Brief report

Trunk muscle activity patterns and motion patterns of patients with motor complete spinal cord injury at T8 and T10 walking with different un-powered exoskeletons

Xinyu Guan¹, Shengzheng Kuai^{2,3}, Linhong Ji¹, Rencheng Wang¹, Run Ji⁴

¹Division of Intelligent and Bio-mimetic Machinery, The State Key Laboratory of Tribology, Tsinghua University, China, ²Department of Mechanical Engineering, Tsinghua University, China, ³Biomechanics and Biotechnology Lab, Research Institute of Tsinghua University in Shenzhen, China, ⁴Human Biomechanics Laboratory, National Research Center for Rehabilitation Technical Aids, China

Objective: The aim of this study was to explore how neurological injured levels of spinal cord affect the performance of patients walking with different un-powered exoskeletons.

Study design: Case series observational study.

Setting: Gait and Motion Analysis Laboratory at the National Research Center Rehabilitation Technical Aids.

Methods: Electromyography and motion data from two subjects with complete spinal cord injury at T10 and T8 walking with un-powered exoskeletons were collected simultaneously.

Outcome measures: Surface electromyography of trunk muscles and motion data including joint angle and center of mass (COM).

Results: Compared to T10 subject, T8 subject activated trunk muscles in higher levels walking with all tested un-powered exoskeletons and had greater pelvic obliquity walking with reciprocating gait orthosis (RGO) and energy-stored exoskeleton (ES-EXO). ES-EXO can redistribute muscle forces, recruit trunk muscles evenly, increase walking speed and improve COM trajectory in frontal plane.

Conclusion: This study revealed differences in kinematics and muscle activities in walking with three un-powered exoskeletons between two patients with different neurological injured levels. ES-EXO had advantages over conventional un-powered exoskeletons on recruiting muscles evenly and improving walking speed, step length and COM trajectory.

Keywords: Spinal cord injuries, Motion, Electromyography, Walking, Orthotic devices

Introduction

Walking can benefit patients with lower-limb paralysis to improve the functional abilities and reduce the complications such as osteoporosis, pressure sores and peripheral circulation disorder, etc.^{1,2} Therefore, many un-powered exoskeletons were developed and widely used in clinical situations to help patients with spinal cord injury (SCI) for ambulation.

Conventional un-powered exoskeletons include the knee-ankle-foot orthosis (KAFO) and the reciprocating gait orthosis (RGO). KAFO consists of a thigh and shank

shell to support the femur and tibia as well as a lock to prevent the knee joint from bending. Swing-through gait pattern is employed when walking with KAFO.³ RGO consists of a pair of KAFOs connected by a fixed hip band and a rocking pelvic band. Patients adopt reciprocal gait by rotating the trunk to shift the weight to the forward leg and facilitate the contralateral leg to move forward.⁴ Energy-stored exoskeleton (ES-EXO) is a novel un-powered exoskeleton developed by Tsinghua University consisting of bilateral KAFOs and two energy-stored components. Patients achieve leg swing through the energy-stored components alternatively storing and releasing energy along with hip extension and flexion.⁵

As patients injured at thoracic levels lost ability to control lower limb motion, they have to use upper

Correspondence to: Prof. Linhong Ji, Corresponding address: 1029 Room, Lee Shau Kee Science and Technology Building, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China. Email: jilh@tsinghua.edu.cn

limb and trunk muscles to drive the whole body forward,⁶ in which un-powered exoskeletons play a role in transferring power from trunk to lower limbs. Motor functional outcomes are strongly associated with the neurological injured levels.⁷ For example, the trunk control ability of patients with complete T5–T9 injury is moderate as only a part of their back and abdominal muscles are innervated by nerves,⁸ while patients injured completely at T10–T12 are able to control trunk much better due to fewer muscles being affected.⁹ Therefore, patients with different injured levels may perform differently walking with KAFO, RGO and ES-EXO.

We hypothesized that (1) patients with a higher injured level were likely to have greater pelvic range of motion (ROM) and spend more trunk muscle efforts, and (2) compared with conventional exoskeletons ES-EXO can redistribute trunk muscle forces and recruit trunk muscles evenly due to its energy-stored-and-released mechanism. The aim of this study was to explore how neurological injured levels of spinal cord affect the performance of patients walking with different un-powered exoskeletons.

