Clinical research of lower extremity exoskeleton robot in post-stroke hemiplegic patients

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Research

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Abstract

Background In recent years, the number of people suffering from stroke-induced motor function lost increased considerably. Recovery of motility is essential in improving their quality of life. However, the existing rehabilitation methods cannot fulfill patients’ training requirements. As a new rehabilitation technology, exoskeleton robot provides a new treatment scheme for post-stroke hemiplegic patients.

Objective To explore the safety and effectiveness of exoskeleton-assisted gait training for post-stroke hemiplegic patients.

Methods A lower extremity hip joint exoskeleton robot was designed by the cooperation team, and 9 post-stroke hemiplegic patients were included for exoskeleton-assisted gait training. The three-dimensional gait parameters, plantar pressure and surface electromyography were used to validate the effectiveness of the exoskeleton robot in post-stroke hemiplegic patients.

Results Exoskeleton-assisted ambulation training for post-stroke hemiplegic patients can correct the asymmetry of gait and abnormal phase of gait cycle, increase the toe-ground clearance and the angle of hip joint, reduce the pressure of non-paretic plantar and the impulse of bilateral feet, which help balance the plantar pressure distribution. It can also improve the integral electromyography value of specific muscle, which means that corresponding muscles are stimulated to generate activities.

Conclusions The exoskeleton robot designed by our team can correct the hemiplegic gait and foot drop phenomenon of post-stroke patients, protecting them from damage caused by long-term abnormal gait, which contributes to the recovery of lower extremity motor function in hemiplegic patients. The results also provide important information for the design of lower extremity exoskeleton robot. In the future, we should further explore the rehabilitation function of exoskeleton robot in post-stroke hemiplegic patients, as well as the ambulation and rehabilitation function in other lower extremity motor dysfunction patients.

1. Introduction

Stroke is a medical problem facing the whole world, which is characterized by high morbidity, recurrence, mortality and disability[1]. Moreover, there are very limited treatment methods for stroke and the only drug approved by the FDA (Food and Drug Administration, USA) is tPA (tissue plasminogen activator)[2]. A study conducted by American Heart Association including millions of cerebral infarction patients shows that only 3.7% of them used tPA to thrombolysis[3]. Up to 80% stroke patients are leaved with varying degrees of disabilities due to the limited treatment methods[4]. The disability of motor function, especially the malperformance of lower limb, seriously affects their quality of life, so it is important to reestablish their motor function safely and effectively[5]. The rehabilitation guidelines and clinical experience have proved that early and scientific rehabilitation training can reduce the disability rate of stroke and improve the quality of patients’ life[6]. At present, the rehabilitation of patients' lower extremity motor function mostly depends on therapists for one-to-one training, which can hardly meet the requirement of high-intensity and personalized training, and the curative effect is difficult to be objectively evaluated[4].

Exoskeleton robot, as a burgeoning rehabilitation technology, has been greatly developed in recent years[7]. Exoskeleton robot is a kind of wearable bionic device, which integrates rehabilitation medicine,
robotics and artificial intelligence. Its application in the field of rehabilitation medicine is a research hotspot in various countries. Compared with traditional rehabilitation methods, it can not only provide highly controllable, high-intensity and personalized rehabilitation training to relieve clinical staff of huge burden, but also can evaluate the improvement of motor function objectively and accurately. Latest research results in the field of neural rehabilitation indicate that the central nervous system is highly plastic, which provides theoretical basis for the combination of rehabilitation medicine and robot technology, thus driving the application of exoskeleton robot in stroke rehabilitation to the focus direction.

By the end of January 1, 2020, searching the keywords “stroke” and “exoskeleton” in the U.S. clinical trial database turns out 70 clinical studies, among them 26 are related to lower extremity motor dysfunction. Through the analysis of the above clinical researches, it is found that the rehabilitation effect of exoskeleton robot varies in different stages of stroke and different joints of limbs, the key to improving its clinical effect lies in the mechanism design and software control, and there is no mature research paradigm of gait training assisted by exoskeleton robot for stroke patients.

