Design and Experimental Evaluation of a Lower-Limb Exoskeleton for Assisting Workers With Motorized Tuning of Squat Heights

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***Abstract*— This paper presents the E-LEG, a novel semi-passive lower-limb exoskeleton for worker squatting assistance, with motorized tuning of the assistive squatting height. Compared with other passive industrial exoskeletons for the lower-limbs, the E-LEG presents novel design features namely inertial sensor for measuring the tilt angle of thigh and the novel electromagnetic switch for adjusting squat height. These features could enhance the effectiveness of the system. In addition to the introduction to exoskeleton design, this paper also reports the systematic experimental evaluation of human subjects. With the assistance of different conditions, the variability of muscular activity was evaluated in long-term static squatting task. The set of metrics to evaluate the effect of the device included leg muscle activity, plantar pressure fluctuation, plantar pressure center fluctuation and gait angles. Results show that the exoskeleton can reduce the muscular activity of the user during squatting, and it will have little affect the normal gait of the user during walking. In this study, we found that the E-LEG exoskeleton has potential effectiveness in reducing the muscular strain on long-term continuous squatting activities.**

***Index Terms*— Industry 4.0, lower-limb exoskeletons, workers assistance, wearable robotics.**

Manuscript received June 14, 2021; revised October 21, 2021 and December 2, 2021; accepted January 11, 2022. Date of publication January 14, 2022; date of current version January 31, 2022. This work was supported in part by the Shenzhen Joint Key Fund Project of National Natural Fund under Grant U1813212; in part by the National Natural Science Foundation of China under Grant 52175061; in part by the Xinjiang Major Science and Technology Project 2021A02002-3; in part by the Shaanxi Provincial Key Research and Development Program under Grant 2020GXLH-Y-007, Grant 2021GY-333, Grant 2021GY-286, and Grant 2020GY-207; in part by the Shanxi Provincial Key Research Project 2020XXX001; and in part by the Tiandi Science and Technology Development Fund under Grant 2020-TD-ZD009 and Grant M2020-ZD03. *(Corresponding author: Aibin Zhu.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Biomedical Ethics Committee of Medical Department of Xi'an Jiaotong University.

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Digital Object Identifier 10.1109/TNSRE.2022.3143361

I. Introduction

WORK related musculoskeletal diseases (WRMSDs) can occur to any part of the musculoskeletal system, such as upper limbs, lower limbs, waist, etc. [1]. Statistics from 2016 Health and Safety Authorization Report indicate that 11% of WRMSD occurs in the lower limbs [2]. Especially working condition that need standing or squatting for several hours during the day, such as mining, assembly lines and surgery, etc. All of these activities will increase the fatigue of lower limb muscles and reduce its exercise performance [3]. Medical research shows that standing or squatting for a long time will probably not only lead to lower limb skeletal muscle disease [4], [5] but also increased risk of cardiovascular disease, which caused leg congestion, increased venous pressure and oxidative stress.

Considering the need to keep standing or squatting for a long time at work, automobile assembly line [6] is one of the most extensive industries facing the risk of lower limb WRMSDs. In the automobile assembly line, due to space constraints, workers can only stand or squat for assembly operation. This situation requires a new method to support the workers' body. Exoskeleton is a mechanical structure worn on the human body, which can not only enhance human strength [7], but also reduce the physical burden of manual workers. With the continuous increase in industrial demand, exoskeleton is gradually promoted and applied to the industry [8], [9]. When the lower limb joints must be kept bent for a long time, the lower limb exoskeleton is expected to alleviate the stress and strain of the musculoskeletal system. In addition, workers may work at different heights and need to continuously shift between different workstations. Thus, the exoskeleton of assisted squatting shall be able to switch between walking and squatting freely, and the height of squatting can be adjusted according to the required working height.

In recent years, the lower limb exoskeleton, which is used to prevent lower limb musculoskeletal diseases, has attracted much attention, and some research institutions and companies have carried out research on it. According to the function characteristics of exoskeletons, existing exoskeletons can be divided into two types. One type of exoskeleton can provide dynamic weight-support when the user is walking, which helps to reduce the burden on the legs during walking [10], and the other type of exoskeleton provides static weight-support when the user squats, which helps to reduce leg muscle fatigue during squatting [11]. This paper focuses on the latter.In order to reduce the leg burden of people that need to stand or squat for a long time at work, the lower limb exoskeleton for assisting squat has been widely studied. With major automobile companies such as BMW, Honda, Volkswagen and Daimler showing great research enthusiasm for developing and using exoskeletons to help workers squat [12], emerging products such as CC (Chairless Chair) [13], Archelis [14], HUST-EC [15] and ChairX [16] have emerged. Most designs provide freely walking between different workstations and freely switching between walking and squatting, but can only provide a fixed assisted squatting height. Chairless Chair provides three possibilities to adjust the squat heights, and Archelis only supports two squat heights. Most of these designs employ passive locking mechanisms, therefore, these designs require manual operation when adjusting the assisted height, which has greatly affected the work efficiency of workers.

At present, there are many methods of the evaluation of lower limb exoskeleton. In order to study whether the lower limb exoskeleton can reduce the metabolic cost, Andrej *et al.* [17] measured the parameters of oxygen consumption and heart rate in the experiment, and the results showed that the exoskeleton can significantly reduce the energy consumption during squatting.Some researchers had evaluated CC's effects. Bridger *et al.* [11] studied the effect of CC on user's attention and conducted an attention response test. The test results showed that although CC reduced the physical burden during squatting, it reduced attention due to the tightening of knee joint. Luger *et al.* [18] proposed that CC reduced muscle activity in the gastrocnemius muscle but increased muscle activity in the gluteus maximus. Han *et al.* [15] designed a CC-like exoskeleton named HUST-EC and verified by sEMG experiments that it could effectively reduce the physical burden of workers. Although the above evaluation methods can reflect the auxiliary effect of exoskeleton on the human body, they cannot fully reveal the auxiliary mechanism of exoskeleton. Therefore, a new set of exoskeleton evaluation indicators must be proposed to the perspectives of kinematics, dynamics and biomechanics.

