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Design and control of an active ankle–knee orthosis inspired by biarticular musculoskeletal structure of the human lower limb☆

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HIGHLIGHTS

- This paper proposes a novel mechanism for orthotic devices.
- A biarticular elastic mechanism with an active joint actuator is utilized.
- The proposed mechanism transmits torques from the active joint actuator efficiently.
- Theoretic fundamentals for analyzing the proposed mechanism are provided.
- Virtual hook control is proposed to control the proposed mechanism.

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ABSTRACT

This paper proposes a novel mechanism for orthotic devices, which has an active joint actuator with a biarticular elastic mechanism that connects two joints simultaneously. The biarticular elasticity in the proposed mechanism is adopted to utilize the energy transfer function of the biarticular muscles so that (1) the torque from the active joint actuator is efficiently transmitted, and (2) the forces required to propel the upper body forward are assisted in a more efficient and sophisticated way. In recent years, many researchers have discovered that the biarticular elasticity is a key mechanism of humans' efficient movement and implemented the biarticular principle into various types of robots. However, the application of the biarticular mechanism has been hindered by the coupling and redundancy which the mechanism induces. This paper provides theoretic fundamentals for analyzing the kinematics and dynamics of the biarticular elasticity to help engineers design assistive mechanisms and controllers using the biarticular elasticity. The effectiveness of the proposed methods are verified by simulation studies in this paper.

1. Introduction

A demand for assistive technologies has been increased as many societies are confronting with aging population where there are many people who need any type of assistance, while there are relatively lesser number of people who can provide the assistance. Among various assistive technologies, assistive robotics is considered as one of the most promising technologies which can provide direct and physical help and support to people with physical impairments. The expectation on the assistive robots is not only to supplement muscular forces of people with muscular weaknesses but also to be utilized for effective rehabilitation of people with temporary disabilities.

As the range of application of the assistive robots widens, the required specification also becomes rigorous and various. In addition to safety, comfort, and precision of assistive force, the energy efficiency and the maximum torque output have become important issues in the recent assistive robotics. The efficiency of actuation mechanisms, in particular the power-to-weight ratio, determines the size and weight of the whole assistive robot. Also the characteristics of actuators often require the use of an appropriate energy source, such as a battery, which is one of the main factors that increase the weight of the overall system. For these reasons, many researchers recently have intensively investigated

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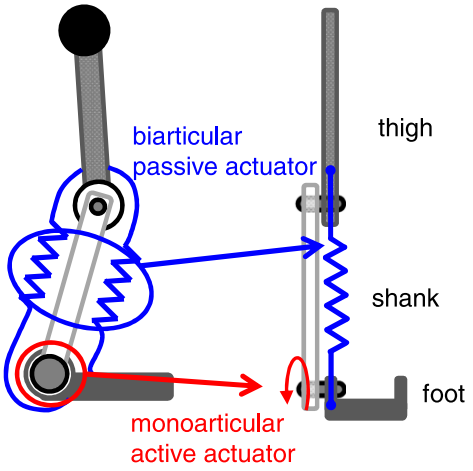

Fig. 1. Basic structure of the proposed ankle–knee orthosis system.

on passive mechanisms such as springs and counter-weights [1–4] as a new means of effective assistive mechanisms.

Human musculature realizes a high energy efficiency using the dynamic property of muscles, i.e., the complicated coordination of muscles enables efficient distribution of forces required for muscles to conduct various behaviors. The biarticular muscle has been studied as the key mechanism that allows this efficiency in human musculoskeletal activities. Research on the biarticular muscle is important from various perspectives: it can shed insights on understanding of human motions and the functions of musculoskeletal system during motions and thus facilitate the development of more useful and human-friendly assistive robots [5–7].