Stroke patients display special hemiplegic gait and foot drop phenomenon, which we aims to correct in this study by designing a hip joint exoskeleton, also with the hope of improving prognosis. To evaluate the curative effect objectively, comprehensively and accurately, we used three-dimensional motion capture system, conducted surface electromyogram (sEMG) and recorded plantar pressure.

2. Materials And Methods

2.1 Research protocol

1) Objective: To explore the safety and effectiveness of exoskeleton-assisted gait training for post-stroke hemiplegic patients.

2) Study design: prospective, non-randomized, self-controlled clinical study.

3) Sample size: about 10 post-stroke hemiplegic patients.

4) Inclusion criteria:

   a. Age > 18 years;
   b. Anterior circulation ischemic stroke attacked one month to two years before admission;
   c. Unilateral limb dyskinesia (paretic side muscle strength level is III or above);
   d. Sign the informed consent and agree to complete follow-up.

5) Exclusion criteria:

   a. Age > 80 years;
b. Major operation history one week before admission;
c. Acute coronary events occurred within 3 months before and after stroke;
d. Gastrointestinal hemorrhage or other serious bleeding diseases within one month;
e. Complications including coagulation disorders, mental disorders, pregnant women;
f. Other situations not suitable to participate in the experiment.

6) Test procedure:

a. Cautious physical examination, record body parameters;
b. Paste the fluorescent markers (Figure 1A) and sEMG sensors (Figure 1C), correct equipment;
c. Walk 30 meters on the test platform without exoskeleton;
d. Wear the exoskeleton (Figure 1B), train adaptively and choose appropriate training mode;
e. Walk on the test platform with exoskeleton around 30 minutes (Figure 1E);  
f. Test over, questionnaire investigation.

7) Evaluation index:

a. Primary end point: safety of exoskeleton (occurrence of adverse events);
b. Secondary end point: gait function improvement.

8) Possible adverse events:

a. Accidental fall, fracture and other injuries;
b. Other injuries caused by exoskeleton.

2.2 Exoskeleton design

Benefiting from the intensive study on mechanical structures, materials, motors and software algorithm, the lower extremity exoskeleton robot designed by our team is lightweight and comfortable, whose mass is 2.6kg and is lower than all similar exoskeleton robots on the market\textsuperscript{[15, 25]}. According to ergonomics and mechanics, we designed the mechanical structure of the exoskeleton robot (Figure 1B), which meets the requirements of convenient wearing, comfortable carrying and wide adjustable range. At the same time, we adopted carbon fiber as the structure framework, endowing it with characteristics of high strength, low density and low friction resistance\textsuperscript{[26]}. Proper motor can reduce the mass of the exoskeleton robot and ensure the user’s comfort. By comparing and testing the commonly-used motors, we selected the brushless servo planetary reducer motor (Brand: INNFOS, Model: QDD-NU80-6), with rated torque of 6.6 nm, peak torque of 19.8 nm and weight of only 453.1g.
Software control is the other key point to improve the curative effect. The training mode of exoskeleton robot is mainly divided into two kinds: passive and active. The former is relatively mature and has been put into practice, while the latter is still under research and is considered to be the future direction[27]. The exoskeleton robot used in this clinical study has both passive and active training modes. The training mainly uses the more mature passive mode, while also allows patients to experience the active mode and compare the two modes subjectively.

2.3 Biomechanical and statistical analysis

Gait parameters, such as hip angles and toe-ground clearance, were computed by VICON (Nexus 1.8.5, UK, Figure 1E). Plantar pressure was collected and analyzed by Footscan (Footscan 7 gait 2\textsuperscript{nd} generation, Belgium, Figure 1D). Surface electromyogram was acquired through Telemyo 2400R G2 Wireless system (Noraxon, USA, Figure 1C) and the Noraxon MR3.10 software was used for signal processing. MATLAB version R2019a (MathWorks, USA) was used to further process the gait parameters and sEMG data. SPSS 25 was used for Statistic operation. For each condition and result measurement, means and standard deviations were calculated for the paretic and non-paretic limbs. Paired t-test was used to evaluate a small number of comparisons and the statistical significance was set at $\alpha < 0.05$.

