Exoskeleton-Assisted Walking for Pulmonary and Exercise Performances of SCI Individuals

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Abstract*— *Objective: **To determine whether exoskeleton-assisted walking (EAW) improves pulmonary ventilation function, motor function and related body structure, and activities equivalently as the conventional exercise program for people with spinal cord injury (SCI).** ***Methods:*** **Forty participants (7 females and 33 males; age 37.1±12.0 years) with thoracic SCI were randomized into two groups and undertook 16 sessions of 50-60 min training (4 days/week). Participants in the EAW group received EAW trainings, such as assisted standing, walking, and climbing the stairs. The control group received a conventional exercise program. Outcomes were measured at baseline and upon completion of treatment.** ***Results:*** **After trainings, the EAW group improved more than the control group in the forced vital capacity (FVC, 0.53 L [0.01–1.06 L]), predicted FVC% (19.59 [6.63–32.54]) and forced expiratory volume in 1s (0.61 L [0.15–1.07 L]), basic activities of daily living (BADL) (19.75 [10.88–28.62]), and distal femoral cartilage. Participants in the EAW group completed 6-minute walk test with median 17.3 meters while wearing the exoskeleton. There was no difference in trunk and lower extremity motor function, bone mineral density, and adverse events ($P > 0.05$).** ***Conclusion:*** **In people with lower thoracic neurological level of SCI, EAW training has potential benefits to facilitate pulmonary ventilation function, walking, BADL and thickness of cartilage comparing to a conventional excise program.** ***Significance:*** **This study provided more evidence for using EAW in clinic, and partly proved EAW had equivalent effects as conventional exercise program, which may combine with conventional exercise program for reducing burden of therapists in the future.**

***Index Terms*—** **Spinal cord injury, exoskeleton, exercise, pulmonary function, fitness.**

I. INTRODUCTION

SPINAL cord injury (SCI) is a worldwide life-disrupting pathological condition with estimated 17,810 injuries occurred in the United States in 2017 [1], [2], and 3.5 per million in the United Kingdom each year [3]. Restoring functions (neuromusculoskeletal and pulmonary function, etc.), activities of daily living (walk, grasp, lift, etc.), quality of life and life expectancy post-SCI remain to be medical challenges [4]. Despite great progress in treatments, it is still difficult to achieve the recovery of motor that leads to immobility [5]. Due to accelerated aging, lifestyle factors, and decreased mobility, even incomplete spinal cord injury lesions as low as L4 should be considered as risk factors for cardiopulmonary disability [6]. A longitudinal decline was reported in forced vital capacity (FVC) and forced expiratory volume in 1 second (FEV_1) [7], that indicates persons with SCI are more likely to suffer pulmonary capacity deficit [8].

Exercise and Sports Science Australia recommended people with SCI to undertake a combined exercise program which contained moderate aerobic exercise (>30min, >5d/week), moderate strength training and flexibility training (>2d/week) for maintaining respiratory function, quality of life and functional independence [9], [10], [11], [12]. However, the improvements are limited for people with SCI due to lower extremity motor lesions and training types [13]. Exercise of upper body limits their maximal exercise capacity and puts them at a disadvantage compared with leg exercise among paralympic athletes[14], which might also affect general individuals with SCI. Hence, a new rehabilitation therapy containing leg exercise is needed for improving the function and independence of people with SCI.

Exoskeleton-assisted walking (EAW) refers to a robotic suit worn on the body enabling a person with paralysis to stand and walk [15], [16], [17], that has been confirmed to help individuals with thoracic and lumbar SCI to walk safely [18], [19], [20]. A number of studies [21], [22] has manifested the EAW can be used a moderate-intensity level of exercise according to the heart rate, oxygen demand, and rate of perceived exertion. Besides this, Knezevic et al., [23] reported EAW training improves oxygen uptake efficiency, such as

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This work involved human subjects in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ethics Committee of West China Hospital of Sichuan University.

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oxygen consumption per unit time. Nevertheless, these clinical trials were designed as observational studies, and the changes of pulmonary ventilation function followed by an EAW program have not been reported yet. It is unclear that whether better pulmonary functions caused by EAW training performed better exercise capacity in walking. There is lack of evidence that related to the effect of EAW training on respiratory function, quality of life and functional independence for people with SCI. Furthermore, the relation between musculoskeletal function, pulmonary function, and walk ability are not yet completely understood. Moreover, EAW training is with a mechanical stimulation that may has effect on bearing bone and cartilage. Previous studies have inconsistence in effect on bone mineral density (BMD). Bass et al., [24] reported an increased risk of fracture, while others [25], [26] not. As for cartilage, there is lack of clinical study.

Therefore, we conducted a prospective randomized controlled clinical trial to determine whether EAW training provide equivalent benefits on the physical function (pulmonary ventilation and musculoskeletal function) and related body structure, fitness, and activities to those obtained in a conventional exercise program among individuals with SCI.

II. METHODS

A. Ethics Approval

This randomised controlled study was designed in accordance with the Consolidated Standards of Reporting Trials Guidelines and received approval from the Ethics Committee of West China Hospital of Sichuan University. This study was registered at the Chinese Clinical Trial Registry with the following identifier: ChiCTR2000034623. Participants gave written informed consent according to the 1964 Declaration of Helsinki prior to their participation.

B. Participants

From July 2020 to March 2021, we prospectively enrolled all individuals aged between 15 and 65 years with a SCI between T4 and L1 at least 1 month. Participants were recruited from inpatients in 3 units of Rehabilitation centre, West China Hospital, Sichuan University. In addition, the eligible individuals met the following inclusion criteria: (1) American spinal injuries association impairment scale (AIS) [27] classified with A, B or C, (2) the height was between 1.50 meters and 1.85 meters and (3) stopped smoking for over 6 months.

The exclusion criteria were: (1) spasticity of any lower extremity muscle scored over 2 according to the Modified Ashworth Scale [28], (2) unstable fracture, (3) previous experience with EAW, (4) hypertension, (5) severe osteoporosis (bone mineral density with a T-score $<$ -3.5), (6) any respiratory or other neurological diseases, (7) overweight ($>$ 100 Kg).

C. Sample Size

As for the sample size calculated by G$*$power version 3.1.9.6 (HHU, German), a pilot study [29] was performed for determinizing the effect size (1.04) of primary outcome (FVC). It was calculated that at least 16 participants were required for each group according to a significance level of 0.05 and study power of 80%. The final sample size was 40 participants when considered the rate of dropping out as 20%.