Unlike other design of orthoses of a knee joint which mostly focuses on the precise and practical design of one joint [8–10], this paper introduces a biarticular elastic mechanism into an ankle–knee orthosis in order to improve the torque transmission efficiency; a leg system to assist a person with a physical impairment in his/her lower limb is designed with one active actuator at the ankle joint and one passive mechanism that acts as the biarticular elasticity connecting the ankle joint and the knee joint. Fig. 1 shows the basic structure of the proposed leg orthosis system which has a motor at the ankle, which corresponds to an active monoarticular actuator, and a spring that connects the foot and the thigh, which plays the role of a passive biarticular elastic mechanism.

The proposed mechanism is inspired by the bio-mechanic structure, i.e., the biarticular muscle [11,12] which distributes the muscular forces of the ankle across the shank and thigh. Such an actuation force distribution, which is closely related to the energy distribution, contributes to the improved energy efficiency of the whole human body system [13]. In spite of this advantage of the biarticular elastic mechanism, the overall system becomes underactuated with a complicated coupling, and therefore it becomes difficult to precisely control all the connected joints simultaneously.

In this paper, the dynamics and kinematics of the biarticular elastic mechanism are analyzed for a better understanding of the human muscular mechanism and are utilized for applications of the biarticular elastic mechanism to the design of controllers and hardware of assistive robots. At first, the features of the biarticular muscle's role in human motion is introduced to reveal how the mechanism introduced in the proposed orthosis and the theoretic fundamentals developed in the paper are related to and utilized to analyze the biarticular muscle. Then the kinematic and dynamic characteristics of the proposed mechanism are analyzed to explore the functions of the introduced biarticular elasticity. Then a control algorithm for the ankle joint actuator to provide the required force for the overall assistive robot is designed based on the derived dynamics. Lastly, simulation studies validate the derived dynamics and the effectiveness of the proposed mechanism and algorithm.

Table 1
Monoarticular and Biarticular muscles of the lower limbs.

Monoarticular	IL	Iliopsoas
	GU	Gluteus maximus
	VAS	Vasti (lateralis and medialis)
	TA	Tibialis anterior
	SOL	Soleus
Biarticular	HA	Semitendinosus (ST) Semimembranosus (SM) Biceps Femoris (BF)
	RF	Rectus femoris
	GA	Gastrocnemius

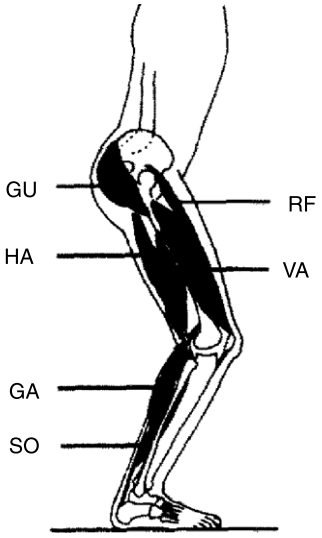

Fig. 2. Main muscles of the lower limbs [18].

2. Biarticular musculoskeletal structure of the human body

2.1. Anatomical analysis of the human lower limb

Human bodies consist of monoarticular, biarticular, and polyarticular muscles as in Table 1 and Fig. 2, which present the representative monoarticular and biarticular muscles of the lower limbs as reported in literature. The biarticular muscles are muscles, which can produce moment at two adjacent joints simultaneously [14]. A lot of research works have been carried out to reveal the exact functions of biarticular muscles since any net joint moments can be achieved by a given set of monoarticular muscles [15]. The main function of the biarticular muscles is often related to the movement coordination where smooth, efficient, and safe movements are needed. The biarticular muscles have a special function as they are able to combine acceleration of one body segment with deceleration of another body segment, which is very beneficial to ensure smooth movements while preventing joint damage. It is assumed that efficient solutions for movement problems can be provided through the nature of biarticular muscles [16].

For example, the fact of having biarticular muscles spanning the knee joint is very beneficial for ensuring joint deceleration during knee extension. It should be noted that during knee joint extension and in order to prevent knee joint damage, the speed of the movement decreases till reaching the hyperextension with a joint velocity equal to zero. This is done using antagonist muscular