Despite some achievements have been made in studies on lower extremity assisted exoskeleton, they have not been widely used in industry. There are three main problems: short endurance, hindering the normal walking of the human, and a single support posture. Powered exoskeleton [13] can cause endurance problems, like the CC which is a battery-powered device and can only provide a limited 8-hour battery life on a single charge. In particular, the change of this exoskeleton joint angle depends on the motor response speed, which is not conducive to the movement of the wearer. The passive lower limb assisted exoskeleton [19] can only provide a single assisted support posture after setting, and the assisted support posture can only be changed by manually changing the mechanical setting of the exoskeleton. In addition to the simple function of supporting the body, a semi-passive device can be designed to enhance the ability of the passive system to adapt to different tasks by actively adjusting the height of the auxiliary squatting posture. Although this function is considered to be an interesting possibility and provides a certain degree of adaptability to the exoskeleton, as far as the author knows, there is no lower limb exoskeleton with such a capability in the existing technological features, but the existing semi-active upper extremity exoskeleton [20] and quasi-passive spinal exoskeletons [21] can be used as a design reference.

In order to develop this possibility, a new type of semi-passive lower limb assisted exoskeleton, E-LEG, is introduced in this paper. E-LEG has a structure similar to the existing CC exoskeleton, but compared to CC, it has two new key design features, making the device smarter and more adaptive. One is an active tuning mechanism, that is, a squat height adjustment mechanism, which is composed of a pawl coupled to a push-pull electromagnet, allowing the exoskeleton joint to lock at a variable height. Another is composed of an exoskeleton inertial sensor and a pressure sensor on the bottom of the exoskeleton, which can be used to estimate the user's current posture and control the exoskeleton with finite state machine automatically.

While describing the mechanical and electrical design of exoskeleton, this paper presents an experimental result of functional equipment evaluation. Similar to other studies evaluating the effectiveness of the lower extremity exoskeleton through objective indicators [22]–[26], we studied a set of indicators to simultaneously evaluate the effects of assistance on muscle activity and muscle fatigue in the lower limbs, as well as on gait during walking.

The rest of this paper is structured as follows: Section II describes the design of mechanical and electrical integration of E-LEG, while Section III reports on the experimental evaluation protocol. The Section IV presents the experimental results, followed by the discussion of key results and proposed future developments in Section V.

II. Design of the E-LEG Exoskeleton

The E-LEG (Fig. 1(a)) is a lower limb exoskeleton developed by our teams [27]. The exoskeleton, weighing 3 kg, consists of the following main sub modules: (1) the physical Human-Exoskeleton Interaction (pHEI), (2) the main structure, (3) the mechanism for squat height tuning, and (4) the control system. Similar to CC, the design of E-LEG is based on safety related design standards, with compact structure and ergonomics.

A. Physical Human-Exoskeleton Interface

The central part of the pHEI is a wearable vest like strap that includes a nylon shoulder strap and belt (Fig. 1(a)). Shoulder strap and belt are ergonomically designed to distribute the weight of the exoskeleton evenly around the waist and shoulders. The end part of the pHEI is a wearable shoe cover, including a foot plate made of aluminum alloy and a foot ring hinged to the foot plate. The exoskeleton device in contact with the human thigh is covered with a soft cushion fabric. The belt and shoe cover design makes the process of wearing and removing E-LEG quick and simple. On a wide soft belt, a pair

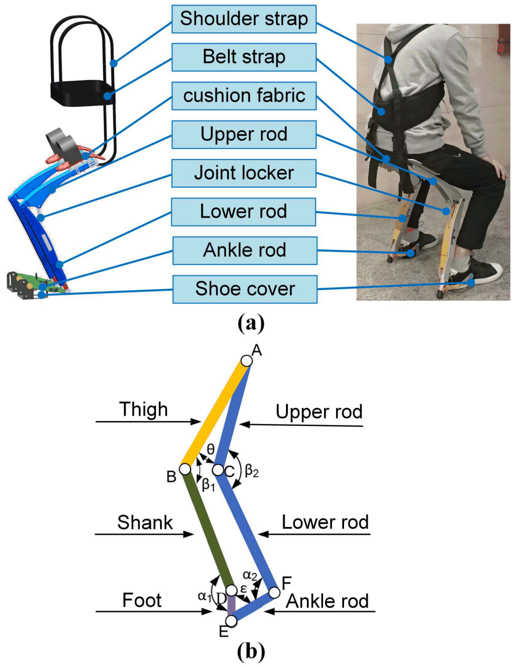

Fig. 1. Design of the E-LEG exoskeleton. (a) Overview of the exoskeleton. (b) Schematic diagram of dimension constraint of exoskeleton main structure.

of staggered shoulder belts are fixed to the exoskeleton. The thigh rod of E-LEG is connected to the user's thigh through a nylon cuff, which can be tightened with Velcro belt, and the foot plate of E-LEG is connected to the user's shoes through a C-shaped rubber belt. The fabric used for all soft parts is very breathable.

B. Main Structure

The main structure of exoskeleton is composed of two aluminum alloy bars connected by hinged joints, which allow [0:100] deg in flexion/extension. The size design of the main structure (Fig. 1(b)) should not only meet the physiological parameters of the human body, but also ensure that people can freely switch between sitting and walking. In order to minimize the negative impact of this wearable chair on the normal gait of users, the design of this E-LEG exoskeleton should follow the following three constraints:

a. The vertical distance from point C to rod BD should greater than a positive constant a, which is related to the outer diameter dimension of the user's shank:

$$L_{C-BD} > a \tag{1}$$

b. The vertical distance from point F to rod BD should greater than a positive constant b, which is related to the outer diameter dimension of the user's shank:

$$L_{F-BD} > b \tag{2}$$

c. The bottom of the exoskeleton should not touch the ground during the user walking:

$$L_{AB} + L_{BD} > L_{AC}\cos\theta + L_{CF} \tag{3}$$

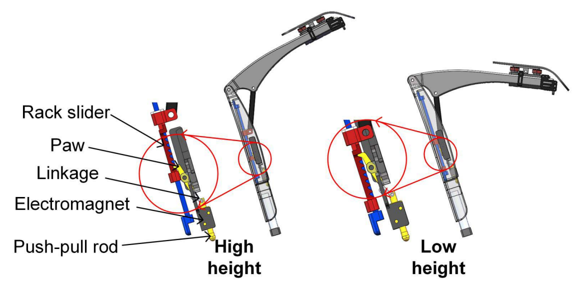

Fig. 2. Overview of squat height tuning mechanism.