Methods

Subjects

Two male subjects with SCI were recruited: one (age 29 years old, height 1.72 m and weight 62 kg) was injured at T10, and the other (age 30 years old, height 1.76 m and weight 85 kg) was injured at T8. Both were diagnosed with ASIA (American Spinal Injury Association) classes A and muscle function strength grade 0. Their upper limb muscles were intact and strong. They both had at least one-year experience to walk with bilateral KAFOs indoors. The two subjects were trained to use reciprocating gait orthosis (RGO) and energy-stored exoskeleton (ES-EXO), respectively for two months. Two 20–30 minute gait-training sessions that the subjects walked in a 30-m corridor back and forth was carried out each day. A walker was used to keep balance. ES-EXO spring parameters are shown in Table 1. Study approval was granted by the Institutional Review Board and the ethics committee.

Experiment procedure

EMG patterns of bilateral rectus abdominis (RA), obliquus externus abdominis (OE), latissimus dorsi (LD) and erector spinae (ES) were collected by Telemyo DTS (Noraxon, Scottsdale, Arizona, USA) with 1500 Hz sample frequency and 1000 times amplification. Ag/AgCl surface electrodes (Tianrun Sunshine Medical Supplies Co., Ltd, Beijing, China) were used. Maximal voluntary contractions (MVC) were carried out for eliminating the variance and allowing for comparison between the two subjects. MVC of 4–5 seconds against external resistance were carried out in supine or prone position, and the corresponding movements included attempted trunk flexion, trunk extension, trunk flexion with leftward and rightward rotation and shoulder elevation.¹⁰ Each MVC test was repeated three times and the maximum value was recorded. The order of MVC tests was random.

The two subjects were asked to walk along 6-m walk-away with KAFO, RGO and ES-EXO, respectively at comfortable speeds and maintain balance by a walker (Fig. 1). The passive reflective markers were placed on the body and un-powered exoskeletons based on the Plug-in-Gait Marker configuration.¹¹ A motion capture and analysis system (Vicon Nexus v1.8.5, Oxford Metrics, Oxford, UK) and Telemyo DTS were used to record the motion (100 Hz sample frequency) and EMG data simultaneously. Five valid trials were collected for each subject in each condition. The three conditions were carried out in random and subjects were allowed 2 minutes for rest between two trials. All data were collected in the Gait and Motion Analysis Laboratory at the National Research Center Rehabilitation Technical Aids (Beijing, China).

Data analysis

The envelopes of EMG signals were created by a band-pass 10–500 Hz filter, electrocardiogram artifact reduction, a high-pass 60 Hz filter, a full wave rectification and a low-pass 4 Hz filter in sequence, and normalized to corresponding MVC value. EMG data were processed with software (MR-XP 1.07 Master Edition). The total muscle efforts spent in stance

Table 1 Parameters of spring 1 and spring 2

Subject	Spring	Stiffness (N/mm)	Original length (mm)	Initial length (mm)	Initial force (N)	Initial force arm (mm)
T10	Spring 1	0.75	60	140	60	60
	Spring 2	0.56	75	150	42	15
T8	Spring 1	1.03	60	140	82	60
	Spring 2	0.77	75	150	58	15

The initial length, initial force and initial force arm were tested when the participant stood in upright posture.

Figure 1 Two subjects walked with three un-powered exoskeletons, respectively and maintain balance by a walker: (a) KAFO, (b) RGO and (c) ES-EXO.

and swing phase were evaluated by integrated EMG (IEMG). Times series of averaged trunk, pelvic and hip angles and EMG envelopes were normalized to 0–100% of the gait cycle. Step length and walking speed were divided by the leg length,¹² and IEMG was divided by the body mass.¹³ Trajectories of center of mass (COM) in frontal plane were analyzed based on mass-weighted average of body segment parameters in Vicon Nexus. Averaged angles, EMG data and COM trajectories were calculated based on 5 trails.

Results

MVC tests

Table 2 indicates the results of trunk muscle MVC tests as quantitative baselines for motor output of two subjects. All values of T10 subject were greater than their counterparts of T8 subject and the differences were significant in bilateral RA, OE and ES.