D. Randomization and Masking

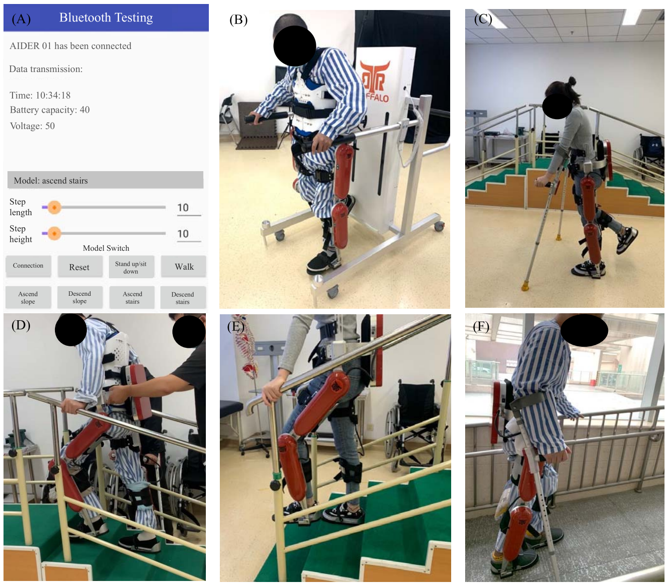
This was a single-blinded, randomized controlled efficacy trial with 2 parallel groups and intention-to-treat analysis. After researchers confirmed the eligibility, the individuals were randomly divided into one of two groups in a 1:1 ratio by simple randomization method, using a computer-generated simple random table. The sequences were preserved using closed envelop method by one researcher who was not involved in the trainings or assessments. Clinical data except walking parameters were measured at baseline and post-training by two clinical researchers who were blinded and did not know the group to which each participant belonged. Walking parameters were assessed by two researchers who participated in EAW trainings or the conventional program. Clinical data was recorded after averaging.

E. Interventions

All participants were received 16 sessions of exercise training for 50 to 60 minutes per session, 1 session per day, 4 sessions per week for 4 weeks. Exercise intensity was requested to reach 60% to 70% maximal heart rate (HR, HRmax $= 220 - \text{age}$) that is checked with the values of a heart rate sensor (Polar H10, POLAR® China). If the participant does not reach the intensity, oral prompting and encouragement were given by the therapist. All participants were scheduled to perform occupational therapy, endurance training cycling using upper limb, and biofeedback therapy once per day. Medications and rehabilitation nursing were ordered based on the medical condition.

The AIDER (AssItive DEvice for paRalyzed patient) powered robotic exoskeleton (generation IV, Buffalo Robot Technology Co. Ltd, Chengdu, China) was used for the EAW training. A dedicated Android application (alpha, China) as an additional control system switched different training modes (from sit to stand, walk, sit down, climb the slope, and go stairs, shown in Figure 1A). Body-weight-supported AIDER system was applied at the beginning of this program to protect users. All subjects were individually fitted to the robotic exoskeleton according to pelvic width, thigh length, and shank length. Training session included sitting, standing, walking, climbing stairs and slope with maximal assistance-walking mode under monitoring of experimented therapists (Fig. 1). A progressive EAW program was designed for participants that shown in Table I.

Individuals in the control group undertook a conventional exercise program that included strength training using dumbbell between 5 kg and 20 kg, dynamic balance training in sitting or standing position, flexibility training, and walking training with brace based on the recommendations of Exercise and Sports Science Australia. The time proportion of each training depended on the situations of individuals.



AIDER 01 has been connected

Data transmission:

Time: 10:34:18
Battery capacity: 40
Voltage: 50

Model: ascend stairs

Step length 10
Step height 10

Fig. 1. AIDER powered exoskeleton illustration used in this study. (A) a mobile phone application; (B) walk with body-weight-supported AIDER system; (C) walk in exoskeleton; (D) go upstairs in exoskeleton; (E) go downstairs in exoskeleton; (F) ascend slope in the exoskeleton.

TABLE I
DESCRIPTION OF THE EAW ROGRAM IN THE EXPERIMENTAL GROUP

Exercise	Session
From sit to stand and standing training using body-weight-supported AIDER system, controlled by therapist.	1
From sit to stand, standing training and shifting of the body centre of gravity using body-weight-supported AIDER system, controlled by patient.	2
From sit to stand, standing, and walking training using body-weight-supported AIDER system, controlled by patient.	3
From sit to stand, standing training and shifting of the body centre of gravity using AIDER system, controlled by patient.	4-5
From sit to stand and standing, and walking training (walk straight) using AIDER system, controlled by patient. Turning around with the help of therapists.	6
From sit to stand, standing, and walking training (walk straight and turn around) using AIDER system, controlled by patient.	7-12
From sit to stand, standing, and climb the slope using AIDER system, controlled by therapist.	13
From sit to stand, standing, and climb the slope using AIDER system, controlled by patient.	14
From sit to stand, standing, and take the stairs using AIDER system, controlled by therapist.	15
From sit to stand, standing, and take the stairs using AIDER system, controlled by patient.	16

EAW = exoskeleton-assisted walking, AIDER = AssItive DEvice for paRalyzed patient

F. Outcome Measures

Outcome measures were collected and analysed at the baseline and end of 16-session intervention period.

1) Primary Outcome: Pulmonary ventilation function test was performed with a computerized spirometer (Vyntus™SPIRO PC Spirometer, Vyaire Medical Inc., Mettawa, US) based on the standardized procedures as the American Thoracic Society [30] described. To determine pulmonary ventilation function, participants performed test seating in the wheelchair and were forbidden to disclose their intervention assignment to the assessor. The test was performed with the participants wearing a nose clip. If the participant coughed or made a mistake, the numerical values were not recorded. Three repeated maneuvers were performed, separated by a five-minute rest and the best result was recorded automatically. The test consisted of the assessments of FVC, predicted FVC%, FEV_1, forced expiratory flow ($FEF_{25/50/75}$), peak expiratory flow (PEF), and maximal voluntary ventilation (MVV) [31].

2) Secondary Outcomes: Motor function was reflected by the trunk control test (TCT) [32], [33], [34], lower extremity motor score (LEMS) [35], and muscle tone of lower limb estimated by modified Ashworth scale (MAS) [36]. During TCT, participants were asked to lie supine on the bed and then roll to each side, sit up, and sit in a balanced position on the edge of the bed, with feet off the ground for at least 30 seconds. There was a total of 100 scores for TCT, that higher scores indicate higher function of trunk control. Score of each item was 0 for "unable to perform movement without assistance," 12 for "able to perform movement, but in an abnormal style," or 25 for "able to complete movement normally." TCT and LEMS were also reported to clarify the reasons of ventilation and walking improvement, and the recovery of muscle strength.

The related body structures mainly consisted of the conditions of cartilage and bone in weight-bearing joints. Hence, the conditions of knee joint and the conditions of hip joint were chosen for represented the related body structures. The thickness of distal femoral cartilage that consisted of medial condyle, intercondylar area, and lateral condyle measured by musculoskeletal ultrasound were compared [37]. The value of Wards triangle BMD evaluated by dual-energy X-Ray absorptiometry were recorded. Modified Barthel index (MBI) were reported to demonstrate the ability of basic activities of daily living (BADL) [38]. The rate of adverse events was used for safety indicator.

