Gait analysis of powered exoskeleton designed for spinal cord injury using markerless motion capture in healthy individuals

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Abstract. In this study, we conducted gait analysis on individuals wearing the prototype exoskeleton using a markerless motion capture system designed like a bodysuit. The results of the gait analysis demonstrated that the patterns of hip and knee joint angles during one gait cycle were nearly identical between normal walking and walking with the prototype. This indicates that the prototype exoskeleton exhibits walking assistance capabilities. However, fine-tuning of the prototype's knee joint angle and gait velocity settings is required. The markerless motion capture system effectively addresses common issues encountered in traditional measurement methods, such as conventional optical motion capture systems where markers can be obscured by the exoskeleton frame or mechanical goniometers that may interfere with the exoskeleton frame. This approach provides valuable insights into the performance of the walking assistance feature of the exoskeleton.

Keywords: powered exoskeleton, spinal cord injury, gait rehabilitation, assistive technology, safety, usability

1. Introduction

Exoskeleton technology holds promise for gait rehabilitation in individuals with spinal cord injuries (SCIs), potentially recovering their motor function and facilitating reintegration into daily life and work. Although prior clinical reports and systematic reviews have underscored the positive impact of exoskeletons in helping individuals with paraplegia regain walking independence, persistent challenges, such as device malfunctions, skin injuries, misalignments, user errors, and falls, have been noted (Federici et al. 2015; Miller et al. 2016; He et al. 2017; Oyama et al. 2020). Furthermore, the size and weight of exoskeletons, coupled with their potential fitting problems related to lower-limb alignments, present additional hurdles. To overcome these challenges, we have developed a prototype exoskeleton that prioritizes safety and usability (Oyama & Ikeda 2023). This device incorporates actuators at the hip and knee joints, controlled by a computer, and features a gait trigger sensor. The adaptable frame of the prototype exoskeleton addresses variations in height and leg alignment.

Assessing the performance of exoskeletons through quantitative evaluation, such as gait analysis, poses its own set of challenges. Traditional methods are beset with difficulties, such as marker occlusion caused by the exoskeleton frame in optical motion capture systems, and mechanical joint goniometers are impeded by exoskeleton interference, compromising accuracy. In contrast, our study employs a markerless motion capture system designed as a bodysuit (Amimori 2021), minimizing interference with the exoskeleton frame.

The current study aims to determine the possibility of analyzing the gait of individuals wearing exoskeletons using a markerless motion capture system. Additionally, we verified the feasibility and effectiveness of the prototype exoskeleton.

2. Method

2.1 Participants

Ten healthy adults (seven men and three women) participated in this study. The mean height was 167 ± 10 cm (range: 152–179 cm), the weight was 58 ± 9 kg (range: 41–70 kg), and the body mass index was 21 ± 2 (range: 17–25).

2.2 Instruments

The prototype exoskeleton was used as the experimental device (Figure 1). The primary unit consisted of a structure resembling a hip-knee-ankle-foot orthosis, equipped with actuators, a gait trigger sensor, a control unit, and a battery. Additionally, a Lofstrand clutch with an operational interface and a tablet personal computer (PC) equipped with adjustment software were included.

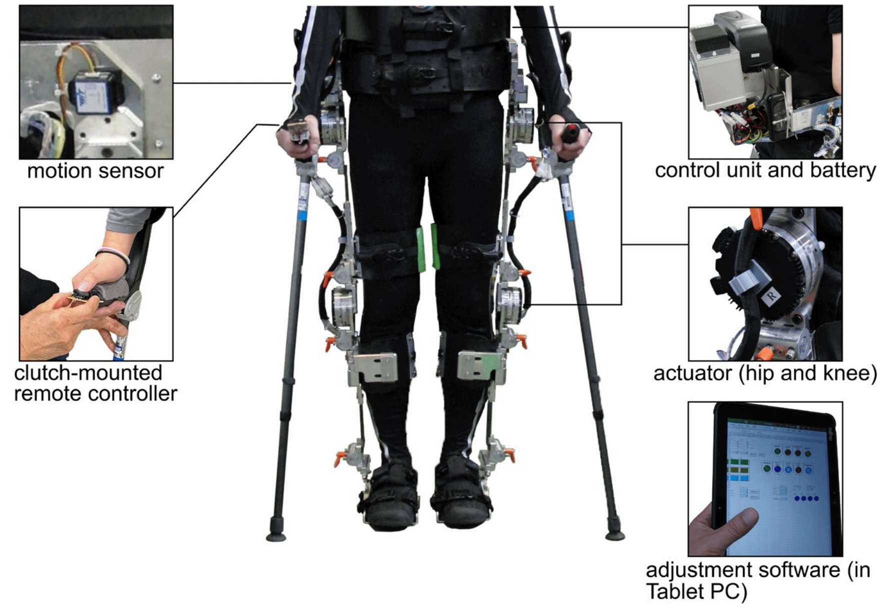

Figure 1: *Appearance of the prototype-powered exoskeleton for spinal cord injuries.*