θ depends on the tightness of the band between the exoskeleton and the thigh and the contour of the human's thigh:

$$5^{o} < \theta < 10^{o} \tag{4}$$

By geometric relationship:

$$\begin{cases} L_{C-BD} = L_{AB}\sin\beta_1 - L_{AC}\sin(\beta_1+\theta) \\ L_{EF}^2 = L_{DE}^2 + (L_{AC}\sin\theta + L_{CF}\sin\theta_1)^2 \\ L_{F-BD} = L_{EF}\sin(\alpha_1-\varepsilon) - L_{DE}\sin\alpha_1 \end{cases} \tag{5}$$

According to the above analysis, the length design of exoskeleton rod determines the size of each rod. In order to meet the needs of people with different heights, an adjustable length exoskeleton rod was designed. In addition, the exoskeleton was only attached to the user's foot and hip, and there are two hinge pairs between the top and end of the exoskeleton, as shown in (Fig. 1(b)). Therefore, the exoskeleton and the human leg form a redundant link, which can avoid high knee-joint interaction torque caused by dis-aligned hinge joints [28].

C. Squat Height Tuning Mechanism

The squat height tuning mechanism contains the mechanism which can keep the joint locked. The auto-locking mechanism consists of a rack which can slide along the lower leg of the exoskeleton and a pawl which can mesh with the rack (Fig. 2). The pawl is connected to the push-pull rod of the electromagnet through a linkage. The pawl is connected to the shell of the lower leg rod of the exoskeleton through the hinged pair, so the pawl is a lever structure. When the electromagnet is powered on, the push-pull rod generates a downward pull force, which makes the pawl and the rack mesh to lock the joint. When the electromagnetic switch is powered off, the push-pull rod loses magnetism, and the pawl and the rack are separated. It is worth mentioning that when the user sits down and the joint is auto-locking, even if the electromagnet is not powered on, the exoskeleton joint can still keep one-way auto-locking. When the user stands up, the rack slides upward, the pawl and rack are separated, and the joint is one-way unlocked.

When the locked joint is released, by changing the angle of the knee joint combined with the auto-locking mechanism, the assisted squat height of the E-LEG exoskeleton can be changed from about 0.4m to 0.8m. The electromagnetic switch (KAKCOM, KK-0520, China) allows the joints of the

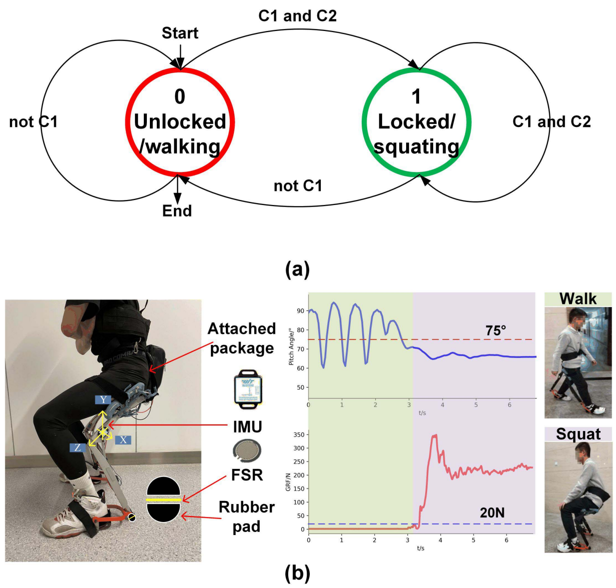

Fig. 3. Control system of the E-LEG exoskeleton. (a) Model of finite state machine. (b) Sensor setting of control system.

exoskeleton to be locked at variable angles by actively applying tension to the push-pull rod. An inertial sensor (DOFLY, WT901BLECL, China) is assembled on the upper leg of the exoskeleton to measure the angle between the upper rod and the horizontal direction through the rolling angle of the inertial sensor. When starting the system (reset procedure), the pressure between the end of the exoskeleton and the ground is measured. For this purpose, a pressure diaphragm sensor (Tekscan, Inc., Flexiforce, USA) is use.

D. Control System

The E-LEG control system is constituted by a finite state machine (FSM) (Fig. 3(a)). The FSM is divided into two states according to the instantaneous value of every sampling point measured by the inertial sensor and pressure sensor within 1 s window. State 0 is defined as the exoskeleton joint unlocking state, and state 1 is defined as the exoskeleton joint locking state. The state switch of state machine includes two conditions, condition 1 (C1) is that the measured instantaneous value of every sampling point of pressure sensor is greater than 20N in continuous 1s window, condition 2 (C2) is that the pitch angle instantaneous value of every sampling point measured by inertial sensor is less than 75 degrees in continuous 1s window. When the user walks, the exoskeleton joint is in the unlocking state, and when the user squats, the exoskeleton joint is in the locking state (Fig. 3(b)). The exoskeleton joint is initially in the unlocking state. When the bottom of the exoskeleton leg hits the ground, that is, the instantaneous pressure of every sampling point measured by the pressure sensor is greater than 20N in a continuous 1s window, and the thigh instantaneous pitch angle of every sampling point measured by the inertial sensor is less than 75 degrees in a continuous 1s window, it is judged that the user is in a stable squatting position, and the exoskeleton joint state changes. Since the control frequency is 100Hz, the minimum delay for switching from the unlocking state to the locking state is 1.01s. When the user changes from a squatting state to a walking state, the bottom of the exoskeleton leg leaves the ground first, and the instantaneous value measured by the pressure sensor is less than 20N. At this time, it just need one sample of FSM sensor measurement which is less than 20N to switch from squatting to walking, therefore, the exoskeleton joint state changes from locking state to unlocking state at a minimum lag of 0.01s, which will not affect the normal walking of the user. When the user wants to switch the squat height, first the bottom of the exoskeleton leaves the ground to unlock the joint, then squat, wait until the appropriate angle makes the exoskeleton leg contact the ground and maintain the squat position for 1 s, then the exoskeleton joint can be locked.