Moreover, walking parameters were assessed by the 6MWT (6-minute walk test) for distance and 10MWT (10-metre walk test) for speed. Tests were performed in door in accordance with the guidelines of the American Thoracic Society [39]. The participant's heart rate, and the rate of perceived exertion (RPE) based on the Borg scale [40] during the 6MWT were recorded. Participants in EAW group were allowed to wear the exoskeleton, while those in control group using the knee-ankle-foot orthoses if they had one. The rate of adverse events was used for safety indicator.

G. Statistical Analysis

Analyses were completed according to intention-to-treat principle in the full analysis set and the missing data were supplemented with the last observation carried forward method. The statisticians were blinded to the program and completed analyses utilized SPSS version 25 (SPSS Inc, Chicago, Illinois). The Shapiro-Wilk test was used to determine if data were normally distributed. Data with normally distributed were recorded as means±SDs and 95% confidence interval (CI),

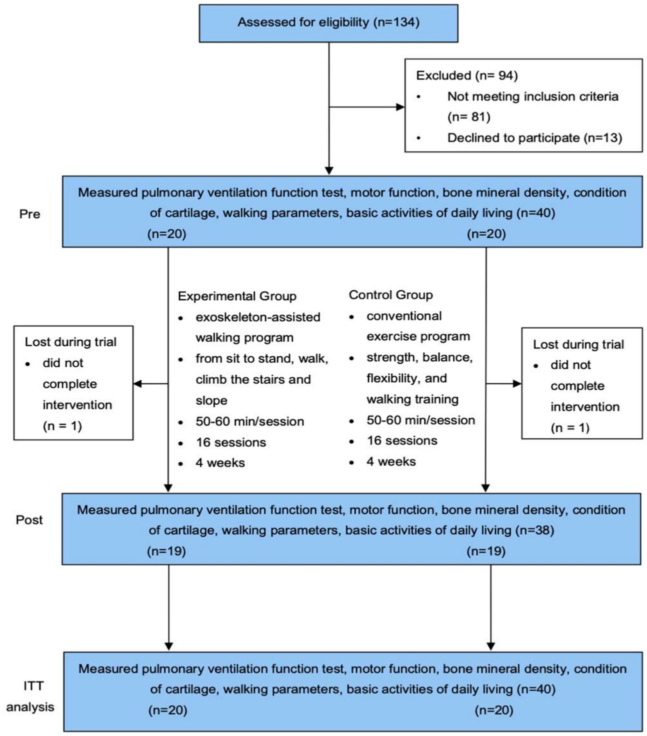


Fig. 2. Design and flow of participants through the trial. ITT: intention-totreat.

others were described as median (IQR) where necessary. Independent Student t-test was used to compare continuous data related to clinical features between two groups. Paired Test Student t-test was used to compare varies between pre- and post-intervention. Furthermore, the Fisher's exact and Pearson's Chi-square tests were used if the data were categorical variables. Wilcoxon rank-sum test and Mann–Whitney U test were used if the data was not normally distributed. Pearson correlation test or Spearman rank correlation test was performed to discuss the relation between the results of 6MWT, TCT and ventilation parameters with statistically significant difference between groups. In all statistical tests, a P-value < 0.05 was defined as significant.

III. RESULTS

A. Baseline Characteristics of Participants

The process of this study represented by the Consolidated Standards of Reporting Trials (CONSORT) diagram was shown in Fig. 2. A total of 134 individuals with SCI were screened from July 2020 to March 2021, of which 94 were excluded as per exclusion criteria (n = 81) or declining to commit the full participation (n = 13). 40 eligible individuals were randomized to either EAW group (n = 20) or control group (n = 20). After pre-intervention assessment, one individual in the EAW group, and one in the control group withdrew the study and did not accept the final assessment because of own desires to be discharged from hospital. Table II shows the baseline demographic and clinical characteristics for both groups. Two groups were comparable on the baseline characteristics.

TABLE II
BASELINE CHARACTERISTICS OF PARTICIPANTS

Characteristic	EAW (n=20)	Con (n=20)	P-value
Demographic			
Age (yr), mean±SD	36.6±11.7	37.7±12.6	0.786
Height (cm), mean±SD	166.2±6.4	170.0±6.2	0.064
Weight (kg), mean±SD	56.1±9.1	64.0±10.0	0.054
Gender, No. (%)			0.677
Female	4 (20.0)	3 (15.0)	
Male	16 (80.0)	17 (75.0)	
Clinical			
NLI, No. (%)			0.999
T4-T10	12 (60.0)	12 (60.0)	
T11-L1	8 (40.0)	8 (40.0)	
AIS, No. (%)			0.091
A	15 (75.0)	10 (50.0)	
B	3 (15.0)	2 (10.0)	
C	2 (10.0)	8 (40.0)	
DOI (mth), median (IQR)	2.0 (4.5)	2.0 (0.5)	0.273

EAW = exoskeleton-assisted walking group, Con = control group, NLI = Neurological level of injury, AIS = American spinal injuries association impairment scale, DOI = duration of injury, mth = month, IQR = interquartile range

B. Effect of EAW Program on Pulmonary Ventilation Function

EAW program was estimated to be more favourable than conventional exercise program for several measures of pulmonary ventilation function. Differences between the two groups at post-training testing, including FVC (0.53, 95% CI 0.01 to 1.06 L, $P = 0.048$), predicted FVC% (19.59, 95% CI 6.30 to 32.54, $P = 0.004$), and FEV_1 (0.61, 95% CI 0.15 to 1.07 L, $P = 0.011$). The results for FEF_{25-75}(0.61, 95% CI -0.38 to 1.59 L/s, $P = 0.220$; 0.79, 95% CI -0.23 to 1.61 L/s, $P = 0.057$; 0.40, 95% CI 0.28 to 1.07 L/s, $P = 0.242$, respectively), PEF (0.78, 95%CI -0.28 to 1.84 L/s, $P = 0.145$), and MVV (13.59, 95% CI -4.33 to 31.51 L, $P = 0.133$) supported that EAW training might be equivalent to conventional exercise program. Comparing with these at the baseline, EAW group showed statistical improvements in FVC (0.40, $P = 0.010$), predicted FVC% (14.41, $P < 0.001$), FEV_1 (0.53, $P < 0.001$), FEF_{75} (1.36, $P < 0.001$), FEF_{50} (0.67, $P = 0.017$), FEF_{25} (0.40, $P = 0.035$), PEF (1.04, $P = 0.004$) and MVV (11.65, $P < 0.001$) by the end of 16-session intervention period. The estimates are presented in Table III.