Measurement instruments included a markerless motion capture system (e-skin MEVA, Xenoma Inc., Tokyo, Japan) to measure hip and knee joint angles (Figure 2). The e-skin system has a bodysuit-type design that can be worn like clothing, thereby ensuring minimal interference with the exoskeleton frame. The system uses an inertial measurement unit (IMU) sensor comprising three-axis acceleration and gyro sensors to calculate motion based on sensor data. The IMU sensors were positioned in 18 locations, with one on the headband, ten on the upper body shirt, and seven on the lower pants. The sensor itself is remarkably slim, measuring 20 mm in width, 35 mm in height, and 2 mm in thickness. The accelerometer has a ± 30 G range and 16-bit resolution, while the gyro sensor has a ± 4000 dps range and 16-bit resolution. When compared to optical methods, this particular system yields joint angle differences of approximately 2 degrees with an impressive correlation coefficient of 0.98 for hip and knee joint angles in the sagittal plane (Teufl et al. 2018). Additionally, the system implements an algorithm developed by Teufl et al. (2018), enabling motion calculation solely through the accelerometer and gyro sensors without relying on geomagnetism. Consequently, the system remains unaffected by geomagnetic interference, which has been a drawback of IMU, ensuring stable measurements even in the presence of a motor in the exoskeleton. In this study, data was recorded at a sampling frequency of 100 Hz, transferring all measurements to a PC via Bluetooth.

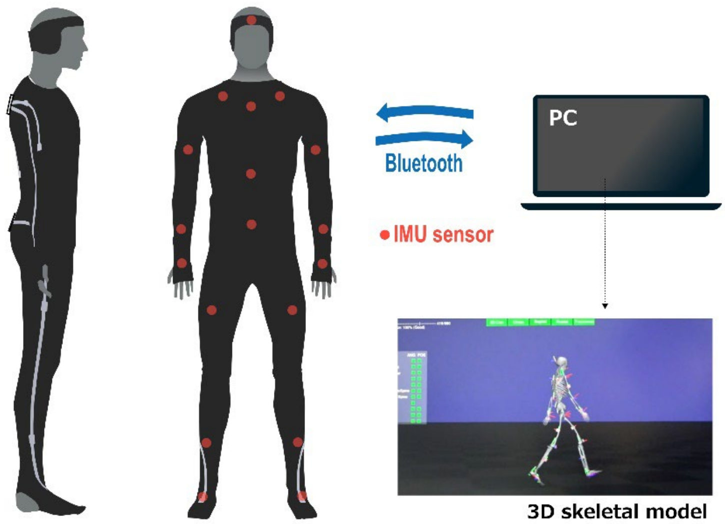

Figure 2: *Markerless motion capture system (e-skin MEVA).*

2.3 Experimental procedure

The participants walked 6 m twice under two conditions: normal walking and walking with the prototype. Throughout this phase, motion capture technology recorded joint angles, while a stopwatch measured the walking time, and video cameras captured frontal and side views. When using the prototype, the participants used crutches along with the option of either bilateral simultaneous or alternating thrusting motions. They were then explicitly instructed not to exert any force on their lower limbs while walking with the prototype. Additionally, to ensure safety and prevent falls, a caregiver stood behind each participant.

2.4 Analytical methods

For the gait analysis, data from the second trial were utilized. To account for variations in walking times among the participants, the joint angle data were normalized within a single gait cycle, encompassing both the swing and stance phases, defined as 100%. Then, we used the maximum (peak flexion angle value) and minimum (peak extension angle value) hip and knee joint angles to represent and compare differences attributed to exoskeleton usage. The gait cycle was divided into eight distinct phases (initial contact 0% of the gait cycle, lording response = 0–12%, mid stance = 12–31%, terminal stance = 31–50%, pre-swing = 50–62%, initial swing = 62–75%, mid swing = 75–87%, terminal swing = 87–100%) * following the Rancho Los Amigos Hospital method (Götz-Neumann 2002). Stable hip and knee joint angles were extracted at each of these phases. Subsequently, correlations were made between the normal gait and the gait with the prototype for the above-mentioned data sets.

