Increasing exercise intensity during outside walking training with a wearable robot

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Increasing exercise intensity during outside walking training with a wearable robot

Florian L. Haufe, Peter Wolf, Jaime E. Duarte, Robert Riener and Michele Xiloyannis

***Abstract*— For many neuromuscular conditions including spinal cord injury, physical exercise training is a recommended part of treatment. High intensity exercise has been found to more effectively promote ambulatory function than moderate intensity exercise. To reach optimal intensity levels, fully ambulatory individuals can adjust their walking speed. In contrast, individuals with neuromuscular deficits may not be able to walk, or only at slow speeds that elicit an insufficient cardiovascular response.**

In our case study with one spinal cord injured patient, we investigated if assistance from a wearable robot, the Myosuit, can increase exercise intensity towards more effective training.

During outside uphill-walking trials, assistance from the Myosuit allowed the patient to increase his walking speed by 30 % to 0.48 m/s and increased energy expenditure by 17 % compared to not wearing the suit. An analysis of gait kinematics suggests that the Myosuit facilitated faster walking by replacing missing hip extensor function and promoting a more upright posture. The metabolic equivalents (METS) during walking with the Myosuit of 7.15 indicate a consistently high exercise intensity. In contrast, one of two unassisted trials only reached a moderate intensity (METS < 6). The concurrent increase in speed and energy expenditure when wearing the Myosuit corresponds to a 9 % increase in the efficiency of walking.

Our findings show that the Myosuit can increase the efficiency of walking for a user with incomplete spinal cord injury and suggest that the Myosuit can act as a tool to increase the efficacy of movement training.

I. INTRODUCTION

Physical exercise training is a recommended part of treatment for patients with incomplete spinal cord injury (SCI) [1], heart failure [2], chronic obstructive pulmonary disease [3], dementia [4], following stroke [5] and even for apparently healthy adults [6]. Studies comparing various exercise intensities suggest that high intensity exercise is more effective than moderate intensity exercise in promoting ambulatory function [1, 2]. Exercise intensity is consequently an important factor to consider when choosing exercise protocols and assistive technology such as wearable robots.

Fully ambulatory individuals can readily adapt their walking speed to achieve the desired exercise intensity [7]. For individuals with reduced mobility – e.g. due to SCI – this is often not possible. Neuromuscular deficits such as decreased hip and knee extensor function might prohibit ambulation completely, or dictate slow walking speeds [8]. As an effect, the cardiovascular and metabolic response to exercise, even at the highest voluntary walking speed, might be insufficient to reach the recommended intensity levels. Alternative methods to increase exercise intensity, e.g. adding weights, might further degrade ambulatory function of individuals with reduced mobility and hence are less attractive.

Figure 1. Photograph of the participant at the site of the outside walking experiments. The participant is wearing the Myosuit, a lightweight, cable-driven robot, and a mobile respirometer as well as forearm crutches.

Various rigid exoskeletons were developed to substitute the ambulatory function of fully paralyzed users during training and allow for overground walking (e.g. [9-12]). These rigid exoskeletons can provide large assistive torques and effectively support large fractions of the user's weight. For example, a rigid exoskeleton allowed otherwise non-ambulatory patients with motor-complete SCI to perform moderate intensity exercise at walking speeds of 0.2-0.3 m/s

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[10]. The observed metabolic response was attributed to the increased trunk and arm activation that was elicited during walking [10].

For people with residual mobility – e.g. individuals with motor incomplete SCI – higher walking speeds may be required to allow for moderate or even high intensity exercise. In this regard, current exoskeletons are limited due to their typically large masses that increase limb inertia and thereby impede physiological walking at elevated speeds.

As an alternative, soft, lightweight, and portable wearable robots have been developed, often actuated by cables. These devices aim to support users with residual mobility during movements while allowing for, and requiring, active user contributions. One example of this device category is the Myosuit, a wearable robot that actively assists hip and knee extension and passively supports hip flexion and ankle dorsiflexion. In our previous work [13], we have shown that assistance from the Myosuit enabled an individual with incomplete SCI to walk substantially faster than without the Myosuit.

In the current work, we investigated if such an increase in walking speed also increases exercise intensity. The underlying rationale is that the partial assistance provided to the most severely affected muscles, e.g. the hip extensors, allows for increased walking speed. In turn, the higher speed might elicit more active contributions from other, still functional leg muscles. Contrary to [10], we do not expect a larger and perhaps undesirable load on the arms. In fact, the Myosuit has been shown to reduce the required arm support during walking [14].

