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An Inflatable and Foldable Knee Exosuit Based on Intelligent Management of Biomechanical Energy

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Abstract**—**Wearable robotics is a potential solution in aiding gait rehabilitation of lower limbs dyskinesia patients, such as knee osteoarthritis or stroke afflicted patients. Many wearable robots have been developed in the form of rigid exoskeletons, but their bulk devices, high cost and control complexity hinder their popularity in the field of gait rehabilitation. Thus, the development of a portable, compliant and low-cost wearable robot for gait rehabilitation is necessary. Inspired by Chinese traditional folding fans and balloon inflators, the authors present an inflatable, foldable and variable stiffness knee exosuit (IFVSKE) in this paper. The pneumatic actuator of IFVSKE was fabricated in the shape of folding fans by using thermoplastic polyurethane (TPU) fabric materials. The geometric and mechanical properties of IFVSKE were characterized with experimental methods. To assist the knee joint smartly, an intelligent control profile for IFVSKE was proposed based on the concept of full-cycle energy management of the biomechanical energy during human movement. The biomechanical energy of knee joints in a walking gait cycle of patients could be collected and released to assist the joint motion just by adjusting the inner pressure of IFVSKE. Finally, a healthy subject was involved to walk with and without the IFVSKE to evaluate the assisting effects.

Keywords**—**Biomechanical energy management, gait rehabilitation, knee exosuit, wearable robotics.

I. INTRODUCTION

DYSKINESIA of the lower extremities is a common disease, especially in patients with stroke and knee osteoarthritis. Stroke, as the number one cause of chronic disability worldwide, is known to cause paresis-weakness of muscles or plegia-complete loss of muscle action, in limbs depending on the severity of the stroke episode and locus of brain damage [1]-[4]. And the knee osteoarthritis is the common degenerative joint disease, especially in the elderly, obese individuals and people who do strenuous exercises frequently [5], [6]. Apart from the traditional medical treatments for lower limb dyskinesia, such as the palliative medication, surgery, and nursing-assisted rehabilitation training, wearable assistive robots become a potential way to help healthy people prevent dyskinesia, and to help patients do rehabilitation exercises in their daily activities.

There have been extensive researches on wearable lower limb robots in the form of passive, quasi-passive and active devices to assist human movement. However, most of them are impractical, such as exoskeletons [7]-[11], because they are heavy, bulky, high energy consuming, expensive, not portable and may require a team of clinicians for supervised therapy sessions [12]. It is necessary to develop an energy saving and comfortable wearable robot.

Humans are a rich source of energy. An average-sized person stores as much energy in fat as a 1000-kg battery [13]. Many researchers have studied on the area of biomechanical energy harvesting from human motion [13]-[18]. They mainly focused on the designing of energy harvesting devices that take advantage of human power capacity to produce electricity [15]-[18], but few of them collected and transferred the biomechanical energy to assist human movement directly.

Research on soft robots made of various soft materials is gaining momentum in the field of wearable robotics [19], [20], such as the shape-memory alloys actuators [21] and electroactive polymer (EAP) actuators [22] driven by high temperature and high voltages respectively. A kind of wearable robots made of Bowden cables for walking assistance and gait rehabilitation in patients have been successfully developed [23]-[25]. However, because of their linear mechanisms, Bowden cables require metal structures and bearings to serve as a transmission that converts linear motion into rotary motion. Recently, soft pneumatic wearable robots have also attracted more and more attentions of researchers in the areas of robotics [26]-[30].

In this paper, the biomechanics of walking gait is analyzed and an intelligent energy management profile for knee assistive robotics is proposed in Section II. Then, the fabrication process of IFVSKE is presented in Section III. Section IV describes the experimental evaluation scheme and results. Finally, we make a conclusion in Section V.

II. BIOMECHANICAL ENERGY MANAGEMENT

A. Biomechanical Analysis of Walking Gait

As shown in Fig. 1, the stages of walking during a stride by the right foot are diagrammed. The stride is decided to start with initial contact of the right heel, then the cycle will continue until the right heel contacts the ground again. According to the biomechanical analysis results which will be presented in Section II *B*, we subdivide the gait cycle into six periods, in which four in the stance phase, and two in the swing phase.

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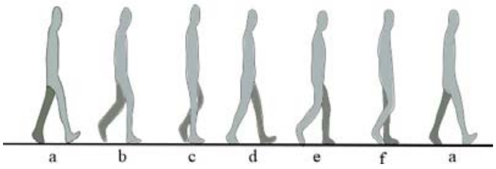