Table 2 Trunk muscle MVC values of subjects

Subject	RA (mV)		OE (mV)		LD (mV)		ES (mV)	
	L	R	L	R	L	R	L	R
T10	100	101	46	44	102	104	28	39
T8	13	12	14	12	77	51	16	15

Spatiotemporal parameters

Table 3 presents the spatiotemporal parameters of two subjects walking with three un-powered exoskeletons. In KAFO and ES-EXO conditions, T8 subject walked with less step length, lower walking speed and longer stride duration. All tested spatiotemporal parameters in RGO condition were close between the two subjects. Both subjects walked the fastest with ES-EXO.

Range of motion

Fig. 2 illustrates the kinematics of hip, pelvis and trunk walking with different un-powered exoskeleton. There were differences in hip movement trends between two subjects in three conditions: T10 subject experienced hip extension and then flexion during double support phases while T8 subject altered slightly; T8 subject extended hip during single limb stance phase while T10 subject maintained almost unchanged. The motion patterns and ranges of trunk were similar between two subjects in each condition. Compared to T10 subject, T8 subject had a contrary trend of pelvic tilt in ES-EXO condition and greater ranges of pelvic obliquity in RGO and ES-EXO conditions. Their pelvic rotation ranges were close in each condition.

Table 3 Temporal spatial data of subjects walking with different un-powered exoskeletons

Un-powered exoskeleton	Step length/leg length (dimensionless)		Walking speed/ leg length (s^{-1})		Stride duration (s)		Swing duration (%)	
	T10	T8	T10	T8	T10	T8	T10	T8
KAFO	0.19	0.17	0.11	0.07	4.11	4.44	14.6	16.0
RGO	0.13	0.13	0.07	0.07	4.91	4.92	15.3	15.2
ES-EXO	0.20	0.18	0.13	0.11	3.50	3.97	14.6	15.1

Swing duration was normalized to gait cycle.

Center of mass

Fig. 3 shows COM trajectories in frontal plane of two subjects walking with different un-powered exoskeletons. Compared to T10 subject, T8 subject had greater lateral COM displacements and smaller vertical COM displacements in three conditions. For two subjects in ES-EXO condition, COM displacements in lateral direction (T10: 34 mm and T8: 80 mm) were smallest and in vertical direction (T10: 42 mm and T8: 24 mm) were greatest.

EMG activities

Fig. 4 illustrates trunk muscle activities of two subjects walking with different un-powered exoskeletons. They activated bilateral RA, OE, LD and ES in similar patterns, but muscle activation levels of T8 subject were significantly higher than T10 subject. Two subjects increased RA and OE EMG normalized amplitude rapidly at heel striking in KAFO and RGO conditions. Additional sudden bursts also appeared in OE of T8 subject in ES-EXO condition. In three conditions, the onsets of ES for two subjects were nearly at toe off, and T8 subject had relatively longer muscle burst durations. In ES-EXO condition, ES burst duration of T8 subject lasted the longest.

Fig. 5 indicates the trunk muscle efforts of two subjects walking with different un-powered exoskeletons. The IEMG of most tested muscles in T8 subject were greater than T10 subject. Compared to KAFO and RGO conditions, in ES-EXO condition two subjects had smaller RA and OE IEMG during stance and swing phase and greater left ES IEMG during swing phase. For T8 subject, bilateral LD IEMG in RGO condition were the greatest in stance and swing phase.

Discussion

We investigated gait patterns and trunk muscle activities of two subjects with motor complete SCI (T10 and T8 injured level, respectively) walking with three different un-powered exoskeletons. The main findings were summarized: (1) Despite differences in neurological injured levels, many motion and muscle activity patterns were

similar; (2) The kinematic differences between the two subjects were mainly presented in trends of hip flexion and pelvic tilt, and ranges of pelvic obliquity; (3) The EMG differences were predominantly observed in muscle activation levels. The effects of neurological injured levels on kinematics and muscle activities walking with different un-powered exoskeletons were discussed below.

KAFO

It was contrary to our first hypothesis that compared to T10 subject the weak trunk movement control ability of T8 subject did not cause significant changes in joint angular ranges, which could be explained by the structure of KAFO lacking the constraints on pelvis and the swing-through gait pattern. T8 subject activated trunk muscles especially RA, OE and ES in higher levels and spent more muscle efforts to maintain the similar ROM to T10 subject.