3. Results

3.1 Participant information

This study included 9 patients who were hospitalized in the Department of Neurology of Renji Hospital, Shanghai Jiaotong University School of Medicine from January 2018 to December 2019 due to anterior circulation ischemic stroke. All participants finished the test in Shanghai Institute of Traumatology and Orthopaedics from August 2019 to December 2019. The basic information is shown in table 1.

Among the selected stroke patients, 55.6% (5 / 9) were male, 44.4% (4 / 9) were female, 61.5 ± 4.1 years old (mean ± standard deviation, the same below), 62.6 ± 9.4 kg in weight, 1.63 ± 0.07 m in height, 0.82 ± 0.04 m in lower extremity, 107.2 ± 40.7 days after stroke, and the muscle strength of the paretic lower extremity was between 3 and 5-.

3.2 Gait

3.2.1 Hip joint angle

Drag step is a special phenomenon of hemiplegic patients, which is closely related to the limited hip joint angle[28]. Fig.2 B1 illustrates the hip joint angle, and Fig.2 C1 shows the normal hip joint angle curve across the gait cycle. Fig.2 A1 shows the hip joint angle curve across the gait cycle of 9 participants in
turn. In the figure, the black curves represent the conditions without exoskeleton, the colorful curves represent them with exoskeleton, and the shadows represent the variety range of hip joint angle under multiple gait cycles.

The abnormal hip joint angle curve of post-stroke hemiplegic patients is characterized by a decreased amplitude or an unsmooth appearance\cite{29}. As Fig.2 A1 (black) indicates, patients suffer from a limited hip joint movement, leading to drag step. However, with exoskeleton robot assistance (color), most of the subjects (P2, P3, P4, P6, P8, P9) had smoother hip joint angle curves and increased amplitude compared with that without assistance (black).

The maximum hip joint angle was calculated in order to test exoskeleton’s effect on patients in a more compelling way. The results show that the average maximum hip joint angle increment after exoskeleton robot assistance reaches 11.3° on the non-paretic side (Fig.2 D1) and 14.1° on the paretic side (Fig.2 E1), which demonstrates that the exoskeleton can increase hip joint angle on both sides of post-stroke hemiplegic patients, and the increment on the paretic side is higher.

3.2.2 Toe-ground clearance

Drop foot is another special phenomenon in hemiplegic patients, which is bound up with the limited toe-ground clearance. The toe-ground clearance is a wildly-used index to measure the severity of drop foot, and can also be used to evaluate the advantage of exoskeleton robot-assisted walking training\cite{30}. Fig.2 B2 depicts the toe-ground clearance, and Fig.2 C2 illustrates the normal toe-ground clearance curve across the gait cycle. Fig.2 A2 shows the toe-ground clearance curve across the gait cycle of 9 participants in turn. In the figure, the black curves represent circumstances without exoskeleton, the colorful curves represent them with exoskeleton, and the shadows represent the variable range of hip joint angle under multiple gait cycles.

The abnormal toe-ground clearance curve of post-stroke hemiplegic patients is shown with a decreased amplitude, a unsmooth curve and multiple wave peaks\cite{31}. As Fig.2 A2 (black) indicates, patients experience limited toe-ground clearance, leading to drop foot. Most of the subjects (P2, P3, P5-P9) had smooth hip joint angle curves and increased amplitude when assisted by exoskeleton robot (color) compared with that without assistance (black).

The maximum toe-ground clearance was calculated in order to further demonstrate the advantage of exoskeleton assistance. The results show that the average maximum toe-ground clearance increment with exoskeleton robot assistance is 63.7 mm on the non-paretic side (Fig.2 D2) and 73.1 mm on the paretic side (Fig.2 E2). It indicates that the exoskeleton can increase the toe-ground clearance of post-stroke hemiplegic patients on both sides, and the increment on the paretic side is higher.

3.2.3 Gait symmetry
Hemiplegic gait manifests a lack of symmetry between the paretic side and the non-paretic side\textsuperscript{[32]}. Evaluating and improving the gait symmetry of post-stroke patients helps correct their hemiplegic gait.

The spatial and temporal gait parameters of stroke patients is shown in table 2.