We defined an increase in exercise intensity as an increase in energy expenditure per unit time and increased heart rate. To assess if moderate or high exercise intensity was reached, we calculate the metabolic equivalents (METS) [7]. High (or sometimes “vigorous”) intensity exercise is characterized by METS of 6 or larger [6].

Previous research has identified the hypoactive lifestyle of individuals with SCI after inpatient rehabilitation as a major cause of morbidity and mortality [15]. Capitalizing on the portability of the Myosuit, we chose to investigate exercise intensity in an outside walking setting, akin to activities that individuals might perform as part of a more active lifestyle. To identify the kinematic and spatiotemporal characteristics underlying potential changes in exercise intensity, an additional gait analysis session was performed in a lab setting afterwards.

II. Methods

A. Participant

One male participant (age 51 years, 178 cm, 70 kg) with chronic, motor incomplete SCI (C5 lesion since >25 years) was recruited by referral and agreed to participate in our experiment. The participant’s right leg was generally weaker than his left leg. The experimental design and protocol were approved by the institutional review board of ETH Zurich (EK 2019-N-172).

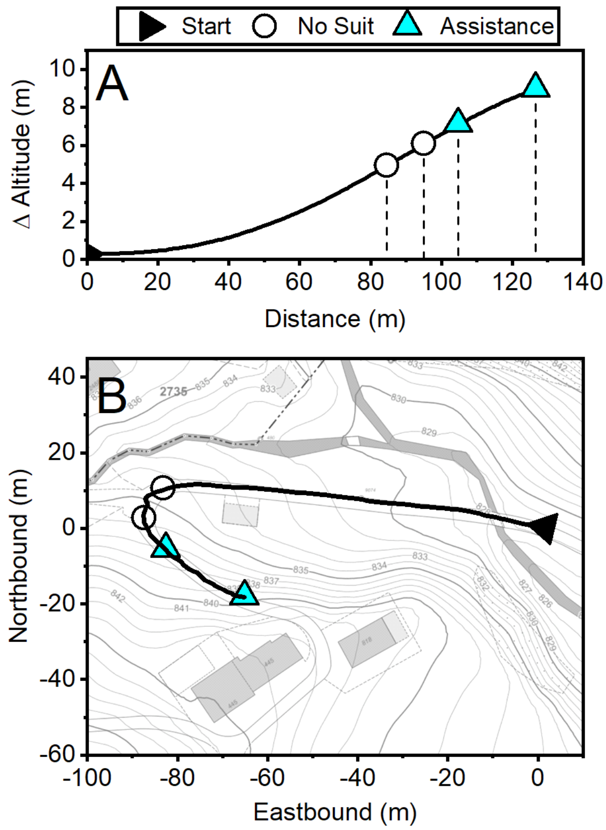

Figure 2. (A) Altitude profile of the mountain path, with white circle symbols marking the end points of the two ‘no suit’ trials and turquoise triangles marking the end points of the two Myosuit-assisted trials. (B) Horizontal projection of the path onto a map of the area.

B. Wearable Prototype

The wearable prototype used in this work (Myosuit Beta, MyoSwiss AG, Switzerland) was a revised version of the device described in [13].

Compared to the previous version, the overall weight and complexity of the device was optimized. The textile layer was now only composed of an upper body vest with a waist belt and load-bearing straps along the legs, while users could wear personal garments underneath. As in the previous version, two passive elastomer springs that frontally crossed the hip joint assisted hip flexion. Two passive “foot-lifters” assisted dorsiflexion and hence ground clearance. Active energy input to the legs was provided from a backpack-style “tendon driver unit” that housed two electric motors, a power bank, and the control electronics. Two cable-pulleys (or “tendons”) were routed from the driver unit along the legs and anchored on the shanks and thighs. The cables were made from ultra-high molecular weight polyethylene and transmitted the forces from the electric motors to the legs.

Inertial Measurement Units (IMUs) were placed on both shank and thigh segments and in the tendon driver unit to measure linear accelerations and rates of rotation. Based on the IMU sensor data, inter-limb angles and trunk posture were estimated using a five-segment body model. Gait events such as heel strike or toe-off were detected using an algorithm similar to the one described in [16]. Assistive cable forces were applied during the stance phase of walking, between approx. 5 % and 35 % of the gait cycle. The force magnitude was globally scaled as percentage of the maximum linear force of approx. 400 N the motors were able to produce and additionally adapted proportionally to the momentary knee angle. Here, more knee flexion resulted in a higher cable force. In this study, the participant received 60 % of the maximally possible cable forces. During swing phase, no forces were applied.