Zajac *et al.* indicated that a moment can contribute to the power of a segment to which it is not applied through the intersegmental reaction forces.¹⁴ Compared to RGO and ES-EXO conditions, two subjects had greater ranges of pelvic obliquity and rotation, by which they were likely to achieve the leg swing-through.

RGO

RGO users extended hip joint to drive the contralateral hip flexion by the rocking pelvic band. Anterior tilt of trunk and pelvis was difficult to extend the hip joint and against the reciprocal gait. Consequently, subjects tried to laterally bend and rotate trunk and pelvis to ensure sufficient foot clearance and swing leg.¹⁵ Due to weak motor control ability, T8 subject produced greater pelvic obliquity, which was consistent with our first hypothesis. The rigid bands of RGO limited motion of T10 subject and caused identical walking speed and step length to T8 subject.

The functions of LD include joining the upper limb with the axial skeleton and facilitating the proper motion of the upper limb. T8 subject generated much more LD power than T10 subject in both stance and

Figure 2 Hip, trunk and pelvic angles of two subjects walking with different un-powered exoskeletons in a gait cycle from right heel strike to subsequent right hell strike.

Figure 3 Center of mass trajectories of two subjects walking with different un-powered exoskeletons in a gait cycle from right heel strike to subsequent right hell strike in frontal plane.

Figure 4 Normalized EMG of trunk muscles of two subjects walking with different un-powered exoskeletons in a gait cycle from right heel strike to subsequent right heel strike.

Figure 5 Trunk muscle IEMG of two subjects walking with different un-powered exoskeletons in stand and swing phase. L, left; R, right.

swing phase, which could provide support for over pelvic obliquity in frontal plane and maintain balance.

ES-EXO

It proved our second hypothesis that compared to KAFO and RGO conditions, (1) for T10 subject, the tensile springs of ES-EXO alternatively storing and releasing energy in a gait cycle decreased RA and OE activities significantly and increased ES activities slightly; (2) for T8 subject, RA were recruited more evenly and in a lower level, and burst durations and activities of ES were increased. The tensile springs redistributing trunk muscle forces was one reason. It could also be interpreted that the pelvic shells and the soft straps of ES-EXO not only limited excessive movements of pelvis but also avoided inharmonious interaction between subjects and exoskeletons. Less residual ES of T8 subject caused more muscle efforts to extend Spring 1 as the energy stored in this tensile spring was generated by contraction of ES on the hip extension side.⁵ This was consistent with our first hypothesis.

Displacements of COM in vertical and lateral directions have effects on walking efficiency and metabolic cost.^{16,17} The total amount of vertical and lateral COM displacements in normal adult men are 5 cm and 4 cm, respectively at usual walking speeds. Compared to KAFO and RGO, ES-EXO effectively improved frontal plane COM trajectory of T10 subject, which was close to the normal. Although it had also improvement for T8 subject in a certain extent, the effect was not as obvious as T10 subject.

Limitations

Measurement error came from marker placement as the lower limb markers were attached to the exoskeletons. The differences of un-powered exoskeletons in weight and size and physical quality of subjects could affect

motion and muscle recruitment. The spring stiffness and location of ES-EXO were related to energy storage and interacted with motion and muscle recruitment, thus the optimal parameters of springs should be determined in the future.

Conclusion

Compared with the patient injured at T10, the patient injured at T8 had greater pelvic obliquity walking with RGO and ES-EXO and trunk muscles including RA, OE, LD and ES were recruited in higher activation levels in three conditions. Compared with KAFO and RGO, ES-EXO can redistribute trunk muscle forces and recruit trunk muscles evenly. ES-EXO can also increase walking speed and improve the COM trajectory in frontal plane. These findings could provide some useful references on the effects of the neurological injured level on kinematics and muscle activities walking with different un-powered exoskeletons.

Acknowledgements

The study was supported by grants from National Key Technology R&D Program of China [grant no. 2012BAI34B02]. The authors are grateful to the subjects who cooperated with the investigation and the National Research Center for Rehabilitation Technical Aids, China for equipment support.

Conflict of interest

The authors have no disclosures.

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