- For the paretic limbs, the cadence, walking speed, stride length, step length decline, and the stride time, single support ascend were compared between assisted and unassisted situation.
- For the non-paretic limbs, the cadence, walking speed decline, and the stride time, step time, single support ascend were compared between assisted and unassisted situation.

The results show that the paretic side holds a slow swing frequency, a large amplitude, and a long support time. The non-paretic side, however, displays a fast swing frequency, a small amplitude, and a short support time. The phenomenon is consistent with the drag step of post-stroke hemiplegic gait\textsuperscript{[33, 34]}. The results are also related to the setting of training model. In order to ensure the safety of training, the pace is controlled so that some parameters such as walking speed maintained low with exoskeleton assistance.

Radar map is a two-dimensional graph used to demonstrate multiple variables, being able to display regular polygons makes it suitable for symmetry comparison\textsuperscript{[35]}. The ratios of the non-paretic side data to the paretic side data were taken as variables to make a radar map. Bilateral symmetry is indicated if the ratio is close to 1, and the shape of the radar image should be close to a regular polygon. Fig. 3 compares the radar map of gait symmetry with or without exoskeleton assistance. It can be seen that the black radar chart (without the assistance of exoskeleton) is an irregular polygon, and the grey radar chart (with the assistance of exoskeleton) is close to regular polygon. The result indicates that the exoskeleton can improve the gait symmetry of post-stroke hemiplegic patients.

[Please see the supplementary files section to view the equation.]

According to the formula (1), we calculated exoskeleton’s improvement ratio of gait symmetry. In the formula (1), XN represents non-paretic side parameters without exoskeleton assistance, XP represents paretic side parameters without exoskeleton assistance, YN represents non-paretic side parameters with exoskeleton assistance, YN represents paretic side parameters with exoskeleton assistance. The results show that the gait symmetry improved 74.18% by exoskeleton.

3.3 Plantar pressure

Plantar pressure is an effective and burgeoning research methods in the rehabilitation field, which can help assess the compression of different foot area, thus guiding interventions to prevent injuries caused by long-term compression\textsuperscript{[36]}. Comparing plantar pressure heat map of P1 (Left hemiplegia, Fig. 4A-B), it can be found that without assistance, the pressure focuses on the healthy side of feet (Fig. 4A), while the pressure distribution tends to be symmetric with exoskeleton assistance (Fig. 4B). Fig. 4C shows ten
plantar regions according to anatomy in order to better compare the bilateral plantar pressure. It can be found in Fig. 4D that the intensity of pressure in bilateral plantar regions varies a lot with or without assistance of exoskeleton. On the paretic side, the intensity of pressure on Toe 1, Toe 2-5 and Meta 1 increases with exoskeleton assistance. At the same time, the non-paretic side intensity of pressure on Meta 1-3, mid foot and heel medial decreases significantly when assisted by exoskeleton. The results prove that the exoskeleton can decrease the plantar pressure of special regions on the paretic side and increase the plantar pressure of special regions on the non-paretic side, which helps balance the bilateral plantar pressure. We calculated the exoskeleton's improvement ratio of plantar pressure symmetry in the same way by formula (1), and it shows an improvement of 50.82%.

Plantar impulse is the multiplication of pressure and time. As the direct estimate of fatigue accumulation, it is of great significance in evaluating vulnerable parts of the foot[37]. Fig. 4E compares the bilateral plantar impulses in different regions with or without exoskeleton assistance. It is found that when unassisted, the impulse in forefoot accounts for about 70% of the whole, and the impulse from the non-paretic side is higher than that on the paretic side, indicating that the forefoot is prone to fatigue and damage. Exoskeleton robot helps reduce the impulse of bilateral forefoot, especially that of the non-paretic side, which balances the plantar impulse. We calculated the exoskeleton's improvement ratio of plantar impulse symmetry in the same way by formula (1), and it shows an improvement of 73.79%.