The control system runs on Arduino UNO microcomputer at the frequency of 100Hz, and monitors the signal reading of the sensor in real time and drives the electromagnet to make the joint locked. The on-off of electromagnet is controlled by a delay relay. When the relay receives the driving signal of electromagnet, it will continue to power the electromagnet for 5S, and the user will maintain a stable squatting position within 5s, and then the relay will be off to save energy. The E-LEG is driven by a 5000mAh 12V lithium battery. The battery and control hardware are placed in the attached package at the user's waist, as shown in (Fig. 3(b)).

III. Experiment Evaluation

A. Participants

Ten healthy subjects (all male, age: 23.5 ± 2.5 years, height: 169.3 ± 6.2 cm, weight: 69.5 ± 10.5 kg) with no history of lower-limb joint injury volunteered to participate in the study with informed consent. The research design and scheme have been approved by the biomedical ethics committee of Medical Department of Xi'an Jiaotong University.

B. Data Recordings

FP (foot pressure) signals were collected using insole-type plantar pressure sensor (NOVEL, Pedar, Germany) at a frequency of 100 Hz. EMG signals were collected using 4 wireless EMG transmitters (BIOPAC, BIOPAC MP150, US) at 2000 Hz. The three-dimensional motion data of the participants were recorded by six Vicon motion capture cameras (Oxford metrics Lid., Oxford, UK) at a rate of 100 Hz.

Through vicon nexus software (Vicon motion systems Ltd., Oxford, UK), the three-dimensional motion data are calculated in real time to obtain the angle of human hip and knee joint. All the kinematics and kinetics data were synchronized in the Vicon system. And the correct state switching times (CTs) and the wrong state switching times (WTs) of FSM are also recorded during each experimental. In addition, all recorded data is output with an absolute timestamp.

C. Experimental Task

To validate the effectiveness of the exoskeleton, subjects were instructed to transfer the parts which was located on the adjustable height platform in front of the subjects from

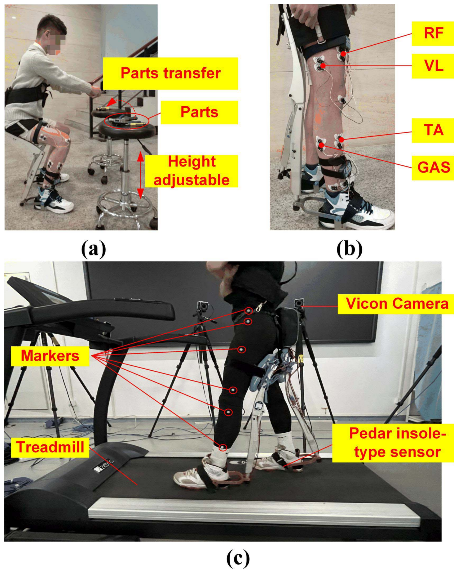

Fig. 4. Experimental setup and sensors placement. (a) Subject wearing the exoskeleton while performing the experimental task. (b) Schematic diagram of EMG electrode placement. RF = Rectus Femoris, VL = Vastus Lateralis, TA = Tibialis Anterior, GAS = Gastrocnemius mediali. (c) Schematic diagram of reflective markers placement.

platform A to platform B at a constant speed of self selection (Fig. 4 (a)).

The setup are adjusted according to the user's height and different height task requirements to ensure that the user's elbow and platform are parallel during different height tasks.

D. Procedures

Before the test, participants received information about the study and signed an informed consent form. Hydrogel surface electrodes were placed bilaterally in a bipolar configuration according to SENIAM guidelines over four muscles: Vastus Lateralis (VL), Rectus Femoris (RF), Tibialis Anterior (TA), and Gastrocnemius medialis (GAS) (Fig. 4(b)). Then, record the maximum voluntary contractions (MVCs) of each muscle three times for 5 seconds. Six reflective marker points were pasted on the user's waist, thigh, shank, respectively (Fig. 4(c)). In order to measure the foot pressure, the insole force sensor is placed on the bottom of the user's shoes, and the user wore shoes during the experiment.

The 15 minute warm-up phase familiarized participants with the task and practiced the exoskeleton. In this stage, the subjects wear the exoskeleton and perform several squatting tuning movements, as well as several parts transferring actions while maintaining the squatting with wearing exoskeleton.

After the warm-up phase, participants carried out the task in six experimental sessions, namely without wearing the exoskeleton at "low (NO EXO L)", "medium (NO EXO M)," and "high (NO EXO H)" squatting heights, plus wearing the exoskeleton at "low (EXO L)", "medium (EXO M)," and "high (EXO H)" squatting heights of assistive action, respectively. The setup of squat height is determined according to most comfortable squatting height of the participants working on the platform of 0.9m, 1.1m and 1.3m respectively. And before performing the task, the subjects wore exoskeletons and were asked to switch between walking and squatting at different squatting heights to test the accuracy of FSM state switching. In addition, participants walked on the treadmill at the speed of 3.5 Km/h in two experimental sessions, namely walking wearing the exoskeleton "EXO W" and without wearing the exoskeleton "NO EXO W".

Each session consisted of the following sub-phase:

1. *Rest:* subjects were asked to stand still, with arms lying parallel to the body (2 minutes);

2. *Task:* subjects executed the experimental task (3 minutes).

The NO EXO conditions was always performed first, because NO EXO was used as the reference condition for the calculation of the variations in the physiological and electromyography parameters, it was conducted at the beginning of the session to limit the potential ordering effects due to fatigue or stress.

E. Data Analysis

Data analysis was performed using MATLAB R2020a (The MathWorks, Natick, MA, USA) routines.

1) Recognition Times of State Switching: In this study, the recognition of state switching can be described as a binary classification problem, so the accuracy (AC) was selected to verify the performance of FSM, which can be calculated by the following equation.

$$AC[\%] = \frac{CTs}{CTs + WTs} \cdot 100 \tag{6}$$

where AC is the accuracy, CTs is the correct times that the FSM judged and WTs is the wrong times that the FSM judged. Finally, the across-subject average was calculated (median and interquartile range).

