SCIENCE CHINA
Information Sciences

May 2019, Vol. 62 050202:1–050202:3
https://doi.org/10.1007/s11432-018-9717-2

• LETTER •
Special Focus on Human-Robot Hybrid Intelligence

The development of a high-speed lower-limb robotic exoskeleton

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Received 27 August 2018/Revised 3 November 2018/Accepted 30 November 2018/Published online 16 January 2019

Citation Ren Z, Deng C J, Zhao K K, et al. The development of a high-speed lower-limb robotic exoskeleton. Sci China Inf Sci, 2019, 62(5): 050202, https://doi.org/10.1007/s11432-018-9717-2

Dear editor,

With continuously advancing science and technology, the lower-limb robotic exoskeleton, an assistive-type device for humans, has achieved unprecedented development in both the military and civilian fields. At present, several exoskeletons have entered the commercialization stage. The most notable of these is Rewalk, which was developed in Israel1). Several other exoskeletons have control strategies that are similar to those of Rewalk but use different gait-detection methods; for example, Ekso GT, from Ekso Bionics in the United States [1]; Indego, from Parker Hannifin in the United States [2]; and Rex, from Rex Bionics in New Zealand [3]. Also, three exoskeletons have been used as standards for prototype comparison: MINDWALKER, developed at University of Twente in the Netherlands [4]; Mina, from the Institute for Human and Machine Cognition in the United States [5]; and HEXAR, developed at Hanyang University in South Korea [6]. The speed of these exoskeletons was calculated by measuring the time they take to walk on an indoor flat surface for a specified distance. The walking speed of these exoskeletons is much slower than the average natural speed of humans, and most of the exoskeletons need various auxiliary support tools to maintain dynamic balance (see Figure 1(a)). Therefore, we realized the need to develop an exoskeleton for high-speed walking without requiring auxiliary support tools. We propose an exoskeleton that allows subjects to walk at a high speed without the help of auxiliary support or assistive tools (see Figure 1(b)). The design of the exoskeleton that we developed involves three aspects: mechanical design, trajectory generation, and control strategy. The proposed exoskeleton comprises two legs powered by direct-current servomotors. Each leg has four degrees of freedom, including three that are powered and passive one, which govern movement of joints (hip, knee, and ankle). The center-of-mass transition and lateral foot placement require active control of the hip adduction/abduction motion to achieve dynamic balance and to counteract disturbances in the lateral plane. We applied an online step-width adaptation [4] to maintain dynamic balance during hip adduction/abduction motion. To improve applicability and flexibility of the exoskeleton, we used a control strategy based on a predefined gait. Experiments show that healthy subjects wearing the exoskeleton that we developed can achieve a walking speed of 0.8 m/s with and without auxiliary tools. This exoskeleton walking speed is faster than most motor-driven exoskeletons.

Exoskeleton design. The joints of the proposed exoskeleton that we developed were designed to align with human joints in the sequential movements of hip adduction/abduction (HAA), hip flexion/extension (HFE), knee flexion/extension (KFE), and ankle dorsiflexion/plantarflexion (ADP) from pelvis to foot. HAA, HFE, and

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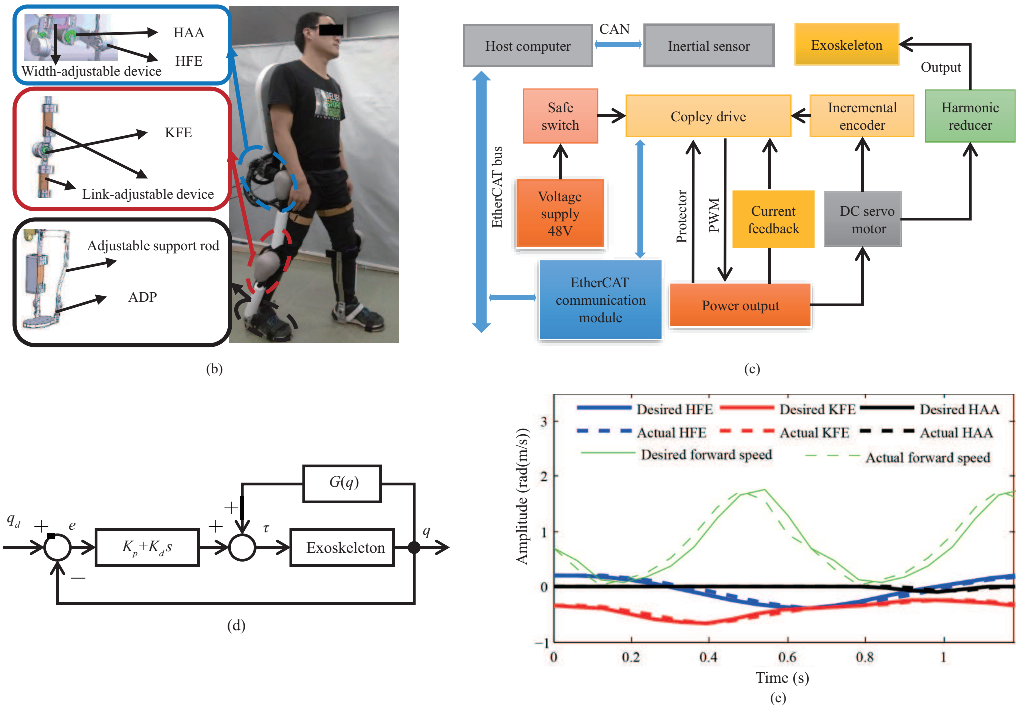
1) http://rewalk.com.