2.5 Statistical analysis

The data is presented in the form of a mean ± standard deviation. Pearson's correlation coefficients were computed to assess the relationship between normal walking and walking with the prototype for the hip and knee joints during a single gait cycle. Additionally, paired t-tests were employed to compare peak flexion and extension angles of the hip and knee joints, gait velocities, and stride lengths during normal walking and walking with the prototype. A significance level of less than 5% was set for all statistical analyses, which were conducted using IBM SPSS Statistics version 28 (IBM Corp., Armonk, N.Y., USA).

3. Results

The results of hip and knee joint kinematic parameters throughout the gait cycle are displayed in Figure 3. Positive correlations were observed between normal walking and walking using the prototype for both hip ($r = 0.70$, $p < 0.001$) and knee joint angle ($r = 0.84$, $p < 0.001$). The comparison of peak values of hip and knee joint angles, gait velocity, and stride length is represented in Table 1. The peak hip flexion angle did not exhibit significant differences between conditions, whereas the peak hip extension angle was significantly smaller when walking using the prototype compared to normal gait ($p = 0.002$). Moreover, the peak knee flexion angle was significantly smaller when the prototype was used for walking compared to normal walking ($p < 0.001$). When utilizing the prototype, gait velocity was significantly slower ($p < 0.001$), and stride length was significantly shorter ($p = 0.003$) compared to that in normal walking.

4. Discussion

The study verified the success of the prototype in executing intended walking programs. The kinematic results demonstrated nearly identical hip and knee joint patterns between normal walking and walking using the prototype, supporting the notion that the prototype provides gait assistance.

* **Abbreviation**: IC (Initial Contact), LR (Lording Response), MSt (Mid Stance), TSt (Terminal Stance), PSw (Pre Swing), ISw (Initial Swing), MSw (Mid Swing), TSw (Terminal Swing).