C. Effect of EAW Program on Motor Function

Both groups showed statistical improvement in the TCT (both $P < 0.01$) by the end of trainings, while the improvement of the EAW training might be equivalent to conventional exercise program ($P = 0.096$, Wilcoxon rank-sum test). Additionally, the control group showed improvement in LEMS by the end of trainings ($P = 0.033$, Wilcoxon rank-sum test). Nonetheless, there was no significant difference in the change in LEMS ($P = 0.387$, Wilcoxon rank-sum test) or MAS

TABLE III

COMPARISON FOR THE PULMONARY VENTILATION FUNCTION

Characteristic, mean±SD	EAW (n=20)	Con (n=20)	*P*-value between groups
FVC, L			
Pre	3.0±0.9	2.9±0.6	0.706
Post	3.4±0.9	2.8±0.8	**0.048**
P-value within groups	**0.010**	0.725	
Predicted FVC%			
Pre	72.4±16.8	67.9±14.1	0.358
Post	86.9±22.6	67.3±17.5	**0.004**
P-value within groups	**<0.001**	0.808	
FEV_1, L			
Pre	2.6±0.8	2.5±0.6	0.824
Post	3.1±0.8	2.5±0.7	**0.011**
P-value within groups	**<0.001**	0.776	
FEF_{75}, L/s			
Pre	5.0±1.6	5.5±1.6	0.293
Post	6.4±1.4	5.7±1.7	0.220
P-value within groups	**<0.001**	0.425	
FEF_{50}, L/s			
Pre	3.6±1.1	3.5±1.2	0.912
Post	4.3±1.4	3.6±1.0	0.057
P-value within groups	**0.017**	0.718	
FEF_{25}, L/s			
Pre	1.5±0.7	1.4±0.9	0.797
Post	1.9±1.5	1.5±1.1	0.242
P-value within groups	**0.035**	0.717	
PEF, L/s			
Pre	5.6±1.5	5.8±1.7	0.763
Post	6.7±1.4	5.9±1.9	0.145
P-value within groups	**0.004**	0.769	
MVV, L			
Pre	99.6±31.1	102.1±30.0	0.799
Post	111.3±28.9	97.7±27.0	0.133
P-value within groups	**<0.001**	0.352	

P-value difference within was calculated by post minus pre, and between groups was calculated by data of EAW minus that of Con.

EAW = exoskeleton-assisted walking group, Con = control group, FVC = Forced vital capacity, FEV_1 = Forced expiratory volume in 1 second, FEF = Forced expiratory flow, PEF = Peak expiratory flow, MVV = Maximal voluntary ventilation

(*P* = 0.999, Pearson's Chi-square tests) between groups at the end of trainings. These results are presented in Table IV.

D. Effect of EAW Program on Bone and Cartilage

EAW training was estimated to be more favourable than conventional exercise program for protecting distal femoral cartilage (Table V). Nonetheless, the effect on BMD was unclear (0.07, 95% CI -0.21 to 0.06 g/cm^3, $P = 0.272$).

E. Effect of EAW Program on BADL

Both groups showed statistical improvement in the BADL after interventions. The score of MBI was estimated to be 19.75 (95% CI 10.9 to 28.6) greater in the EAW group ($P < 0.001$) than in the control group. These better results on the MBI were achieved with a mean difference of 28.8±15.0 within the EAW group ($P < 0.001$) and 14.0±11.5 within the control group ($P < 0.001$) by the end of trainings. These results are presented in Table VI.

TABLE IV

COMPARISON FOR THE MOTOR FUNCTION

Characteristic, mean±SD	EAW (n=20)	Con (n=20)	*P*-value between groups
MAS, n (%)			
Pre			0.989
Grade 0	18 (90)	18 (90)	
Grade 1	1 (5)	2 (10)	
Grade 1+	1 (5)	0 (0)	
Post			0.999
Grade 0	18 (90)	18 (90)	
Grade 1	1 (5)	1 (5)	
Grade 1+	1 (5)	1 (5)	
P-value within groups	0.999	0.999	
LEMS, median (IQR)			
Pre	1.0 (10.8)	0 (7.5)	0.588
Post	1.5 (7.8)	5 (13.8)	0.387
P-value within groups	0.102	**0.033**	
TCT			
Pre	54.4 (23.6)	40.6±19.6	0.185
Post	74.0 (35.8)	61.0±26.0	0.096
P-value within groups	**0.002**	**<0.001**	

P-value difference within was calculated by post minus pre, and between groups was calculated by data of EAW minus that of Con. Data are presented as n (%) or median (IQR).

EAW = exoskeleton-assisted walking group, Con = control group, TCT = trunk control test, MAS = modified Ashworth scale, LEMS = lower extremity motor score

F. Safety of EAW Program

The exercise training in both groups was well tolerated and there were 3 adverse events in the EAW group. Safety evaluation showed no difference between groups (15% in the EAW group and 0% in the control group, $P = 0.072$). Adverse events consisted of fall (n = 1) and pressure ulcer in heel with Grade 1 (n = 2), that disappeared within 24 hours and caused no further injury to participants.

G. Correlation Analysis of Walking Parameters, Pulmonary Ventilation Function, and Trunk Motor Function

Of the 21 participants who completed the final 6MWT and 10MWT, 2 were in the control group, 19 in the EAW group while wearing the exoskeleton in door. The distance and speed in the EAW group were 15.9±5.0 meters and 0.049±0.164 m/s, respectively. RPE and heart rate were 3.47±1.47 and 114.5±18.0 bpm during the 6MWT. A total of 47.3% (9/19) and 57.9% (11/19) participants of EAW during test reached the moderate level based on the results of RPE and heart rate, respectively.

The outcomes of correlation between the distance of 6MWT with exoskeleton, TCT and statistically different item of pulmonary ventilation function are shown in Table VII. The distance showed a significant correlation with predicted FVC% (Pearson correlation coefficient 0.540, $P = 0.017$) and RPE (Pearson correlation coefficient -0.605, $P = 0.006$). Moreover,

TABLE V
COMPARISON FOR THE DISTAL FEMORAL CARTILAGE AND BONE MINERAL DENSITY

Characteristic, mean±SD	EAW (n=20)	Con (n=20)	*P*-value between groups
Medial condyle (L), mm			
Pre	1.49±0.51	1.59±0.54	0.570
Post	1.80±0.31	1.46±0.52	**0.018**
P-value within groups	**0.014**	0.127	
Intercondylar area (L), mm			
Pre	2.02±0.25	1.94±0.50	0.501
Post	2.31±0.45	1.85±0.44	**0.002**
P-value within groups	0.005	0.384	
Lateral condyle (L), mm			
Pre	1.99±0.38	1.91±0.44	0.545
Post	2.13±0.30	1.87±0.43	**0.037**
P-value within groups	0.086	0.576	
Medial condyle (R), mm			
Pre	1.52±0.40	1.55±0.42	0.818
Post	1.78±0.28	1.52±0.39	**0.022**
P-value within groups	**0.003**	0.728	
Intercondylar area (R), mm			
Pre	2.04±0.48	2.05±0.54	0.229
Post	2.30±0.39	1.90±0.51	**0.013**
P-value within groups	**0.003**	0.327	
Lateral condyle (R), mm			
Pre	1.97±0.43	2.05±0.54	0.608
Post	2.20±0.28	1.90±0.51	**0.025**
P-value within groups	**0.031**	0.099	
BMD of Ward's triangle, g/cm^3			
Pre	0.78±0.14	0.90±0.19	**0.023**
Post	0.81±0.20	0.89±0.22	0.272
Change in groups	0.036±0.094	-0.153±0.131	0.162
P-value within groups	0.100	0.610	

P-value difference within was calculated by post minus pre, and between groups was calculated by data of EAW minus that of Con.