C. Outside Tests – Experimental Details

1) Setup

Outside tests were conducted on a paved mountain road situated in the canton of Appenzell Ausserrhoden (Switzerland) at an altitude of approximately 830 meters above sea level. During "assistance" trials, the participant wore the Myosuit and received assistance. During "no suit" trials, the participant did not wear the Myosuit. Throughout the experiment, the participant used forearm crutches for additional balance and body-weight support. The participant additionally used his personal electrical stimulator acting on the right peroneus longus muscle via a surface electrode at similar settings during all trials. Minor adjustments were made if necessary, with the goal of maintaining a constant perceived stimulation and avoiding cramps.

Energy expenditure was approximated via indirect calorimetry using Péronnet's formula [17]. Breath-by-breath respiratory data was collected with a portable gas analyzer (K5, COSMED, Italy). The participant's heart rate was measured with a chest strap (HRM Dual, GARMIN, USA).

Average walking speed was calculated as the quotient of the distance covered and the experimental duration. Here, distance was determined using GPS data and official government charts of the area (Figure 2).

2) Protocol

The participant completed two trials each with assistance and without the Myosuit (no suit). Tests were performed in the order "no suit", "assist.", "assist.", "no suit" to compensate for the effect of fatigue. Before the start of each trial, the participant was instructed to cover as much distance as possible during the next four minutes. Each trial was terminated after a duration of four minutes. Between trials, the participant travelled downhill on a personal electric scooter and rested for at least two minutes while seated.

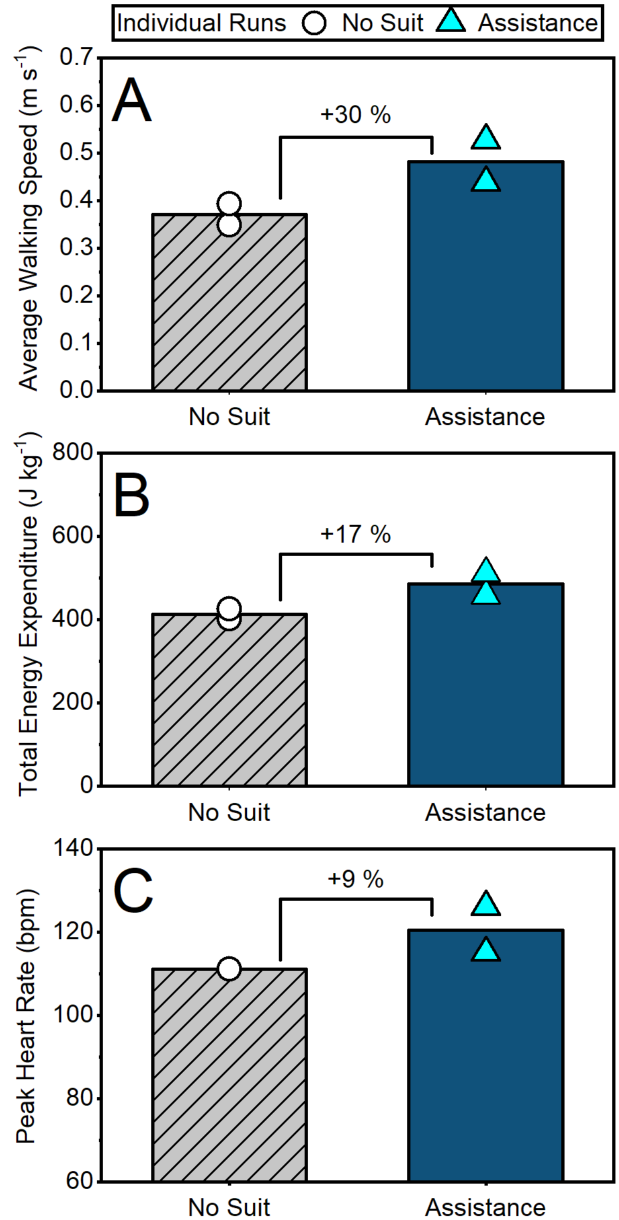

Figure 3. (A) Average walking speed during outside trials without the Myosuit ('No suit') and with assistance from the Myosuit. (B) Total energy expenditure (C) Peak heart rate. White circles and turquoise triangles indicate the results of the individual trials (n=2 for each condition, except for (C) peak heart rate / no suit, where the chest belt detached during one trial).