3.4 sEMG

The surface electromyogram (sEMG) signal is a non-invasive electro-neurophysiology tool which has been widely used in rehabilitation field for evaluating muscle function[38]. sEMG data were rectified and bandpass-filtered(15 to 380 Hz) to generate linear envelopes (Fig. 5A)[39]. The area under the sEMG envelopes were calculated by numerical integration, which is called integral electromyogram (IEMG). IEMG is positively related with muscle strength and activity, which is a practical index for muscle function assessment[19, 40]. Fig. 5 B compares the IEMG of measured bilateral muscles between circumstances with or without exoskeleton assistance. The IEMG of paretic side in Rectus Femoris, Biceps Femoris Long Head and Tibialis Anterior only equal to 63.90%·57.91% and 76.77% of the non-paretic side muscles when unassisted. While the numerical value increase to 98.39%·82.12% and 83.72% in turn when assisted by exoskeleton. The results prove that these muscle activities are significantly enhanced by exoskeleton in participants.

4. Discussion

Exoskeleton robot is a wearable device combining mechanical equipment and artificial intelligence, which can provide controllable and multi-sensory stimulation, enhance the plasticity of neural connection in the process of movement, and promote the biological and epigenetic changes of nervous system[41]. The exoskeleton robot used in this experiment has characteristics of convenient wearing, comfortable structure, high-intensity and low-weight, which is lighter than all listed exoskeletons. It was equipped with
passive and active auxiliary training modes; the former is relatively mature, and the latter is the future direction of development. In this experiment, three-dimensional gait parameters, plantar pressure and sEMG signals were used to objectively and comprehensively evaluate the improvement of motor function by exoskeleton robot.

Post-stroke hemiplegic patients have drag step, drop foot and asymmetric gait\(^{29,42}\). Evaluating and correcting the gait parameters, such as improving hip joint angle, toe-ground clearance and gait symmetry, help improve hemiplegic gait, thus promote rehabilitation\(^{43-45}\). The phenomenon of hemiplegic gait results from post-stoke nervous system damage, which will seriously affect patients’ daily life\(^{46}\). Compared with normal people, post-stroke hemiplegic patients have the characteristics of asymmetric gait, low walking efficiency and higher risk of falling, which are caused by decreased muscle strength, abnormal gait and sensory disorders\(^{47-49}\). They need to be corrected as soon as possible after stroke for better rehabilitation prognosis\(^{50}\). Post-stroke hemiplegic patients also have imbalanced weight-bearing on bilateral foot. By evaluating the plantar pressure and correcting them can exoskeleton probably improve patients' walking efficiency and reduce their falling risk\(^{51}\). The asymmetric plantar pressure and impulse of post-stroke hemiplegic patients can be significantly corrected when assisted by exoskeleton robot. As a non-invasive electro-neurophysiological analysis method, sEMG is widely used in rehabilitation field. IEMG can reflect the intensity of EMG activity, which is a good index for examining and evaluating muscle functions. This study found that the IEMG of rectus femoris, biceps femoris longhead and tibialis anterior muscle in the paretic side was significantly lower than that in the non-paretic side. While the exoskeleton can significantly improve the IEMG of these muscles, it means that the exoskeleton positively stimulates these muscles to generate activities and helps restore motor functions\(^{52}\).

In the nervous system, the diseases of central nerve, peripheral nerve, neuromuscular junction and muscle can lead to lower extremity dyskinesia\(^{53}\). There are many other clinical studies on exoskeleton in patients with lower extremity motor dysfunction, such as spinal cord injury\(^{54}\), postoperative\(^{55}\), age-related gait disorder\(^{14}\), child cerebral palsy\(^{39}\), multiple sclerosis\(^{56}\) and Parkinson's disease\(^{57}\), etc. Our research findings not only exhibit more accurate clinical requirements for the research and renovation of exoskeleton robot, but also provides a new vision for clinical motor function improvement of lower extremity, including in stroke patients. When developing exoskeleton robot, we need to emphasize gait characteristics of different diseases, such as hemiplegia of stroke and paraplegia of spinal cord injury, so as to better design the hardware structure and software algorithm.