2) Electromyography: EMG signals were processed to compute the linear envelope by band-pass filter (fourth-order Butterworth filter, cut-off frequency: 20-400 Hz), rectification and low-pass filter (zero-lag 100 ms moving average filter). For each condition. The root mean square (RMS) value of EMG signal in the duration was calculated, and then for each muscle, the RMS value was normalized by the corresponding maximum MVC value. Finally, the percentage change of RMS value of EMG signals relative to the NO EXO condition (ΔEMG) was calculated according to the following formula.

$$\Delta EMG[\%] = \left(\frac{EMG_{RMS}^{EXO} - EMG_{RMS}^{NOEXO}}{EMG_{RMS}^{NOEXO}} \cdot 100 \right) \tag{7}$$

where EMG_{RMS}^{EXO} is the mean normalized RMS of EMG signals computed for one of the EXO conditions and EMG_{RMS}^{NOEXO} is the mean normalized RMS of EMG signals computed for one of the NO EXO conditions. Finally, the across-subject average was calculated (median and interquartile range).

In addition, the EMG signals were segmented according to the time of 10s, and the root mean square value of each segment is calculated respectively, and normalized according to the maximum MVC of each muscle, and then the data dispersion coefficient of the RMS of EMG signals in the duration under EXO and NO EXO conditions is calculated.

The dispersion coefficient can be obtained by calculating the ratio of the standard deviation and the average of the data. Finally, the percentage change relative to NO EXO condition (ΔVS) is calculated according to the following formula.

$$\Delta VS[\%] = \left(\frac{VS_{RMS}^{EXO} - VS_{RMS}^{NOEXO}}{VS_{RMS}^{NOEXO}} \cdot 100 \right) \quad (8)$$

where VS_{RMS}^{EXO} is the mean dispersion coefficient of EMG signals computed for one of the EXO conditions and VS_{RMS}^{NOEXO} is the mean dispersion coefficient of EMG signals computed for one of the NO EXO conditions. Finally, the across-subject average was calculated (median and interquartile range).

3) Foot Pressure Data: Foot pressure signal was normalized according to the weight of the subjects, and the mean value of foot pressure was calculated, so as to explore the load that the subjects bear during squatting in different conditions. Finally, the percentage variation of foot pressure relative to the NO EXO condition (ΔFP) was calculated according to the following equation.

$$\Delta FP[\%] = \left(\frac{FP_{M}^{EXO} - FP_{M}^{NOEXO}}{FP_{M}^{NOEXO}} \cdot 100 \right) \quad (9)$$

where FP_{M}^{EXO} is the mean value of FP signals computed for one of the EXO conditions and FP_{M}^{NOEXO} is the mean value of EMG signals computed for one of the NO EXO conditions. Finally, the across-subject average was calculated (median and interquartile range).

4) Joint Angle: According to the foot pressure, the joint angle data of the subjects during walking were divided into gait cycles, and the average joint angle of the subjects in a gait cycle was calculated, then it was resampled to 100 points in a gait cycle. Finally, the gait similarity (GS) of EXO W and NO EXO W condition was judged by calculating Cosine Similarity of two resampled gait, which can be calculated by the following formula.

$$GS = \frac{\sum_{i=1}^{100} (JA_i^{EXO} \cdot JA_i^{NO\ EXO})}{\sum_{i=1}^{100} (JA_i^{EXO})^2 \cdot \sum_{i=1}^{100} (JA_i^{NOEXO})^2)} \quad (10)$$

where JA_i^{EXO} is the i-th value of resampled joint angle in a gait cycle computed for one of the EXO conditions and $JA_i^{NO\ EXO}$ is the i-th value of resampled joint angle in a gait cycle computed for one of the NO EXO conditions.

F. Statistical Analysis

Statistical analysis was carried out to evaluate the influence of the exoskeleton under different auxiliary conditions (i.e. the tested conditions -NO EXO L, NO EXO M, NO EXO H, EXO L, EXO M, EXO H). For each condition, Shapiro-Wilk and Levene tests were used to verify the normal distribution and homogeneity of variances of the computed metrics.

AC and GS were normally distributed and their variances were homogeneous under different conditions. Therefore, parametric one-way repeated measures analysis of variance (ANOVA) was applied to the data to check the

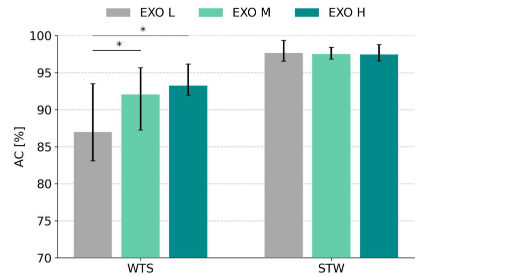

Fig. 5. The accuracy of FSM in judging squatting and walking states under multiple working conditions. WTS = walking to squatting, STW = squatting to walking, EXO L = wearing E-LEG work on 0.9m high platform, EXO M = wearing E-LEG work on 1.1m high platform, EXO H = wearing E-LEG work on 1.3m high platform. Asterisks mark statistically significant differences between EXO conditions.

differences across conditions. For gait similarity data, each subject was tested separately. When appropriate, independent sample t-tests were used for *posthoc* comparison.

ΔEMG, ΔVS and ΔFP were not normally distributed, therefore non-parametric one-way repeated-measures ANOVAs (Mann-Whitney test) were applied to data to check for across-condition differences. The test was applied for each muscle, for each item of the ΔEMG, ΔVS. When appropriate, the Wilcoxon signed-rank test was used for *posthoc* paired comparisons.

According to the normal distribution evaluation of data, the independent sample t-tests were applied to AC and GS data, whereas the Wilcoxon signed-rank test was applied to ΔEMG, ΔVS and ΔFP data. All statistical analyses were conducted in MATLAB R2020a using a significance level $\alpha < 0.05$.

IV. Results

A. Performance of FSM

As shown in Fig. 5, no significant differences were observed in the accuracy of FSM state switching from squatting to walking across conditions, and the accuracy was about 97.65% (EXO L), 97.55% (EXO M), and 97.20% (EXO H). But the accuracy of FSM state switching from walking to squatting was significantly different for the low and high level of squat height, and the accuracy was about 86.75% (EXO L), 91.35% (EXO M), and 93.50% (EXO H).