D. Inside Gait Analysis

1) Setup

During the subsequent gait analysis, the participant walked on a split-belt treadmill with embedded force plates (V-Gait Dual Belt, Motekforce Link, The Netherlands). Bilateral handrails were available for additional balance and body-weight support. Ground reaction forces were measured at a frequency of 1000 Hz for each side during walking. A system of ten cameras (Bonita B10, VICON, UK) was used to track the position of sixteen passive reflective markers at a measurement frequency of 100 Hz. The markers were placed on relevant anatomic landmarks and components of the Myosuit, following a standard model template ("Plug-in Gait lower body model", Nexus, VICON, UK) that was also used to calculate leg kinematics. To determine the joint centers of rotation and three-dimensional rotation axes, range-of-motion trials were performed at the beginning of the session and repeated after donning the Myosuit.

Continuous video recordings were made from three principal directions to facilitate data analysis and visualization.

2) Protocol

The participant completed two trials each with assistance and without the Myosuit as during outside tests. Instructions and test durations were identical to outside tests.

To accommodate for natural variations in the participant's walking speed, the treadmill was paced relative to the

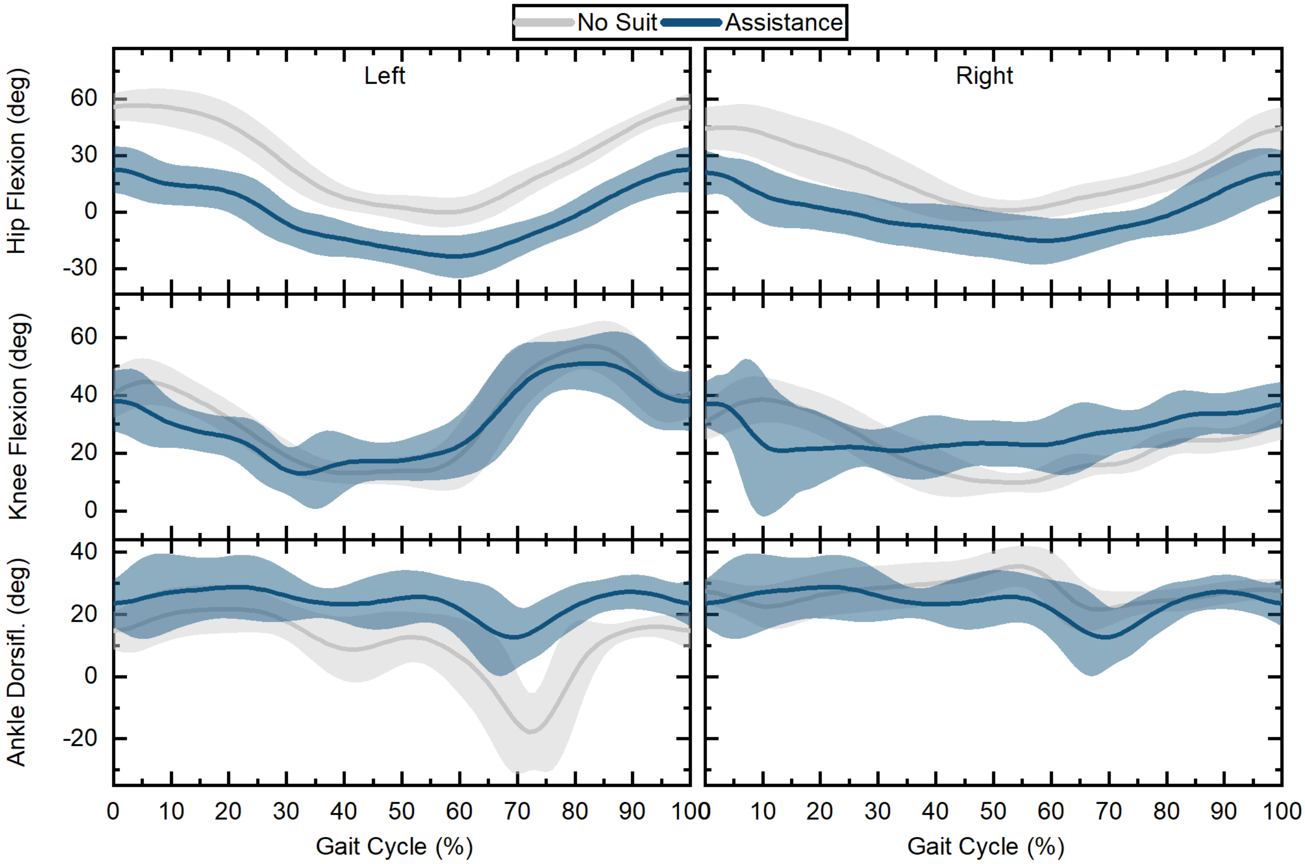

Figure 4. Mean joint angle curves of the participant with incomplete SCI walking without the Myosuit (light grey lines) and with the Myosuit (dark blue). Data is presented for uphill walking on a treadmill during the gait analysis session, for the left and right leg. The 95 % confidence intervals of the mean curves are shown as shaded areas. The participant's right leg was generally weaker than the left leg.

anteroposterior position of the markers placed on the left and right anterior iliac spine. The participant was thus able to walk at a continuously adjusted self-selected speed as during the outside tests. Additionally, the treadmill's pitch was continuously adapted to match the recorded uphill slope of the mountain road from the outside tests.

E. Data Processing

During the inside gait analysis, cadence, stride length and the ratio between stance duration and stride duration were calculated based on marker kinematics and ground reaction forces. A lowpass-filter with a cutoff frequency of 14 Hz was applied to the measured forces. Based on the vertical ground reaction forces, the data was segmented into separate strides. A threshold of 60 N was used to identify heel contact and segment strides.

III. RESULTS

A. Results from Outside Tests

The participant was able to continuously walk during all four outside trials over the test duration of four minutes. A brief halt was only required at most once per trial if the stimulation of the peroneus muscle had to be adapted. When receiving assistance from the Myosuit, the participant increased his walking speed by 30 % (see Figure 3) to 0.48 m/s. Total energy expenditure and peak heart rate increased by 17 % and 9 %, respectively in comparison to the no suit condition. For the two no suit trials, the METS were 5.6 and 6.6, for the two assisted trials 6.9 and 7.4.