Name	Weight (kg)	Speed (m/s)	Price (USD)	Degrees of freedom	Auxiliary tools
Rewalk 6.0	23.3	0.72	77000	4	Yes
Ekso GT [1]	23.0	0.55	160000	6	Yes
Indego [6]	11.8	0.55	70000	4	Yes
Phoenix[a)]	12.3	0.49	45000	4	Yes
HEXAR [5]	21.0	0.42	–	15	Yes
Mina [4]	34.0	0.20	–	4	Yes
Rex [1]	38.0	0.05	110000	10	No
MINDWALKER [3]	28.0	0.08	–	10	No
Our developed exoskeleton	25.8	0.80	35000	8	No

a) https://www.suitx.com/phoenix-medical-exoskeleton.

(a)



(b)

(c)

(d)

(e)

Figure 1 (Color online) (a) Available walking exoskeletons; (b) developed exoskeleton; (c) schematic of exoskeleton system controls; (d) block diagram showing exoskeleton controls, where τ is the control input, q_d and q are the desired and actual positions, respectively, in joint space, K_p and K_d represent adjustable-control gain, and $G(q)$ is used to compensate for the gravity torque of the exoskeleton; (e) trajectories of joints and human walking velocities.

KFE are powered, while ADP is passive. Various adjustable mechanisms (e.g., a width-adjustable pelvic device, a link-adjustable thigh/shank device, and an adjustable support rod) were designed to accommodate anatomical diversity among subjects or users. Each motor (manufactured by Maxon Motor company), equipped with a harmonic transmission drive, can provide a nominal torque of 70.4 N·m. The control structure of the exoskeleton system is shown in Figure 1(c). The communication protocol of the exoskeleton network system is EtherCAT, and the controlling computer can communicate with Copley drives via the EtherCAT field bus. The sampling frequency of the network is 1000 Hz. The output torque of two motors can be controlled by a single Copley drive, which can communicate with the incremental encoders to measure the rotation angle and direction of the motors. The inertial sensor shows the absolute gravity orientation. The supply voltage of the exoskeleton is 48 V.

Trajectory generation and control strategy. At present, there are five main control strategies: (1) sensitivity-amplification strategy; (2) predefined-gait strategy; (3) gait-based predefined-drive control strategy; (4) hybrid control strategy; (5) dynamic-based control strategy. For HFE and KFE, we adopted the predefined-gait control strategy (because of its applicability and flexibility) and used the clinical gait-analysis data obtained from healthy adults to provide trajectories. For HAA, we generated the trajectory in real time by an online step-width adaptation to maintain the stability of the human-robot system. As shown in Figure 1(d), we used the joint-feedback controller with gravity compensation to control the exoskeleton.

Experiments and results. To evaluate performance of the exoskeleton that we developed, we designed three experiments: (1) exoskeleton walking without any load; (2) healthy subject wearing exoskeleton walking with crutches down a corridor of 10-m length; and (3) healthy subject wearing exoskeleton walking without crutches down a corridor of 10-m length. These experiments were performed using two healthy test subjects. Because currently there is no analytical approach for the selection of the control parameters, they were adjusted by trial-and-error to make the controller optimal and effective. Results of the third experiment for one of the two test subjects (Figure 1(e)) show that the actual positions of joints converge to the desired trajectory and the actual forward speed converges to the desired value. Therefore, the controller is optimal and effective. The speed of the exoskeleton without any load reached 1.02 m/s, and healthy test subjects wearing the exoskeleton achieved a walking speed of 0.8 m/s with and without crutches.

Conclusion. In this research, we developed an exoskeleton for high-speed walking without the help of auxiliary tools. HAA was controlled to maintain the stability of the human-robot system by using an online step-width adaptation. When the exoskeleton was tested on healthy subjects, the walking speed of the exoskeleton without any load was able to reach 1.02 m/s, and test subjects wearing the exoskeleton could achieve a speed of 0.8 m/s with and without crutches. The walking speed of the exoskeleton that we developed was faster than that of other exoskeletons (Figure 1(a)).

Acknowledgements This work was supported in part by National Natural Science Foundation of China (Grant Nos. 61573147, 61625303, 61751310), National Key Research and Development Program of China (Grant No. 2017YFB1302302), Guangdong Science and Technology Research Collaborative Innovation Projects (Grant Nos. 2014B090901056, 2015B020214003, 2016A020220003), Guangdong Science and Technology Plan Project (Application Technology Research Foundation) (Grant No. 2015B020233006), and Anhui Science and Technology Major Program (Grant No. 17030901029).

References

1 Gardner A D, Potgieter J, Noble F K. A review of commercially available exoskeletons' capabilities. In: Proceedings of International Conference on Mechatronics and Machine Vision in Practice (M2VIP), Auckland, 2017. 1–5

2 Tefertiller C, Hays K, Jones J, et al. Initial outcomes from a multicenter study utilizing the indego powered exoskeleton in spinal cord injury. Top Spinal Cord Injury Rehab, 2018, 24: 78–85

3 Cardona M, Destarac M A, García C E. Exoskeleton robots for rehabilitation: state of the art and future trends. In: Proceedings of IEEE 37th Central America and Panama Convention, Managua, 2017. 1–6

4 Wang S, Wang L, Meijneke C, et al. Design and control of the MINDWALKER exoskeleton. IEEE Trans Neural Syst Rehabil Eng, 2015, 23: 277–286

5 Neuhaus P D, Noorden J H, Craig T J, et al. Design and evaluation of Mina: a robotic orthosis for paraplegics. In: Proceedings of IEEE International Conference on Rehabilitation Robotics, Zurich, 2011. 1–8

6 Kim W, Lee H, Kim D, et al. Mechanical design of the Hanyang exoskeleton assistive robot (HEXAR). In: Proceedings of International Conference on Control, Automation and Systems (ICCAS), Seoul, 2014. 479–484