B. Muscular Activity

Fig. 6 shows that the VL, RF, TA and GAS muscles exhibited significantly decreased EMG activity in all EXO trials compared to NO EXO. Reductions were up to 75.90% for VL in EXO M ($p = 6.3 \times 10^{-3}$), up to 91.70% for RF in EXO L ($p = 9.9 \times 10^{-4}$), up to 57.55% for TA in EXO L ($p = 9.5 \times 10^{-3}$), and up to 33.05% for GAS in EXO H ($p = 5.2 \times 10^{-3}$).

C. Physical Stability

As shown in Fig. 7, the ΔVS values averaged across subjects were as the index of global physical stability. VS of VL muscle decreased by approximately 48.85% in

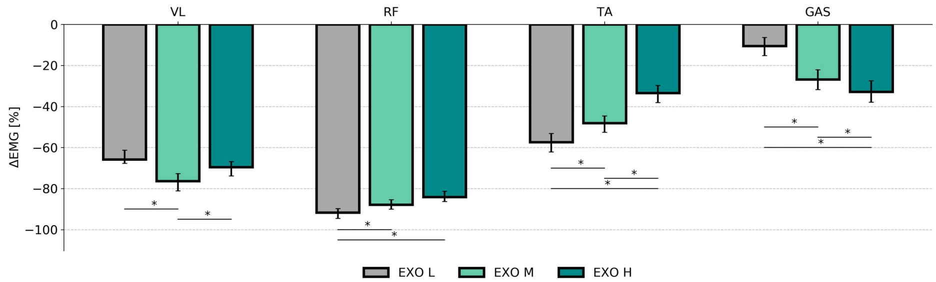

Fig. 6. EMG results are shown for VL, RF, TA, GAS. VL = Vastus Lateralis, RF = Rectus Femoris, TA = Tibialis Anterior, GAS = Gastrocnemius medialis, EXO L = wearing E-LEG work on 0.9m high platform, EXO M = wearing E-LEG work on 1.1m high platform, EXO H = wearing E-LEG work on 1.3m high platform. Bars represent the percentage variation (ΔEMG), with respect to the NO EXO, of the different squatting heights. Negative values mean reduced EMG activity with respect to the NO EXO condition. Asterisks mark statistically significant differences between EXO conditions; all EXO conditions are significantly different from NO EXO.

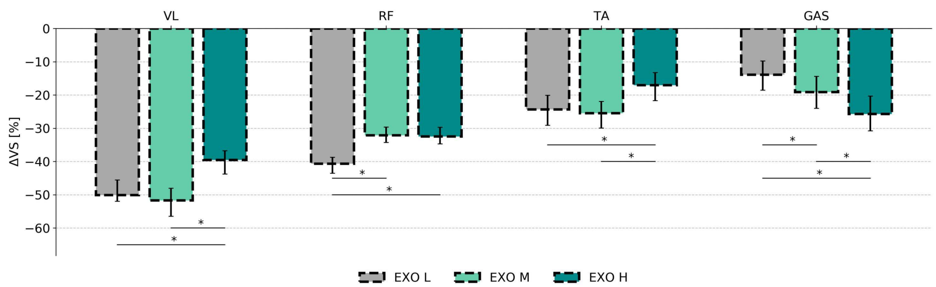

Fig. 7. EMG fluctuation results are shown for VL, RF, TA, GAS. VL = Vastus Lateralis, RF = Rectus Femoris, TA = Tibialis Anterior, GAS = Gastrocnemius medialis, EXO L = wearing E-LEG work on 0.9m high platform, EXO M = wearing E-LEG work on 1.1m high platform, EXO H = wearing E-LEG work on 1.3m high platform. Bars represent the percentage variation (ΔVS), with respect to the NO EXO, of the different squatting heights. Negative values mean reduced EMG fluctuation with respect to the NO EXO condition. Asterisks mark statistically significant differences between EXO conditions; all EXO conditions are significantly different from NO EXO.

EXO L ($p = 9.9 \times 10^{-4}$), by 52.05% in EXO M ($p = 4.2 \times 10^{-4}$), by 39.2% in EXO H ($p = 1.5 \times 10^{-3}$). VS of RF muscle decreased by approximately 39.0% in EXO L ($p = 1.8 \times 10^{-3}$), by 32.5% in EXO M ($p = 3.6 \times 10^{-3}$), by 32.55% in EXO H ($p = 3.6 \times 10^{-3}$). VS of TA muscle decreased by approximately 24.05% in EXO L ($p = 6.2 \times 10^{-3}$), by 25.55% in EXO M ($p = 6.2 \times 10^{-3}$), by 16.7% in EXO H ($p = 9.8 \times 10^{-3}$). And VS of GAS muscle decreased by approximately 25.5% in EXO L ($p = 6.2 \times 10^{-3}$), by 19.2% in EXO M ($p = 9.6 \times 10^{-3}$), by 14.15% in EXO H ($p = 9.9 \times 10^{-3}$).

D. Gravity Transfer

The variation of foot pressure values averaged across subjects can been seen as the gravity transfer from the lower limbs when the subjects in the EXO trials compare to NO EXO trials, which was shown in Fig. 8. Significant differences were found in EXO conditions compare to NO EXO conditions. FP decreased by approximately 77.65% in EXO L ($p = 3.8 \times 10^{-4}$), by 73.55% in EXO M ($p = 3.9 \times 10^{-4}$), and by 65.50% in EXO H ($p = 4.6 \times 10^{-4}$).