B. Results from Inside Gait Analysis

Compared to the no suit condition, the participant's cadence increased when receiving assistance from the Myosuit (see Table 1). Mean stride length was 0.13 m shorter than in the no suit condition, while the ratio of stance to stride time was similar in both conditions.

An examination of joint angle curves revealed a marked bilateral shift of the hip angle towards more hip extension (see Figure 4). Data on the orientation of the pelvis (not shown) indicates that the participant's trunk was more upright when walking with assistance from the Myosuit. In addition, the left and right hip angle curve appear more similar in the assistance condition compared to the no suit condition.

Knee angle curves are generally similar in both conditions. Bilaterally, a slight tendency towards an earlier onset of knee extension already before 10 % gait cycle was found.

The left ankle angle shows a pronounced reduction in peak plantarflexion in the assistance condition compared to the no suit condition. With assistance, both ankle angles are relatively constant throughout the gait cycle.

Table 1. Spatiotemporal gait parameters (mean ± std. dev.) measured during inside gait analysis. Outside tests were closely replicated.

		No Suit	Assistance
Cadence		58 steps/min	72 steps/min
Stride Length		1.07 ±0.12 m	0.94 ±0.19 m
Stance-to-Stride Time Ratio	Left	66 ±4 %	67 ±4 %
	Right	65 ±3 %	65 ±6 %

IV. Discussion

A. *Walking speed increases with assistance*

Consistent with our previous work [13], assistance from the Myosuit enabled the participant to increase his walking speed. This observation extends our previous findings from an inside setting and shorter distances (10 MWT) to an outside, real-world scenario and longer distances of more than 100 m. Even over this longer distance, the participant was able to stay above the speed threshold of 0.44 m/s indicative of community ambulation [18], in spite of the uphill slope of the track.

B. *Exercise intensity increases with assistance*

Assistance from the Myosuit was associated with increased exercise intensity. This was reflected by the increased total energy expenditure and higher peak heart rate. Increased exercise intensity has been shown to improve the efficacy of movement training for individuals with motor-incomplete SCI [1]. Importantly, both trials with assistance from the Myosuit were categorized as high intensity exercise with METS larger than 6. For the no suit trials, only in one of two repetitions the participant was able to engage in high intensity exercise. Only moderate intensity (MET of 5.6) was achieved in the other. Further, the achieved METS with Myosuit assistance surpassed the threshold for high intensity exercise by an average margin of 1.15 METS, without performing any personalized tuning of the assistance. An open area for investigation is whether variations in the assistive settings of the Myosuit correlate to METS during training. If so, this might allow for automated targeting of certain METS for individuals during training.