Fig. 1 A walking gait cycle

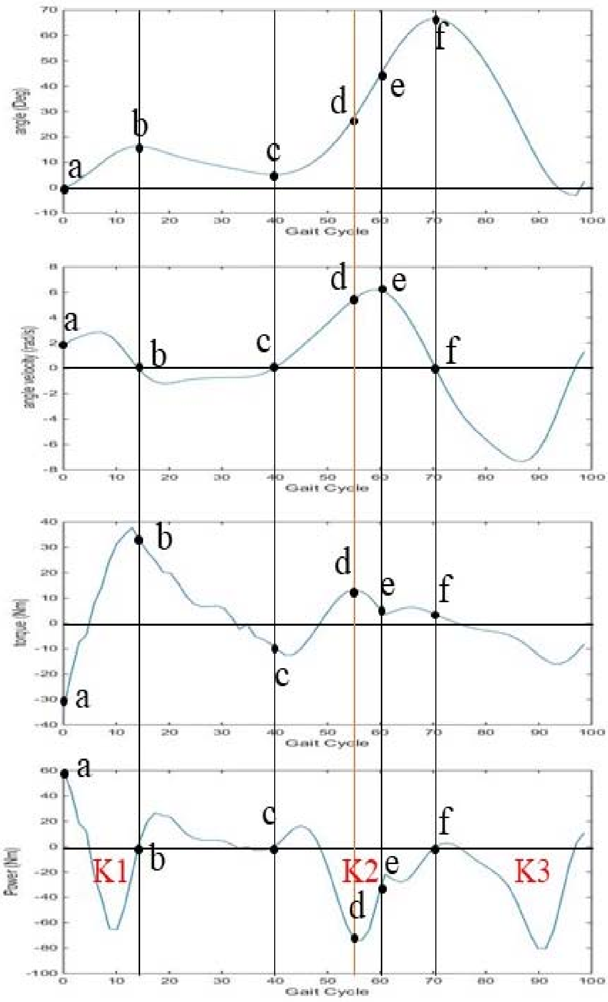

Fig. 2 Kinematics and dynamics of knee joints

Considering that walking is a cycling process, we extracted the kinematic and dynamic data of a walking gait cycle from the book [31] and analyzed the data in detail. Fig. 2 presents the analysis results about the variation regulations of knee joint angle, angular velocity, torque and power.

B. Intelligent Energy Management Profile

As shown in Fig. 2, the knee generates a large amount of negative power that is marked by K1, K2 and K3. Harvesting this part of the negative work to assist the positive stage of the knee joint may greatly reduce human metabolism and help the body save energy. To facilitate this idea, we first investigated the quasi-stiffness to characterize the spring-like behavior of knee joint. Quasi- stiffness is the physical quantity to represent the variable stiffness behavior of the knee joint in human gait. The moment-angle relationship is depicted in Fig. 3 using the biomechanical data in book [31]. Additionally, the linear fit of the moment-angle curve is also shown in Fig. 3 using red broken lines. Therefore, we proposed an intelligent energy management profile of knee joints during the gait cycle. As shown in Fig. 3, the gait cycle is divided into six stages by six points: a-f. Each stage corresponds to a specific linear spring. By adding a variable stiffness spring in parallel with the knee joint and adjusting its stiffness at these six points according to Fig. 3, we can collect and reuse the biomechanical energy of human bodies and save the physical energy consumption during walking.

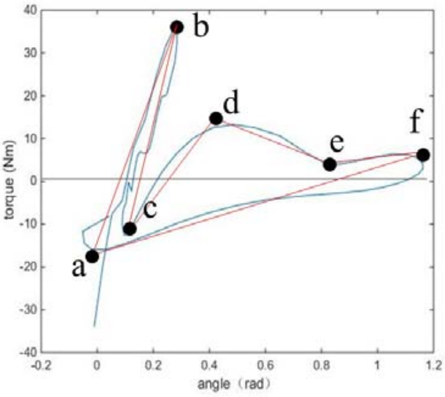

Fig. 3 Quasi-stiffness of the knee joint

III. DESIGN AND FABRICATION OF IFVSKE

Inspired by Chinese traditional folding fans and balloon inflators, we present an IFVSKE to implement the intelligent energy management profile proposed in section II.

Above all, an actuator made of TPU fabric material is fabricated. As shown in Fig. 4, the actuator is essentially a combination of several ventilated air chambers. During fabrication, the TPU fabric is first cut into many rectangular sheets. Then, two of the sheets remain the same and others enter the airflow holes creating stage. In this stage, two holes are created on one of the sheets, while one is created on the rest. A plastic air tap is subsequently mounted on the left small hole of the sheet with two holes by the high frequency welding technique. Afterwards, two pieces of rectangular sheets are sealed to serve as the chamber of the actuator. After all the chambers are finished, they are connected by the high frequency welding technique.

After we have finished the actuator of IFVSKE, we integrate it into an elastic kneecap to facilitate fixation and comfort. The initial physical prototype of IFVSKE is shown in Fig. 5.

Control units and a series of pneumatic components are also integrated in the IFVSKE. As shown in Fig. 6, pneumatic components consist of pneumatic supply, solenoid valve, pressure sensor.

Fig. 4 Actuator of IFVSKE

Fig. 5 Physical prototype of IFVSKE

IV. EXPERIMENT AND RESULTS

Preliminary experiment was conducted to verify the performance of the IFVSKE. A healthy subject took part in the experiment, and the IFVSKE is worn on the subject's left knee joint. It should be noted that all the experimental procedures used in this study were approved by the NPU School Ethics Committee and the subject gave written informed consent and provided permission for publication of photographs for scientific and educational purposes.

Fig. 6 Subject experiment

For comparison, the healthy subject was required to walk 5 minutes with and without the IFVSKE respectively. After the experiment, the subject stated that wearing the IFVSKE is comfortable and energy-saving.

V. CONCLUSION

Inspired by Chinese traditional folding fans and balloon inflators, we designed an IFVSKE in this paper. The concept of intelligent management of biomechanical energy was proposed based on the analysis of the kinematic and dynamic behaviors of human knee joints. The biomechanical energy of knee joints in a walking gait cycle could be collected and reused to assist subjects just by adjusting the inner pressure of IFVSKE. Additionally, we will further improve the design and control profiles of IFVSKE in the following works.

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