EAW = exoskeleton-assisted walking group, Con = control group, BMD= bone mineral density, L = left, R =right

TABLE VI
COMPARISON FOR THE BASIC ACTIVITIES OF DAILY LIVING

MBI, mean±SD	EAW (n=20)	Con (n=20)	Difference between groups, mean (95% CI)	*P*-value between groups
Pre	34.8±14.7	29.8±14.7		0.195
Post	65.0±17.5	42.5±15.0	19.8 (10.9 to 28.6)	**<0.001**
P-value within groups	**<0.001**	**<0.001**		

EAW = exoskeleton-assisted walking group, Con = control group, MBI = modified Barthel index

TABLE VII
OUTCOMES OF CORRELATION OF PULMONARY VENTILATION FUNCTION, TRUNK FUNCTION, AND WALKING DISTANCE

Characteristic	EAW (n=20)	*P*-value
FVC – distance	r=0.122	0.620
Predicted FVC% – distance	r=0.540	**0.017**
FEV$_1$ – distance	r=0.075	0.761
TCT – distance	r=0.427	0.068
PRE – distance	r=-0.605	**0.006**
FVC – TCT	r=-0.062	0.801
Predicted FVC% – TCT	r=0.210	0.387
FEV$_1$ – TCT	r=0.044	0.858
RPE – TCT	r=-0.394	0.095
FVC – RPE	r=-0.295	0.220
Predicted FVC% – RPE	r=-0.596	**0.007**
FEV$_1$ – RPE	r=-0.290	0.228

FVC = Forced vital capacity, FEV$_1$ = Forced expiratory volume in 1 second, TCT = trunk control test, RPE = rate of perceived exertion, r = Pearson correlation coefficient

there was a significant correlation with predicted FVC% and RPE (Pearson correlation coefficient -0.596, $P = 0.007$). These results demonstrated that the greater distance on the 6MWT with exoskeleton was achieved with a higher predicted FVC% and less exertion. Nonetheless, no significant correlation was found between results of TCT, walking distance, and pulmonary ventilation function.

IV. DISCUSSION

For individuals with T4 to L1 SCI, EAW training has more potential benefits to improve the pulmonary ventilation function, trunk control, and BADL than conventional exercise program. Although conventional exercise program is effective for improving trunk control, lower limb muscle strength, and BADL. Moreover, EAW training promoted the walking ability while wearing exoskeleton suit, and protected the cartilage. However, it is estimated that neither were effective for motor function recovery and bone loss prevention. It is essential to consider whether the benefits from EAW training are robust to warrant recommending it over conventional exercise program.

A. Impact on Pulmonary Function

The estimate of the differences between the groups on the predicted FVC% and FEV$_1$ (19.6% and 0.61 L) were more beneficial than the minimal clinically important difference. Because the minimal clinically important difference for predicted FVC% and FEV$_1$ are 2-6% by distribution-based method [41], and 0.1 L according to previous study by the anchor-based method [42]. Moreover, the estimate of the effects on predicted FVC% from post- to pre- intervention in EAW group and control group and were 14.4% and -0.6%, respectively. And effects on changes of FEV$_1$ were 0.53 L and -0.02 L for EAW trainings and conventional exercise program. Both groups were required equal intensity and amounts of time training in this study. Therefore, the effects on pulmonary ventilation function might be considered as a "potential" bonus, that was meaningful for people with SCI. Upper limb exercise are limited for improving a maximal external power output, peak oxygen consumption, heart rate, total peripheral resistance, and responses for cardiac stroke volume [14]. Another underlying mechanism might be the potential of EAW to recruit trunk muscles [43], [44]. Alamro et al., [45] and Guan et al., [46] have demonstrated that overground walking by exoskeleton elicits greater activation of trunk muscles compared to treadmill walking, even after controlling for the use of hand-held assistive devices. The benefits for pulmonary ventilation function are consistent with other research [22], [47], [48], [49], although it reported a higher VO_{2peak} among the incomplete SCI individuals after EAW training.

B. Impact on Motor Function and Related Body Structures

The effects on bone and cartilage were further explored. There was an increase of BDM in the EAW group, although the estimate was unclear and the values before intervention were different. The effect on EAW on BMD of Wards triangle was consistent with the study of Karelis et al., [50] which reported an improvement with clinical meaning measured by peripheral quantitative computed tomography on tibia. Different training prescriptions lead to different effects on joint, although the effect on cartilage was merely reported in EAW training. Optional duration (less than 1 hour) is helpful for increasing the thickness of distal femoral cartilage according to Yilmaz et al., [51] while higher intensity is harmful for cartilage [52], Therefore, the EAW had potential benefit for protecting the cartilage for SCI and the training prescription in this study was suitable.

C. Impact on Walking Ability

The improvement of walking performance was not caused by the recovery of lower limb motor function. All participants were able to perform walking while wearing the exoskeleton, that was similar to McIntosh et al., [53] and Sale et al., [54] Longer training duration may result in longer distance. Benson et al.[55] found the minimal distance of 6MWT after 10-week trainings was 91 meters which was more than 5 times than our average distance. Additionally, we found that individuals with lower neurologic injury level (T11 to L1) had similar mean improvement (15.6±4.8 meters) than others (16.0±5.4 meters). The age or neurologic injury level did not perform as an associated factor for walking distance. Participants who younger than 40 years-old completed 15.5±6.7 meters during 6WMT, with that of 17.3±3.3 meters for older participants. This was inconsistent with previous study [56] that reported walking speed and performances were significantly associated with injury level. The inconsistence caused by product update according to the result of Guanziroli et al., [57].

D. Impact on BADL

The application of EAW and the newest version of exoskeleton suit made participants have access to walking, going slope and stairs. This led to the differences between groups on walking and going stair, that two issues of MBI. Hence, participants in the EAW group were accessible to gain the scores on these two aspects with exoskeleton. However, besides EAW and conventional exercise program, occupational therapy is also benefit for the ability of ADL [58]. Thus, the possible effect of EAW and conventional exercise program on BADL is overestimated and needs to be considered.