There are many factors that affect the rehabilitation effect of exoskeleton, including active or passive training mode, training frequency and intensity, different severity and course stages of stroke\(^{58}\). The training intensity, frequency and start time have not formed a unified standard. Some studies have pointed out that increasing training intensity, increasing training times, and task-based training can promote neural plasticity and functional recovery. The most effective rehabilitation interventions, including gait training, must be conducted in an intensive and task-oriented manner shortly after stroke,
and should include multi-sensor stimulation\textsuperscript{[59]}. In this study, we used a small sample and self-comparison methods to do exploratory research because our exoskeleton is newly developed. In the future, we should further explore the rehabilitating function of exoskeleton robot in stroke hemiplegia patients, as well as in other motor dysfunction patients. In the future, we should continue to explore the mechanisms of exoskeleton robot on the rehabilitation of patients with lower extremity movement disorders, so as to provide a better theoretical basis for its clinical application.

5. Conclusion

This study proves that, first, our exoskeleton robot can correct the asymmetry of gait, add to the distance between toes and ground, and increase the angle of hip joint in post-stroke hemiplegic patients. Second, it can improve the symmetry of bilateral plantar pressure, alleviate the pressure of the healthy plantar and reduce the impulse of bilateral forefeet, which might help avoid plantar injuries caused by long-term abnormal gaits. Third, it can also enhance the integral EMG of Rectus Femoris, Biceps Femoris Long Head and Tibialis Anterior, which implies its positive effect on stimulating corresponding muscles to produce activities. Moreover, this study provides important data for the research and renovation of exoskeleton robot, verifies the significance of exoskeleton robot in rehabilitating stroke patients, and offers a new perspective for assisted-walking as well as rehabilitation in other motor dysfunction-related diseases.

Declarations

6.1 Ethics approval and consent to participate

This clinical research was approved by Ruijin Hospital Ethics Committee, Shanghai Jiaotong University School of Medicine. All participants had signed the informed consent.

6.2 Consent for publication

All presentations of this article have consent for publication

6.3 Availability of data and material

The datasets analysed during the current study available from the corresponding author on reasonable request.

6.4 Competing interests

The authors declare no competing interest.
6.5 Funding

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6.6 Authors' contributions

K.W, Hj.Y and Hm.Z contributed equally to this work. K.W and P.H conducted the experiments. K.W, Hm.Z and P.H analyzed the data. K.W and Hm.Z prepared the figures and tables. K.W, Hj.Y and J.P prepared the manuscript. Wx.Y provides the exoskeleton robot. K.W and Yt.G conceptualized the project. Yt.G P.H and Wx.Y supervised the project. All coauthors have reviewed and approve the contents of the manuscript.

6.6 Acknowledgement

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Tables

Table 1. Participant information.
| No. | Gender | Age (years) | Weight (kg) | Height (meter) | Leg (meter) | Post-stroke (days) | Affected side | Muscle strength |
|-----|--------|-------------|-------------|----------------|-------------|-------------------|---------------|----------------|
| 1   | Male   | 59          | 71          | 1.70           | 0.85        | 79                | Left          | 5-             |
| 2   | Male   | 56          | 74          | 1.75           | 0.88        | 52                | Right         | 4             |
| 3   | Female | 64          | 75          | 1.64           | 0.87        | 119               | Right         | 4+            |
| 4   | Male   | 59          | 61          | 1.65           | 0.83        | 110               | Left          | 3             |
| 5   | Male   | 59          | 52          | 1.54           | 0.78        | 139               | Right         | 4+            |
| 6   | Female | 61          | 62          | 1.60           | 0.77        | 49                | Right         | 4             |
| 7   | Female | 61          | 63          | 1.62           | 0.82        | 129               | Left          | 3             |
| 8   | Female | 69          | 57          | 1.55           | 0.78        | 173               | Left          | 4-            |
| 9   | Male   | 66          | 48          | 1.59           | 0.80        | 115               | Left          | 4-            |

