitation centers or at home. The system can be easily reconfigured into either a knee robot or an ankle robot to suit different symptoms, such as knee hyper-extension and drop foot. In order for the device to be able to provide assistance during human gait, the actuator must be lightweight, compact and have a large range of output force. Thus we developed a novel compact compliant series elastic actuator (SEA) [25], and corresponding linkage mechanism to achieve portable and modular robot design. Experiments have been conducted on four healthy subjects to verify the mechanical performance of the robot.

The rest of this paper is organized as follows. Section 2 characterizes the compact robot, including the biomechanics analysis, robot design, compliant actuator design, mechanical structure optimization and sensing apparatus integration. Section 3 illustrates experiment evaluation method. Section 4 shows the experimental results. Section 5 includes discussion and conclusion.

## 2. Mechanical design

### 2.1. Design specifications

Since the primary goal of the device is to facilitate the subject overground walking and provide assistance, the design specification of the proposed robot is determined by analyzing the biomechanics of human gait [26,27]. Clinical Gait Analysis (CGA) data are utilized to guide the design of the exoskeleton and actuator, which are collected from the CGA normative gait database [28]. Fig. 1 illustrates the biomechanics in terms of torque, joint angle and power of the knee flexion/extension and ankle dorsiflexion/plantarflexion when a healthy subject (70 kg, 0.9 m leg-length) walking at 1.0 m/s. The biomechanical data is normalized into gait cycle percent (1–100%), which starts from the heel strike of the right leg and ends with the next heel strike of the right leg.

Normally, the walking knee flexion is limited to about 60°. The peak knee torque reaches 30 N·m during stance phase (18% gait cycle, red circle in Fig. 1(a)) when knee angle is about 20° (Fig. 1(a)). It is worth noting that knee torque remains under 10 N·m (30% of peak torque) for most of a gait cycle, and goes beyond this value in a small period only (red dashed line in Fig. 1(a)). Correspondingly, the walking ankle angle ranges from −10°–15°, and the peak torque is 60 N·m when the angle is close to 15° (42% gait cycle, blue circle in Fig. 1(a)) during stance phase (Fig. 1(b)). Similarly, ankle torque stays below 20 N·m (30% of peak torque) for more than half of the gait cycle (blue dashed line in Fig. 1(a)). It is worthy to note that this character is a driving factor for our

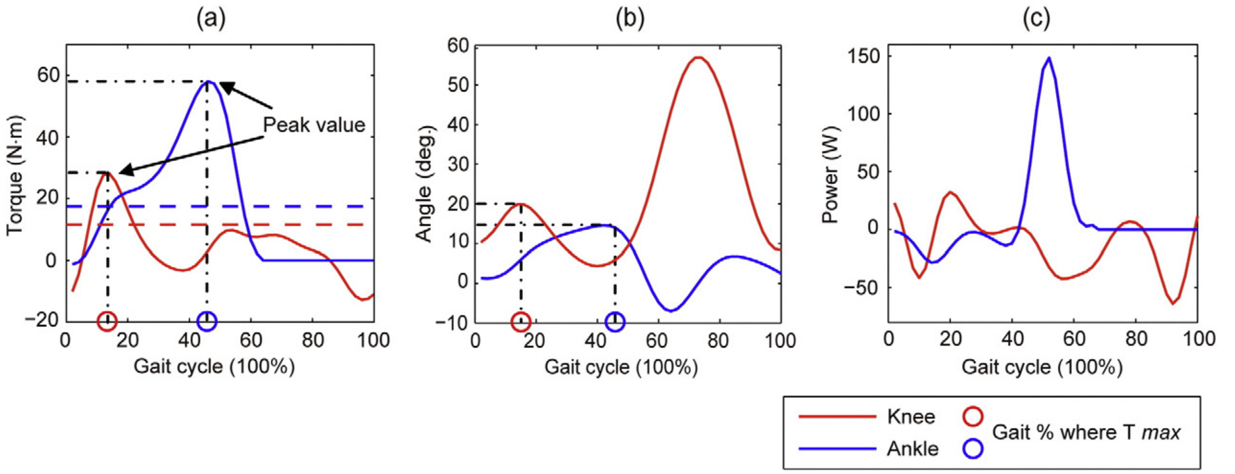


**Fig. 1.** Biomechanics of human ankle and knee joints for a 70 kg healthy subject during normal gait cycle with 1.0 m/s speed, including (a) joint torque, (b) joint angle and (c) joint power. Red and blue lines represent knee and ankle joints respectively. Blue and red circle is the gait percentage where joint torque reaches its maximum. Dot dash line in both (a) and (b) illustrates the joint angles and torques where joint torque is maximum. Dashed line in (a) is 30% of peak torque that covers the most part of a gait cycle.

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