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Special Focus on Bio-Robotic Systems: Modeling, Design, Control and Perception

Development of a lower limb multi-joint assistance soft exosuit

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Dear editor,
Great progress has been made in exoskeleton research over the past decades. Exoskeletons of various types have been developed for a range of purposes, predominantly military and clinical [1, 2]. Some adopt rigid structures to increase the wearer's load carriage capacity, while others utilize external power sources to provide the wearer with assistance using rigid structures. However, traditional exoskeletons with rigid structures are troubled by problems including excessive weight, restricted mobility, relatively low sensitivity, and large inertia. In recent years, soft wearable lower limb assistance exoskeletons have received increasing attention. For example, with support from the Defense Advanced Research Projects Agency, Harvard University designed and built several prototypes providing assistive torque to a combination of hip and ankle joints, and the ankle joint alone [3, 4]. Zhang et al. [5] of Carnegie Mellon University also developed a soft exosuit for augmenting the wearer's ankle torque to reduce metabolic energy consumption. Compared to traditional rigid exoskeletons, soft exosuits predominantly consist of soft textiles and are always designed to assist able-bodied adults such as soldiers rather than people with disabilities, reducing the user's metabolic rate to help boost their performance in particular tasks. Exosuits also have advantages in terms of flexibility, weight, sensitivity, and comfort. In this study, we present the design of a soft wearable lower limb multi-joint assistance exoskeleton for providing assistance in situations including walking on flat ground, uphill walking, and stair climbing. This exoskeleton is capable of assisting multi-articular hip/knee joints or mono-articular hip joint, depending on specific scenario. Development of the proposed exosuit comprises three main elements: mechanical design, target assistance force profile generation, and control strategy. The exosuit weighs 6.6 kg and is composed of an actuation unit, control unit, battery, sensors, cables, and textiles. Experimental results demonstrate that our proposed soft exosuit can reduce average metabolic rate by 6% in walking on flat ground, 10% in uphill walking and 14% in stair climbing tasks.

Design overview. The proposed soft exosuit is designed to aid both knee and hip joints in various tasks, including walking on flat ground, uphill walking, and stair climbing. As shown in Figure 1(a), the exosuit consists of an actuation unit, control unit, battery, textiles, load cells, inertia measurement units (IMUs), soft strain sensor units, a Bowden cable, belt, and knee regions. IMUs and soft strain sensors serve to detect gait and capture the wearer's posture in real-time. Using data from the IMUs (LPMS-B2, Alubi, China)

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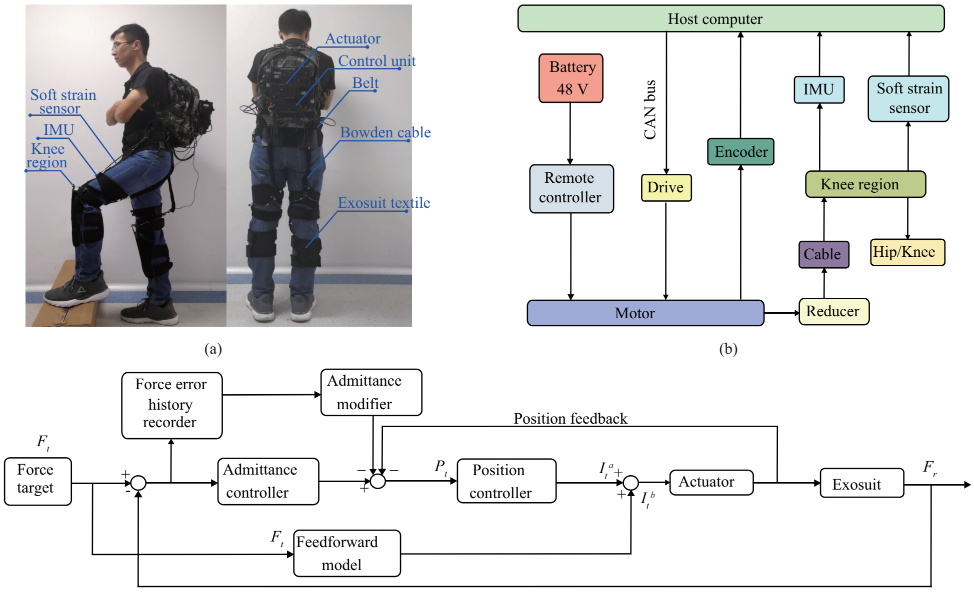

Subject	Ground			Uphill			Upstairs		
	Non-active (W/kg)	Active (W/kg)	Reduction (%)	Non-active (W/kg)	Active (W/kg)	Reduction (%)	Non-active (W/kg)	Active (W/kg)	Reduction (%)
#S1	5.00	4.66	6.8	11.45	10.11	11.7	9.67	8.11	16.1
#S2	5.16	5.00	3.1	9.12	8.39	8.0	9.99	8.60	13.9
#S3	5.72	5.21	8.9	9.10	8.03	11.8	8.62	7.44	13.7

(d)

Figure 1 (Color online) (a) The proposed exosuit with components labeled; (b) schematic of the soft exosuit system; (c) block diagram of control strategy schematic; (d) metabolic testing results for walking on flat ground, uphill walking, and stair climbing.