E. Limitations

This study was limited to the number of training session, although our feasibility study has proved this training period realized the application of EAW and was most achievable in inpatient rehabilitation in the health care system. Although we tried to avoid the detection bias, it was inevitable during the 6MWT. In this study, the range of age is 40 and the used equation underestimates the HRmax in older adults [59]. Moreover, the validity of equation has not been established in a study sample that included an adequate number of individuals with SCI. This might have resulted in misestimation of the training intensity. Further, gait parameters should be recorded and compared while walking without the exoskeleton. More pulmonary function test should be completed, such as tidal volume and inspiratory vital capacity.

V. CONCLUSION

This study successfully manifested that EAW training has the potential to improve performance in pulmonary ventilation function and trunk control among individuals with T4 to L1 SCI at least equivalently with conventional exercise program. Additionally, it promoted BADL the walking ability without hurting the cartilage when wearing the exoskeleton suit. However, it is estimated that neither were effective for motor function recovery and bone loss prevention.

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REFERENCES

[1] N. B. Jain et al., “Traumatic spinal cord injury in the United States, 1993–2012,” *JAMA*, vol. 313, no. 22, pp. 2236–2243, Jun 9, 2015, doi: 10.1001/jama.2015.6250.

[2] L. Ge, K. Arul, T. Ikpeze, A. Baldwin, J. L. Nickels, and A. Mesfin, “Traumatic and nontraumatic spinal cord injuries,” *World Neurosurgery*, vol. 111, pp. e142–e148, Mar. 2018, doi: 10.1016/j.wneu.2017.12.008.

[3] K. Boontanapibul, J. T. Steere, D. F. Amanatullah, J. I. Huddleston, W. J. Maloney, and S. B. Goodman, “Diagnosis of osteonecrosis of the femoral head: Too little, too late, and independent of etiology,” (in English), *J. Arthroplasty*, vol. 35, no. 9, pp. 2342–2349, Sep. 2020, doi: 10.1016/j.arth.2020.04.092.

[4] H. W. Zhai et al., “Ganglioside with nerve growth factor for the recovery of extremity function following spinal cord injury and somatosensory evoked potential,” *Eur. Rev. Med. Pharmacol. Sci.*, vol. 19, no. 12, pp. 2282–2286, Jun. 2015. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/26166655

[5] B. B. Lee, R. A. Cripps, M. Fitzharris, and P. C. Wing, “The global map for traumatic spinal cord injury epidemiology: Update 2011, global incidence rate,” *Spinal Cord*, vol. 52, no. 2, pp. 110–116, Feb. 2014, doi: 10.1038/sc.2012.158.

[6] A. S. Gorgey, D. R. Dolbow, J. D. Dolbow, R. K. Khalil, C. Castillo, and D. R. Gater, “Effects of spinal cord injury on body composition and metabolic profile—Part I,” *J. Spinal Cord Med.*, vol. 37, no. 6, pp. 693–702, Nov. 2014, doi: 10.1179/2045772314Y.0000000245.

[7] K. L. Stolzmann, D. R. Gagnon, R. Brown, C. G. Tun, and E. Garshick, "Longitudinal change in FEV_1 and FVC in chronic spinal cord injury," (in English), *Amer. J. Respiratory Crit. Care Med.*, vol. 177, no. 7, pp. 781–786, Apr. 2008, doi: 10.1164/rccm.200709-1332OC.

[8] F. Malas et al., "Diaphragm ultrasonography and pulmonary function tests in patients with spinal cord injury," (in English), *Spinal cord*, vol. 57, no. 8, pp. 679–683, 2019, doi: 10.1038/s41393-019-0275-3.

[9] S. M. Tweedy et al., "Exercise and sports science Australia (ESSA) position statement on exercise and spinal cord injury," (in English), *J. Sci. Med. Sport*, vol. 20, no. 2, pp. 108–115, Feb. 2017, doi: 10.1016/j.jsams.2016.02.001.

[10] B. L. P. Gaffurini, S. Calza, C. Calabretto, C. Orizio, and M. Gobbo, "Energy metabolism during activity-promoting video games practice in subjects with spinal cord injury: Evidences for health promotion," *Eur. J. Phys. Rehabil. Med.*, vol. 49, no. 1, pp. 9–23, 2013.

[11] B. T. Neville, D. Murray, K. B. Rosen, C. A. Bryson, J. P. Collins, and A. A. Guccione, "Effects of performance-based training on gait and balance in individuals with incomplete spinal cord injury," *Arch. Phys. Med. Rehabil.*, vol. 100, no. 10, pp. 1888–1893, Oct. 2019, doi: 10.1016/j.apmr.2019.03.019.

[12] H. Liu et al., "Short-term effects of core stability training on the balance and ambulation function of individuals with chronic spinal cord injury: A pilot randomized controlled trial," (in English), *Minerva Med.*, vol. 110, no. 3, pp. 216–223, 2019, doi: 10.23736/S0026-4806.19.05952-4.

[13] M. Battikha, L. Sa, A. Porter, and J. A. Taylor, "Relationship between pulmonary function and exercise capacity in individuals with spinal cord injury," *Amer. J. Phys. Med. Rehabil.*, vol. 93, no. 5, pp. 413–421, May 2014, doi: 10.1097/PHM.0000000000000046.

[14] D. Theisen, "Cardiovascular determinants of exercise capacity in the Paralympic athlete with spinal cord injury," *Exp. Physiol.*, vol. 97, no. 3, pp. 319–324, Mar. 2012, doi: 10.1113/expphysiol.2011.063016.

[15] P. R. Geigle and M. Kallins, "Exoskeleton-assisted walking for people with spinal cord injury," (in English), *Arch. Phys. Med. Rehabil.*, vol. 98, no. 7, pp. 1493–1495, Jul. 2017, doi: 10.1016/j.apmr.2016.12.002.

[16] A. S. Gorgey, "Robotic exoskeletons: The current pros and cons," *World J. Orthopedics*, vol. 9, no. 9, pp. 112–119, Sep. 2018, doi: 10.5312/wjo.v9.i9.112.

[17] A. S. Gorgey, R. Wade, R. Sumrell, L. Villadelgado, R. E. Khalil, and T. Lavis, "Exoskeleton training may improve level of physical activity after spinal cord injury: A case series," (in English), *Topics Spinal Cord Injury Rehabil.*, vol. 23, no. 3, pp. 245–255, Jun. 2017, doi: 10.1310/sci16-00025.

[18] A. J. Kozlowski, T. N. Bryce, and M. P. Dijkers, "Time and effort required by persons with spinal cord injury to learn to use a powered exoskeleton for assisted walking," *Topics Spinal Cord Injury Rehabil.*, vol. 21, no. 2, pp. 21–110, Spring 2015, doi: 10.1310/sci2102-110.