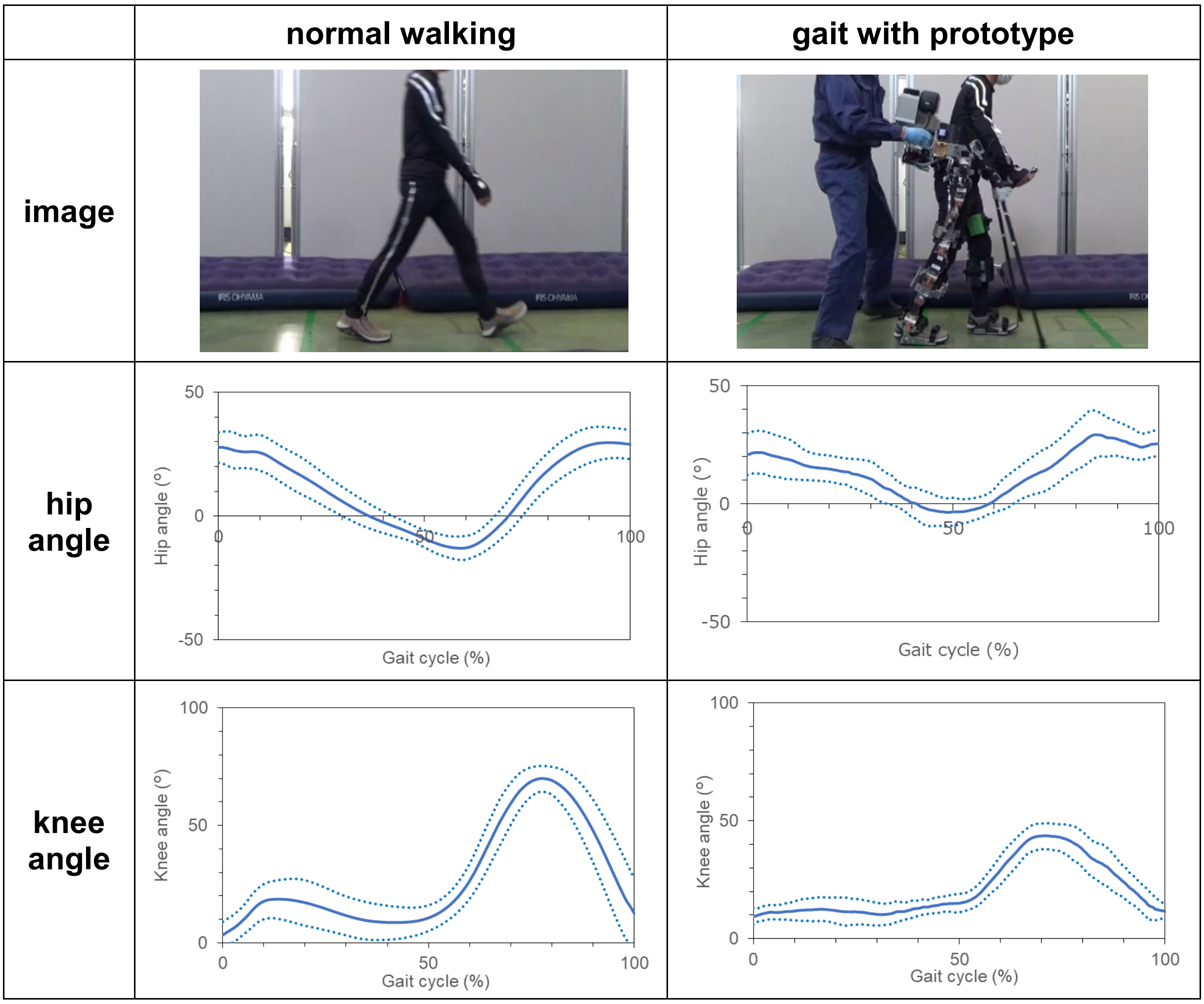

Figure 3: *Change in hip and knee joint angles during one gait cycle under the two conditions. The vertical axis in the figure represents joint angles, with (+) indicating flexion and (−) indicating extension. The horizontal axis is normalized to represent one gait cycle, including the swing phase and stance phase, at 100%. The solid line represents the participant's average, while the dashed line represents the standard deviation.*

Table 1: *Comparison of peak values of hip and knee joint angles, gait velocity, and stride length.*

		normal walking	gait with prototype	p-value
hip angle (°)	**flexion**	30 ± 3.5	30 ± 6.1	0.995
	extension	-13 ± 3.7	-6 ± 5.1	0.002
knee angle (°)	**flexion**	74 ± 4.5	44 ± 5.2	< 0.001
gait velocity (m/s)		1.0 ± 0.1	0.1 ± 0.1	< 0.001
stride length (m)		1.2 ± 0.1	0.8 ± 0.3	0.003

However, significant differences were observed between conditions in the peak values of knee joint flexion angle and hip joint extension angle. When using the prototype for walking, the knee flexion during the stance phase, especially during the lording response phase was insufficient, and the maximum knee flexion angle during the swing phase was smaller compared to that in normal walking. Furthermore, the maximum hip extension angle of the prototype was also smaller than that of normal walking. When using the prototype, one observes that the foot makes contact before the knee is fully extended, and a forward-leaning posture is noticeable due to the use of crutches. These factors may be related to the shorter stride length of the prototype compared to that of normal walking. Therefore, retuning the setting values for the prototype's walking program is necessary.

Furthermore, gait velocities achieved with the prototype were only 10% of those observed during normal walking. This was because the participants were using the exoskeleton for the first time, and the exoskeleton's speed was intentionally set to a slow pace to prioritize safety. Some participants expressed apprehension about going faster. However, according to the opinion of a physical therapist with experience using exoskeletons, the speed tends to be slow at first, but fast speeds would make walking more stable. Given that the prototype's specifications enable it to achieve speeds of up to 0.5 m/s, equivalent to those of a conventional exoskeleton, it becomes essential to progressively tailor the speed based on the user's condition and proficiency level.

5. Conclusion

A prototype exoskeleton for SCI has been developed that enables quantitative measurement of concealed body movements within the exoskeleton frame using a markerless motion capture system. The demonstration of nearly identical gait patterns between normal walking and walking using the prototype provides evidence that the prototype could assist in walking. Further work is required to enhance and fine-tune the device for clinical implementation with patients who have SCI.

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Acknowledgment. The authors thank Dr. Kazunari Furusawa and Mr. Yoshinori Yamada for their valuable advice, as well as the medical staff at Kibi Kogen Rehabilitation Center for their cooperation.

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06. – 08. März 2024

GfA-Press

Bericht zum 70. Arbeitswissenschaftlichen Kongress vom 06. – 08. März 2024

Institut für Arbeitswissenschaft und Technologiemanagement (IAT), Universität Stuttgart
In Zusammenarbeit mit: Fraunhofer-Institut für Arbeitswirtschaft und Organisation (IAO), Stuttgart

Herausgegeben von der Gesellschaft für Arbeitswissenschaft e.V.
Sankt Augustin: GfA-Press, 2024
ISBN 978-3-936804-34-8

NE: Gesellschaft für Arbeitswissenschaft: Jahresdokumentation

Als Manuskript zusammengestellt. Diese Jahresdokumentation ist nur in der Geschäftsstelle (s. u.) erhältlich.

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