**Table 2** Spatial and temporal gait parameters of stroke patients
| Parameter                  | Paretic limbs | Non-Paretic limbs | Paretic limbs | Non-Paretic limbs |
|---------------------------|---------------|-------------------|---------------|-------------------|
|                           | Unassisted    | Exo-assisted      | Unassisted    | Exo-assisted      |
| Cadence(steps /min)       | 81.88 ± 29.12 | 53.52 ± 22.21*    | 88.56 ± 23.45 | 52.42 ± 21.98**   |
| Walking Speed (m/s)       | 0.60 ± 0.25   | 0.32 ± 0.21*      | 0.61 ± 0.24   | 0.32 ± 0.22*      |
| Stride Time(s)            | 1.71 ± 0.70   | 2.55 ± 0.79*      | 1.48 ± 0.49   | 2.61 ± 0.83**     |
| Step Time(s)              | 1.00 ± 0.58   | 1.41 ± 0.54       | 0.69 ± 0.22   | 1.23 ± 0.30**     |
| Opposite Foot Off(%)      | 19.76 ± 9.50  | 16.82 ± 8.79      | 22.20 ± 9.74  | 17.08 ± 8.10      |
| Opposite Foot Contact(%)  | 48.51 ± 6.17  | 48.99 ± 7.34      | 52.35 ± 7.61  | 53.03 ± 8.43      |
| Foot Off(%)               | 54.76 ± 8.26  | 62.77 ± 8.31      | 58.46 ± 8.77  | 63.41 ± 8.70      |
| Single Support(%)         | 0.59 ± 0.15   | 0.79 ± 0.17*      | 0.64 ± 0.20   | 0.90 ± 0.30*      |
| Double Support(%)         | 0.44 ± 0.29   | 0.81 ± 1.20       | 0.40 ± 0.24   | 0.75 ± 0.47       |
| Stride Length(m)          | 0.89 ± 0.21   | 0.68 ± 0.18*      | 0.83 ± 0.18   | 0.68 ± 0.20       |
| Step Length(m)            | 0.47 ± 0.16   | 0.36 ± 0.09*      | 0.45± 0.15    | 0.35 ± 0.11       |

Values are presented as mean ± standard deviation; * P<0.05 and ** P<0.01 vs. Unassisted.

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Figures
Figure 1

Lower-extremity exoskeleton robot study description. A) Image illustrating exoskeleton and measuring tools on a study participant; B) Front view of the lower extremity exoskeleton; C) Sensors of Telemyo 2400R G2 Wireless system (Noraxon, USA); D) Footscan pressure plate (RSscan, Belgium); E) Image illustrating participants walk under the monitor of 3D motion capture system (VICON, UK).
Figure 2

Variance of hip angle and Toe-ground clearance. A1) P1-P9: Hip angle across the gait cycle of nine patients, Black lines: non-assisted, Colored lines: exo-assisted, Shade: variance range of hip angle, B1) Sketch Map of hip angle, C1) Variance of toe-ground clearance, D1, E1) Maximum hip angle histogram of Paretic and Non-paretic limbs, $\Delta$avg: Average of maximum hip angle increment, P: The significance of paired t-test results (maximum hip angle of unassisted and exo-assisted). A2) P1-P9: Toe-ground clearance across the gait cycle of nine patients, Black lines: non-assisted, Colored lines: exo-assisted, Shade: variance range of toe-ground clearance, B2) Sketch Map of Toe-ground clearance, C2) Toe-ground clearance across the gait cycle, D2, E2) Maximum toe-ground clearance histogram of Paretic and Non-paretic limbs, $\Delta$avg: Average of maximum toe-ground clearance increment, P: The significance of paired t-test results (maximum toe-ground clearance of unassisted and exo-assisted).
Figure 3

Radar chart of gait symmetry, Grey Polygon represents radar map with the assistance of exoskeleton and Black Polygon represents radar map without the assistance of exoskeleton.
Figure 4

Plantar pressure. A) Plantar pressure heat map of P1 when unassisted, B) Plantar pressure heat map of P1 when assisted by exoskeleton, C) plantar regions according to anatomy, D) Intensity of pressure in different plantar divisions, E) Impulse distribution of different plantar divisions, *P<0.05, **P<0.01.

Figure 5

Surface electromyography. A) Surface electromyography signal processing (IEMG: Integral Electromyogram), B), Histogram of IEMG, * P<0.05, ** P<0.01.
Supplementary Files

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