[19] N. Birch et al., "Results of the first interim analysis of the RAPPER II trial in patients with spinal cord injury: Ambulation and functional exercise programs in the REX powered walking aid," *J. Neuroeng. Rehabil.*, vol. 14, no. 1, p. 60, Jun. 2017, doi: 10.1186/s12984-017-0274-6.

[20] X. N. Xiang et al., "The safety and feasibility of a new rehabilitation robotic exoskeleton for assisting individuals with lower extremity motor complete lesions following spinal cord injury (SCI): An observational study," *Spinal Cord*, vol. 58, no. 7, pp. 787–794, Jul. 2020, doi: 10.1038/s41393-020-0423-9.

[21] P. Asselin et al., "Heart rate and oxygen demand of powered exoskeleton-assisted walking in persons with paraplegia," *J. Rehabil. Res. Dev.*, vol. 52, no. 2, pp. 58–147, 2015, doi: 10.1682/JRRD.2014.02.0060.

[22] M. J. Escalona et al., "Cardiorespiratory demand and rate of perceived exertion during overground walking with a robotic exoskeleton in long-term manual wheelchair users with chronic spinal cord injury: A cross-sectional study," *Ann. Phys. Rehabil. Med.*, vol. 61, no. 4, pp. 215–223, Jul. 2018, doi: 10.1016/j.rehab.2017.12.008.

[23] S. Knezevic, P. K. Asselin, C. M. Cirnigliaro, S. Kornfeld, R. R. Emmons, and A. M. Spungen, "Oxygen uptake during exoskeletal-assisted walking in persons with paraplegia," *Arch. Phys. Med. Rehabil.*, vol. 102, no. 2, pp. 185–195, Feb. 2021, doi: 10.1016/j.apmr.2020.08.025.

[24] A. Bass, S. N. Morin, M. Vermette, M. Aubertin-Leheudre, and D. H. Gagnon, "Incidental bilateral calcaneal fractures following overground walking with a wearable robotic exoskeleton in a wheelchair user with a chronic spinal cord injury: Is zero risk possible?" *Osteoporosis Int.*, vol. 31, no. 5, pp. 1007–1011, May 2020, doi: 10.1007/s00198-020-05277-4.

[25] C. Shackleton, R. Evans, S. West, W. Derman, and Y. Albertus, "Robotic walking to mitigate bone mineral density decline and adverse body composition in individuals with incomplete spinal cord injury: A pilot randomized clinical trial," *Amer. J. Phys. Med. Rehabil.*, vol. 101, no. 10, pp. 931–936, Oct. 2022, doi: 10.1097/PHM.0000000000001937.

[26] H. S. Kim et al., "Effects of wearable powered exoskeletal training on functional mobility, physiological health and quality of life in non-ambulatory spinal cord injury patients," (in English), *J. Korean Med. Sci.*, vol. 36, no. 12, p. e80, 2021, doi: 10.3346/jkms.2021.36.e80.

[27] T. T. Roberts, G. R. Leonard, and D. J. Cepela, "Classifications in brief: American spinal injury association (ASIA) impairment scale," *Clin. Orthopaedics Rel. Res.*, vol. 475, no. 5, pp. 1499–1504, May 2017, doi: 10.1007/s11999-016-5133-4.

[28] A.-B. Meseguer-Henarejos, J. Sánchez-Meca, J.-A. López-Pina, and R. Carles-Hernández, "Inter- and intra-rater reliability of the modified Ashworth scale: A systematic review and meta-analysis," *Eur. J. Phys. Rehabil. Med.*, vol. 54, no. 4, pp. 576–590, Aug. 2018, doi: 10.23736/S1973-9087.17.04796-7.

[29] X.-N. Xiang et al., "Exoskeleton-assisted walking improves pulmonary function and walking parameters among individuals with spinal cord injury: A randomized controlled pilot study," (in English), *J. Neuroeng. Rehabil.*, vol. 18, no. 1, p. 86, 2021, doi: 10.1186/s12984-021-00880-w.

[30] B. L. Graham et al., "Standardization of spirometry 2019 update. An official American thoracic society and European respiratory society technical statement," *Amer. J. Respiratory Crit. Care Med.*, vol. 200, no. 8, pp. e70–e88, Oct. 2019, doi: 10.1164/rccm.201908-1590ST.

[31] M. R. Miller et al., "Standardisation of spirometry," *Eur. Respir. J.*, vol. 26, no. 2, pp. 319–338, Aug. 2005, doi: 10.1183/09031936.05.00034805.

[32] N. C. Korkmaz, T. C. Akman, G. K. Oren, and L. S. Bir, "Trunk control: The essence for upper limb functionality in patients with multiple sclerosis," *Multiple Sclerosis Rel. Disorders*, vol. 24, pp. 101–106, Aug. 2018, doi: 10.1016/j.msard.2018.06.013.

[33] C. Collin and D. Wade, "Assessing motor impairment after stroke: A pilot reliability study," *J. Neurol., Neurosurgery Psychiatry*, vol. 53, no. 7, pp. 576–579, Jul. 1990. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/2391521

[34] Y. P. Demir and S. A. Yıldırım, "Reliability and validity of trunk control test in patients with neuromuscular diseases," *Physiotherapy Theory Pract.*, vol. 31, no. 1, pp. 39–44, Jan. 2015, doi: 10.3109/09593985.2014.945673.

[35] J. R. Wilson et al., "Natural history, predictors of outcome, and effects of treatment in thoracic spinal cord injury: A multi-center cohort study from the North American clinical trials network," *J. Neurotrauma*, vol. 35, no. 21, pp. 2554–2560, Nov. 2018, doi: 10.1089/neu.2017.5535.

[36] P. Akpinar et al., "Reliability of the modified Ashworth scale and modified Tardieu scale in patients with spinal cord injuries," *Spinal Cord*, vol. 55, no. 10, pp. 944–949, Oct. 2017, doi: 10.1038/sc.2017.48.

[37] E. Naredo et al., "Ultrasound validity in the measurement of knee cartilage thickness," (in English), *Ann. Rheum. Dis.*, vol. 68, no. 8, pp. 1322–1327, 2009, doi: 10.1136/ard.2008.090738.

[38] J. C. Furlan, V. Noonan, A. Singh, and M. G. Fehlings, "Assessment of disability in patients with acute traumatic spinal cord injury: A systematic review of the literature," *J. Neurotrauma*, vol. 28, no. 8, pp. 1413–1430, Aug. 2011, doi: 10.1089/neu.2009.1148.

[39] American Thoracic Society, "ATS statement: Guidelines for the six-minute walk test," (in English), *Amer. J. Respiratory Crit. Care Med.*, vol. 166, no. 1, pp. 111–117, 2002. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/12091180.