and soft strain sensors, the control unit determines the wearer's gait phase and sends control commands to the actuation unit accordingly. The IMUs and soft strains sensors have a sampling frequency of 120 Hz, and the system's control frequency is about 100 Hz. The actuation unit is composed of motors (#6010, DJI, China) and reels, to which one end of the Bowden cable is attached. The other end is attached to the knee region load cells (ZNLBS-v1, Chino Sensor, China). The knee region is formed from a carbon fiber material shaped like a bended "Y", and attached to textile that wraps around the shins. Actuation is applied via the Bowden cable extending from the actuator unit to the knee joint. Utilizing a lever mechanism and straps, tension in the cable creates moment about the knee joint to aid knee extension, with a vertical component to aid hip extension. When walking on flat ground, energy is mainly consumed by the hip joint. During the stance phase, the knee extends maximally, and knee lever mechanism loses its utility. Hence, the exosuit provides only hip joint assistance for walking on flat ground. Assistance mode switching is performed automatically by the mechanism. A computer (ARM Cortex M7) collects all the sensor data and controls the motor drive via controller area network, as shown in Figure 1(b).

Force target generation. Gait recognition is essential to controlling the soft exosuit [6]. In this study, the target assistance force is generated by measuring the joint angle, meaning that the target force generated by the computer is posture-related rather than time-related. Thus, the soft exosuit can track changes in walking speed, and will not interfere with the wearer's normal gait if walking speed changes suddenly. The joint angle is measured by IMUs mounted on the front of the thighs, and key gait events such as heel strike and toe off are also detected by IMUs. A basic target force profile is generated based on gait event detection and real-time joint angle measurement. Target force is then modified in accordance with variation in exercise intensity, detected by soft strain sensors mounted on the front of the thighs.

Control strategy. The proposed soft exosuit employs a control strategy based on an admittance control method, as shown in Figure 1(c). Two load cells are integrated to the end of the cable to measure real-time assistance force. The measured force value is compared with the target force value. The force error and force target values help the admittance controller determine motor position in the next control cycle using the following equation [7], which is also the basis of our control system:

$$x_p = \frac{1}{Ms + C} \cdot (F_r - F_t), \quad (1)$$

where x_p is the desired motor position, F_r is measured assistance force, F_t is target assistance force, and M and C are virtual inertia and damping, respectively. After motor position is generated, it is further modified according to the corresponding force error in the previous gait cycle. The modified motor position tends to produce more accurate assistance force than in the previous cycle. The iterative controller iteratively learns the error history and minimizes it on a step-by-step basis, which works well in practice to compensate for the model-based method. Additionally, a method of cable pre-tensioning is applied to pretighten the Bowden cable before providing assistance, which can significantly reduce latency and improve robustness. The wearer's body parameters are used to initialize pre-tension parameters to adapt to different wearers. An iterative learning control method is also used in the pre-tension procedure to optimize the pre-tension parameters.

Experiment and result. We conduct three comparison experiments on three healthy male subjects over four days, involving walking on flat ground, uphill, and on stairs. On the first morning, the volunteers wear the non-active exosuit to perform ground walking tests. On the second morning, the same test is repeated with volunteers wearing the active exosuit. Tests involving uphill walking are performed on the first and second afternoon, and stair climbing tests are performed on the third and fourth afternoon. Each test includes 5 min resting and 10 min walking/climbing. Ground and uphill walking experiments are performed on a treadmill at 4.5 km/h for both conditions, with an incline of 5° for the uphill walking condition. Stair climbing experiments are performed on stairs from the first floor to the twelfth floor of a building, with time spent climbing stairs between each floor restricted to 21 ± 0.5 s. We then analyze the average metabolic cost of each walking/climbing test. Results from nine groups of experiments are listed in Figure 1(d). We use COSMED K5 to measure volumetric change in gases such as O_2 and CO_2. A subject's metabolic cost rate can be calculated from these data:

$$\Delta H = c_1 \cdot V_{\mathrm{O}_2} + c_2 \cdot V_{\mathrm{CO}_2} - c_3 \cdot M_{\mathrm{N}_2}, \quad (2)$$

where coefficients $c_1 = 16.58$, $c_2 = 4.51$, $c_3 = 5.90$ using Brockway's method [8]. Our experimental results indicate an average net metabolic rate reduction of 6%, 10.5% and 14.6% compared to no assistance in walking on flat ground, uphill walking, and stair climbing tasks respectively, corresponding to reductions of 0.33 W/kg, 1.05 W/kg and 1.36 W/kg, respectively.

Conclusion. In this study, we developed a multi-joint assistance soft exosuit for different walking conditions. The knee lever mechanism engages automatically on knee extension, proving an efficient method for self-determining whether knee assistance should be applied. A spatial target force generation method ensures the system follows a stable target irrespective of gait changes, and eliminates the effects of changes in walking speed. Metabolic test result showed the system can reduce the wearer's metabolic rate by 6%–14%. In the future, we plan to focus on building a more robust control system capable of adapting to complex terrains.

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