E. Gait Variation

Fig. 9 shows the user's hip-joint and knee-joint angle profiles over a gait cycle in EXO and NO EXO conditions. As shown in Fig. 9 (a), there is little change in the hip-joint angle range when the user walks with and without wearing exoskeleton. And in two condtions, the maximum value of hip-joint angle over a gait cycle is both about 29 degrees as well as the minimum value is both about -11 degrees. As shown in Fig. 9 (b), in the stance phase (about the first 60% of a gait cycle), the maximum value of the knee-joint angle range in two conditions is basically same, which is about 21 degrees, but the minimum value of the knee-joint angle range is different between two conditions, which is about 10 degrees in NO EXO condition as well as 7 degrees in

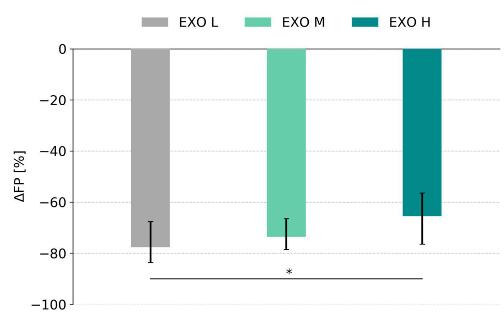

Fig. 8. Percentage variations of the foot pressure for the different EXO conditions relative to the NO EXO. EXO L = wearing E-LEG work on 0.9m high platform, EXO M = wearing E-LEG work on 1.1m high platform, EXO H = wearing E-LEG work on 1.3m high platform. Asterisks mark statistically significant differences between EXO conditions; all EXO conditions are significantly different from NO EXO.

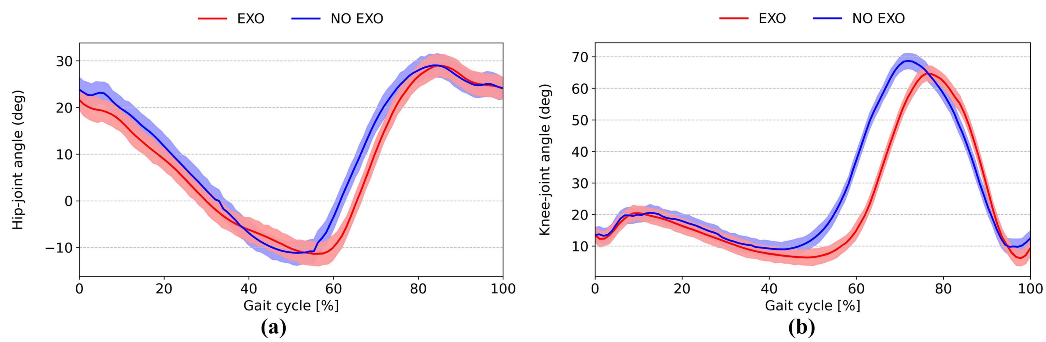

Fig. 9. User's hip-joint and knee-joint angles curves vs. percent gait cycle in EXO (red) and NO EXO (blue) conditions, EXO = walking with wearing exoskeleton, NO EXO = walking without wearing exoskeleton. (a) Hip-joint angle, the shaded part represents the standard deviation. (b) Knee-joint angle, the shaded part represents the standard deviation.

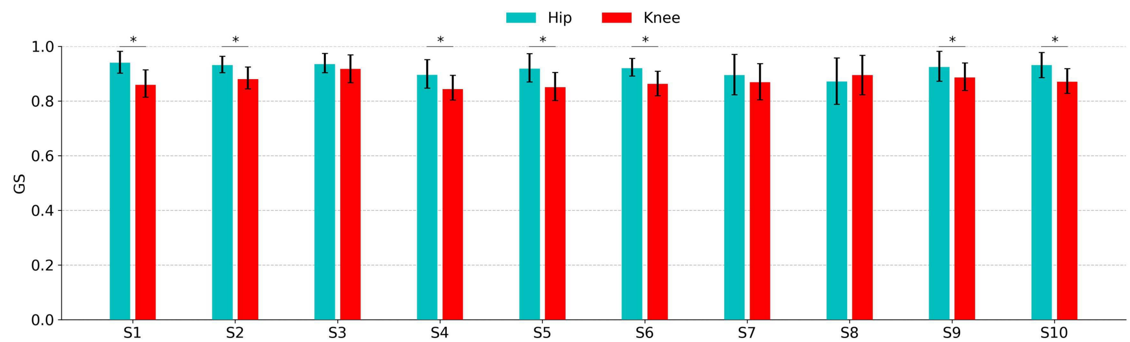

Fig. 10. Similarity of hip and knee angles of different subjects in a gait cycle for the EXO conditions relative to the NO EXO. Asterisks mark statistically significant differences between results of different joints; there are significant differences in the angle similarity of hip and knee joints among most subjects.

EXO condition. In the swing phase (about the last 40% of a gait cycle), the maximum and minimum values of knee-joint angle range in EXO condition are higher than those in NO EXO condition. The maximum value is about 70 degrees in NO EXO condition but 65 degrees in EXO condition. The minimum value is about 10 degrees in NO EXO condition but 6 degrees in EXO conditon. In addition, Fig. 9 also shows the shortening of the swing phase in EXO condition, which is about 5% smaller than that in NO EXO condition.

Fig. 10 shows the similarity of knee joint angle and hip joint angle in one gait cycle of 10 subjects walking when wearing an exoskeleton compared to those not wearing an exoskeleton. The closer the GS value was to 1, the higher the gait similarity was. Additionally, the GS value of hip joint was significantly higher than the GS value of knee joint were found in S1, S2, S4, S5, S6, S9, and S10.

V. Discussion

In this paper, we presented a novel semi-passive lower-limb exoskeleton for assisting workers to keep squat and its experimental evaluation in assisting users in different static squatting task.

A. Design Feature of the Exoskeleton

The E-LEG presents several novel design features in the framework of lower-limb exoskeletons for squatting assistance. First, the E-LEG implements active of assistive squat height. Automatic tunable assistive squat height is a key function because it allows a lower-limb exoskeleton to adapt to different tasks/postures and reduces personnel operation [18]. Usually, the passive lower-limb exoskeleton integrates manual adjustment buttons to change the support of the lower limb exoskeleton at different squat heights, such as CC [29] and SIAT [30]; other device, instead, need to be reassembled, because it only provide specific assistive squat height, like the LegX [31] and CEA-LIST [32], therefore the user has to take off the exoskeleton to change the configuration. Contextually, the possibility of actively and automatically changing the assisted squat height can improve the availability and user acceptance of the exoskeleton in practical application scenarios [33]. Currently, E-LEG's assistive squat height tuning is aimed at human-exoskeleton cooperation. Users can freely change the assistive squat height according to their actual needs after a short period of practice. Second, an IMU is integrated into the thigh of E-LEG to measure the thigh kinematics, and a force sensor is integrated into the end of E-LEG to measure the ground reaction force. On the one hand, when a passive exoskeleton is considered, sensors will not be embedded, mainly because additional electronic equipment and power supply are needed to operate, which increases the complexity of the system. On the other hand, sensors can be positively used for two purposes. Since the posture and operation of workers are important indicators to determine the risk of WRMSDs [34], integrated sensors can monitor the kinematic parameters of specific operators (such as the angle fluctuation of legs during squatting), and may be applied to the ergonomic design of tasks. Secondly, for the active exoskeleton, the sensor signal can be used for exoskeleton control to overcome the limitation that the passive device cannot automatically change the required assistance. This will improve the applicability and efficiency of the lower limb exoskeleton in different tasks.