C. *Underlying Kinematic Changes*

Increasing cadence has been identified as one possible strategy to increase walking speed [19], with increasing step length or increasing both cadence and step length being the others. Increasing cadence does not require substantially increased leg joint moments, in contrast to increasing step length [19]. Considering that our participant's potential to generate leg joint moments was likely limited by his injury, it thus seems coherent that he chose to increase walking speed by increasing cadence.

The active hip extension assistance from the Myosuit during stance phase seems to have been used primarily to maintain a more upright posture. Hip range of motion was similar with and without the Myosuit. In the no suit condition, the forward tilt of the pelvis and the trunk caused a general shift towards increased hip flexion, perhaps rendering locomotion less efficient. Active assistance allowed for substantial hip extension at the end of stance phase, more similar to the physiological walking pattern found in unimpaired individuals [13]. Here, the Myosuit appears to directly compensate for the lack of hip extensor strength which is characteristic of individuals with spinal cord injury.

In the absence of clear changes in knee kinematics and without an analysis of joint moments, it remains unclear what proportion of the observed benefits might originate from the assistance of knee extension. Finally, the bilateral reduction of peak plantarflexion when wearing the suit is most likely explained by the passive dorsiflexion assistance ("foot-lifters"). While these passive elements increase walking safety by providing additional ground clearance, they might inhibit propulsive contributions from the ankle. For the participant in this study, only the left ankle could have potentially generated propulsive moments. In future tests, asymmetrical settings for the passive elements should be investigated to further improve walking speed.

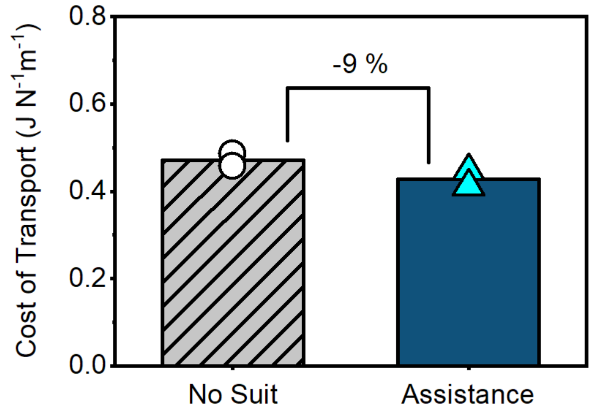

Figure 5. Cost of transport without the Myosuit and with active assistance from the Myosuit. White circles and turquoise triangles indicate the results of the individual trials (n=2 for each condition).

D. *Walking efficiency increased with assistance*

Individuals with incomplete SCI have been reported to consume more than twice as much energy during walking as unimpaired individuals at similar speeds [8]. This reduced energetic efficiency might be a key determinant for the associated mobility impairment of individuals with SCI.

For our study, the concurrent increase in walking speed and total energy expenditure (see Figure 3) raises the question if the cost of transport (CoT) was lower with assistance or without the Myosuit, where CoT is defined as

$$\mathrm{CoT} = \frac{E}{mgd} = \frac{E/m}{g(vT)}$$

with E/m being the total energy expenditure per unit (participant) mass (see Figure 3.B), v the walking speed (see 3.A), T the experimental duration of 4 min, and g gravitational acceleration. A calculation based on this data reveals that CoT is about 9 % lower with assistance from the Myosuit than without the device (see Figure 5). Hence, the Myosuit does improve the efficiency of walking for the study participant.

V. Conclusion

The Myosuit allowed an individual with incomplete SCI to walk 30 % faster over longer uphill distances (>100 m) than without the suit. At the same time, assistance from the Myosuit enabled the study participant to consistently engage in high intensity exercise as indicated by an increased energy expenditure and METS larger than 6. High intensity exercise has been shown to more effectively promote ambulatory function than moderate intensity exercise for individuals with incomplete SCI [1]. Our findings suggest that the Myosuit and similar assistive devices can act as a tool to increase the efficacy of movement training. An analysis of walking kinematics suggested that the assistance from the Myosuit primarily worked towards replacing missing hip extensor function. Thereby, the device facilitated a more upright posture and physiological hip movement pattern during ambulation. This might have contributed to the improved efficiency of walking when wearing the Myosuit. Future research should examine how our findings translate to a larger patient population and different types of lower limb weakness. Additional biomechanical investigation will help to better understand the findings and adapt the assistance from the Myosuit to individual user requirements.

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