[40] T. Holmlund, E. Ekblom-Bak, E. Franzén, C. Hultling, and K. Wahman, "Intensity of physical activity as a percentage of peak oxygen uptake, heart rate and Borg RPE in motor-complete para- and tetraplegia," *PLoS ONE*, vol. 14, no. 12, Dec. 2019, Art. no. e0222542, doi: 10.1371/journal.pone.0222542.

[41] R. M. Du Bois et al., "Forced vital capacity in patients with idiopathic pulmonary fibrosis: Test properties and minimal clinically important difference," *Amer. J. Respiratory Crit. Care Med.*, vol. 184, no. 12, pp. 1382–1389, Dec. 2011, doi: 10.1164/rccm.201105-0840OC.

[42] D. Gompelmann, K. Kontogianni, M. Schuhmann, R. Eberhardt, C. P. Heussel, and F. J. Herth, "The minimal important difference for target lobe, volume reduction after endoscopic valve therapy," *Int. J. Chronic Obstructive Pulmonary Disease*, vol. 13, pp. 465–472, Feb. 2018, doi: 10.2147/COPD.S152029.

[43] R. J. Triolo, L. Boggs, M. E. Miller, G. Nemunaitis, J. Nagy, and S. N. Bailey, "Implanted electrical stimulation of the trunk for seated postural stability and function after cervical spinal cord injury: A single case study," (in English), *Arch. Phys. Med. Rehabil.*, vol. 90, no. 2, pp. 340–347, Feb. 2009, doi: 10.1016/j.apmr.2008.07.029.

[44] N. Hart et al., "Respiratory effects of combined truncal and abdominal support in patients with spinal cord injury," (in English), *Arch. Phys. Med. Rehabil.*, vol. 86, no. 7, pp. 1447–1451, 2005. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/16003679

[45] R. A. Alamro, A. E. Chisholm, A. M. M. Williams, M. G. Carpenter, and T. Lam, "Overground walking with a robotic exoskeleton elicits trunk muscle activity in people with high-thoracic motor-complete spinal cord injury," *J. Neuroeng. Rehabil.*, vol. 15, no. 1, p. 109, Nov. 2018, doi: 10.1186/s12984-018-0453-0.

[46] X. Guan, S. Kuai, L. Ji, R. Wang, and R. Ji, "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," *J. Spinal Cord Med.*, vol. 40, no. 4, pp. 463–470, Jul. 2017, doi: 10.1080/10790268.2017.1319033.

[47] N. Evans, C. Hartigan, C. Kandilakis, E. Pharo, and I. Clesson, "Acute cardiorespiratory and metabolic responses during exoskeleton-assisted walking overground among persons with chronic spinal cord injury," *Topics Spinal Cord Injury Rehabil.*, vol. 21, no. 2, pp. 32–122, Spring 2015, doi: 10.1310/sci2102-122.

[48] Y.-C. Jang, H.-K. Park, J.-Y. Han, I. S. Choi, and M.-K. Song, "Cardiopulmonary function after robotic exoskeleton-assisted over-ground walking training of a patient with an incomplete spinal cord injury: Case report," *Medicine*, vol. 98, no. 50, Dec. 2019, Art. no. e18286, doi: 10.1097/MD.0000000000018286.

[49] P. H. Gorman, W. Scott, L. VanHiel, K. E. Tansey, W. M. Sweatman, and P. R. Geigle, "Comparison of peak oxygen consumption response to aquatic and robotic therapy in individuals with chronic motor incomplete spinal cord injury: A randomized controlled trial," *Spinal Cord*, vol. 57, no. 6, pp. 471–481, Jun. 2019, doi: 10.1038/s41393-019-0239-7.

[50] A. Karelis, L. Carvalho, M. Castillo, D. Gagnon, and M. Aubertin-Leheudre, "Effect on body composition and bone mineral density of walking with a robotic exoskeleton in adults with chronic spinal cord injury," *J. Rehabil. Med.*, vol. 49, no. 1, pp. 84–87, Jan. 2017, doi: 10.2340/16501977-2173.

[51] B. Yilmaz, Y. Demir, E. Ozyoruk, S. Kesikburun, and U. Guzelkucuk, "The effect of knee joint loading and immobilization on the femoral cartilage thickness in paraplegics," *Spinal Cord*, vol. 54, no. 4, pp. 283–286, Apr. 2016, doi: 10.1038/sc.2015.151.

[52] A. J. Teichtahl et al., "The interaction between physical activity and amount of baseline knee cartilage," (in English), *Rheumatology*, vol. 55, no. 7, pp. 1277–1284, 2016, doi: 10.1093/rheumatology/kew045.

[53] K. McIntosh, R. Charbonneau, Y. Bensaada, U. Bhatiya, and C. Ho, "The safety and feasibility of exoskeletal-assisted walking in acute rehabilitation after spinal cord injury," *Arch. Phys. Med. Rehabil.*, vol. 101, no. 1, pp. 113–120, Jan. 2020, doi: 10.1016/j.apmr.2019.09.005.

[54] P. Sale, E. F. Russo, A. Scarton, R. S. Calabro, S. Masiero, and S. Filoni, "Training for mobility with exoskeleton robot in spinal cord injury patients: A pilot study," *Eur. J. Phys. Rehabil. Med.*, vol. 54, no. 5, pp. 745–751, Sep. 2018, doi: 10.23736/S1973-9087.18.04819-0.

[55] I. Benson, K. Hart, J. J. Van Middendorp, and D. Tussler, "Lower-limb exoskeletons for individuals with chronic spinal cord injury: Findings from a feasibility study," *Clin. Rehabil.*, vol. 30, no. 1, pp. 73–84, Jan. 2016, doi: 10.1177/0269215515575166.

[56] D. R. Louie, J. J. Eng, and T. Lam, "Gait speed using powered robotic exoskeletons after spinal cord injury: A systematic review and correlational study," *J. Neuroeng. Rehabil.*, vol. 12, no. 1, p. 82, Oct. 2015, doi: 10.1186/s12984-015-0074-9.

[57] E. Guanziroli, M. Cazzaniga, L. Colombo, S. Basilico, G. Legnani, and F. Molteni, "Assistive powered exoskeleton for complete spinal cord injury: Correlations between walking ability and exoskeleton control," *Eur. J. Phys. Rehabil. Med.*, vol. 55, no. 2, pp. 209–216, May 2019, doi: 10.23736/S1973-9087.18.05308-X.

[58] X. Caizhong, S. Chunlei, L. Beibei, D. Zhiqing, D. Qinneng, and W. Tong, "The application of somatosensory evoked potentials in spinal cord injury rehabilitation," *NeuroRehabilitation*, vol. 35, no. 4, pp. 835–840, 2014, doi: 10.3233/NRE-141158.

[59] H. Tanaka, K. Monahan, and D. Seals, "Age-predicted maximal heart rate revisited," *J. Amer. College Cardiol.*, vol. 37, no. 1, pp. 153–156, 2001, doi: 10.1016/s0735-1097(00)01054-8.