B. Assessment of the Effects of the Exoskeleton

The effects of E-LEG on users were evaluated according to different instruments (EMG, foot pressure, and joint angle). EMG analysis showed that the muscle activity of vastus lateralis (VL), rectus femoris (RF), tibialis anterior (TA), and gastrocnemius medialis (GAS) was significantly reduced, and the fluctuation of muscle activity over a period of time was also significantly reduced. These muscles help to maintain and stabilize the squat posture statically.

The decrease in EMG activity and EMG fluctuation of vastus lateralis and rectus femoris were expected. In fact, these two muscles mainly help to maintain the squat posture in the working position. The decrease in EMG activity can indicate that when maintaining the squat posture, the exoskeleton reduces the muscle strength required to maintain the squat posture. The decrease in the EMG fluctuation can indicate that the exoskeleton reduces muscle fatigue and increases the stability of squatting. These effects were also shown in previous studies [18].

In addition, the tibialis anterior and gastrocnemius medialis also exhibited decreased EMG activity and EMG fluctuation. These results were consistent with the existing literature, in which the decreased TA and GAS co-activation was a direct consequence of reduced strain on the flexor muscle-tendon units.

Additionally, with the decrease in squatting height, the proportion of EMG activity reduction of RF and TA increased, and the decreasing proportion of EMG fluctuation had a similar trend. The observed trend can be explained by the following facts: on the one hand, with the decrease in auxiliary squat height, the overall center of gravity of the human exoskeleton coupling system is decreasing, which leads to the increase of its stability, and the muscle force of RF and TA for coordinating the stability of exoskeleton is decreasing; On the other hand, with the increase of squat height, the human body is closer to the standing posture, so most of the gravity will be transferred along the direction of human leg bones. Similar results can be found in [35].

However, the change trend of GAS was opposite to that of RF and TA, and the decrease proportion of EMG activity and EMG fluctuation decreased with the decrease of squat height. No similar rule was found in the relevant literature. Through analysis, we speculate that with the decrease in squat height, although the center of gravity of the exoskeleton coupling system decreases, the angle between the sole and the calf decreases. In order to maintain the static stability of the sole and the calf, the Achilles tendon of the human heel tends to tension. Therefore, even with the help of the exoskeleton, with the decrease in squat height, the assistive effect of the exoskeleton on GAS will become smaller and smaller. Therefore, users should limit a minimum squat height when using an exoskeleton to assist with squatting.

In this study, we also aimed to evaluate the role of the exoskeleton in gravity transfer [36] by quantifying the changes in users' foot pressure under different conditions. Compared to NO EXO, we observed significant reductions in all three EXO conditions, providing further evidence that the action of the exoskeleton can result in a more global reduction of the users' physical fatigue, and the reason is that the most of the gravity of the human body is transferred to the ground through the exoskeleton. Notably, the reduction of foot pressure in EXO H condition was significantly less than that in EXO L condition. The reason for this phenomenon is that when the squat height increases, the user tends to stand upright, so more gravity will be transferred from the human leg skeleton.

In addition, this paper presented a new index of lower-limb exoskeletons evaluation, the gait similarity index, for the first time. As a kind of wearable equipment, E-LEG should be not affect the normal walking of users, because users usually do not perform tasks in a fixed position. We analyzed the similarity of hip joint angle and knee joint angle of each subject in a gait cycle, and found that 70% of subjects had significantly reduced the similarity of knee joint angle compared with hip joint angle after wearing the exoskeleton. According to the user's experience, we analyzed the reasons for this result. The main reason is that the exoskeleton is only connected with the user's foot, which increased the equivalent inertia of the user's knee joint and had a greater impact on the kinematics of the user's knee joint than hip joint [28]. Therefore, when the user swings the leg, the exoskeleton has a greater traction on the knee joint, so the rotation amplitude of the knee joint is reduced. Therefore, we should try to choose lightweight materials such as carbon fiber in the manufacture of lower-limb exoskeleton.

C. Limitations of the Study

Despite promising results, this study presented the following three main limitations. First, it is a laboratory simulation task performed on a group of healthy and young individuals. Although laboratory evaluation is basic, it should be further verified in actual workers to promote the effectiveness of E-LEG application in factories. Second, although the results of EMG and foot pressure can objectively prove the role of the exoskeleton, there is no evaluation on the subjective feelings of users. In future research, NASA-TLX and Borg questionnaires across experimental conditions can be used to obtain subjective scores. Finally, we only analyzed the electromyography of single leg, but did not study the symmetry of E-LEG in double leg assistance. In fact, although the squatting posture of the human body can be regarded as a symmetrical movement of the left and right legs, due to the personal habits of different users, the center of gravity of the human body will shift to a certain foot, and the results of EMG and plantar pressure may change. For a more comprehensive evaluation of E-LEG, future studies will also investigate the effects of exoskeleton use on leg symmetry. In addition, trunk muscles are very important for the human to maintain squatting posture, so the EMG of trunk muscles should also be considered in future research to evaluate possible adverse/positive effects of the exoskeleton in body regions different from the legs.

VI. Conclusion

In this article, we presented the E-LEG, a novel semi-passive lower-limb exoskeleton designed to assist workers in maintaining squatting. Compared with other passive lower limb industrial exoskeletons, the novelty and uniqueness of E-LEG lies in the realization of the user intention perception and active adjustment mechanism of automatic adjustment assisted squat height. Performance evaluation experiments show that the exoskeleton can reduce the user's muscle activity and muscle fatigue, as well as the gravity transfer from the human leg, but it will slightly affect the normal gait when walking.

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