Assisted hip and knee extension during stair-climbing in older adults: metabolic and muscular effects

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Assisted hip and knee extension during stair-climbing in older adults: metabolic and muscular effects

Master Thesis

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Abstract

Background: Negotiation of stairs is among the most challenging tasks for older adults, as the required cardiopulmonary effort is increased and muscular strength is reduced with age. During the last decade, various wearable robots have been developed and several studies were published on the feasibility and functional improvements with robotic assistance during level walking. More recent studies have investigated the metabolic effects and functional outcomes of wearable robots assisting a single joint during stair-climbing. However, little is known about the metabolic and muscular effects of robotic assistance across multiple joints during the negotiation of stairs. This study aims to investigate the metabolic and muscular effects of robot-assisted hip and knee extension during stair-climbing in older adults.
Methods: Fifteen healthy older adults (five females, ten males; mean age 59.6 | sd ± 3.44 years) participated in this study. The Myosuit, a lightweight wearable robot assisting the synergistic extension of the hip and knee joints, was used. Energy expenditure was calculated based on oxygen and carbon dioxide exchange rates measured by a mobile respirometric system. Muscle activity of the Biceps femoris, Gluteus maximus, Gluteus medius, Rectus femoris, Vastus lateralis, and Vastus medialis muscles were measured by surface electromyography. Participants walked on a stair-treadmill for four blocks of four minutes and differences in the measured metabolic and myoelectric outcomes with and without the assistance of the robot were compared by a paired t-test.
Results: Reductions in energy expenditure and muscle activity with assistance of the wearable robot have been observed. Physical activity energy expenditure was significantly reduced by 8.5% ($p = <0.001$) during assistance condition. Muscle activity with assistance of the robot was reduced by 8.2% ($p = 0.04$) in the Biceps femoris, by 6.0% ($p = 0.10$) in the Gluteus maximus, by 15.2% ($p = <0.01$) in the Gluteus medius, by 8.4% ($p = 0.04$) in the Rectus femoris, by 9.2% ($p = <0.001$) in the Vastus lateralis, and by 11.3% ($p = <0.001$) in the Vastus medialis.
Conclusion: This study demonstrated that assistance in the extension of the hip and knee joint reduces energy expenditure and muscular activity during stair-climbing in older adults. These reductions may delay the onset of cardiopulmonary exhaustion and muscular fatigue and thereby help older adults to overcome the hurdles of climbing stairs.

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Declaration of Originality

I hereby declare that the written work I have submitted entitled

Assisted hip and knee extension during stair-climbing in older adults: metabolic and muscular effects

is original work which I alone have authored and which is written in my own words.[1]

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Symbols

Acronyms and Abbreviations

BMI	Body mass index
bpm	Beats per minute
ETH	Swiss Federal Institute of Technology
EMG	Electromyography
IMU	Inertial measurement unit
PAEE	Physical activity energy expenditure
REE	Resting energy expenditure
SMS	Sensory-Motor Systems Lab
spm	Steps per minute
TEE	Total energy expenditure
TST	Timed Stair Test

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Chapter 1

Introduction

Stair-climbing is considered as one of the most challenging tasks of activities during daily life for older adults [33], with more than 45% of people at the age of 80 years and above reporting difficulties in climbing stairs [7]. Limitations in stair ascent can be caused by multiple factors such as cardiopulmonary limitations, weakness of the lower limbs, or cognitive-, vestibular-, visual-, and somatosensory impairments [34, 38].

Cardiopulmonary limitations strongly affect the ability to climb stairs, as energy expenditure for stair-climbing is increased to 150% to 250% of the values during level walking [1]. Maximum oxygen uptake for 80-year-old adults is reduced by an average of 58% [8] compared to 20-year-old adults. Aging is also accompanied by a reduction in walking efficiency, as older adults show an average increase in energy expenditure for ambulation by 23% [29]. These cardiopulmonary limitations presumably contribute to the difficulties during stair-climbing for people with age [19].

Muscular strength in older adults is often decreased by Sarcopenia (age-related loss of muscle mass), as this disease is reported to affect up to every fifth person in Europe at the age of 60 years or above [37]. But also other factors, which are predominant in the older population, such as peripheral arterial disease, cardiac insufficiency, arthritis, nutritional deficits, or a sedentary lifestyle, can cause weakness in the lower limbs. These factors lead to a decrease in maximal muscle power of the lower limb extensors by up to 50% for older adults [8]. With the decrease in maximum extensor moments in the lower limbs [32] and a decrease in muscular efficiency by 9%-13% [16, 26], older adults require higher muscular effort during stair-climbing, which may accelerate the onset of muscular fatigue [8].

A limited ability to walk and negotiate stairs reduces general ambulation within the community, increases the risk of social isolation, and finally reduces independence and the quality of life of an ever-aging population [25, 34, 29].

During the last decade, various wearable assistive robots (known as exoskeletons) for the lower limbs have been developed to enable and support the ambulation of impaired people. These exoskeletons completely substitute or reduce the required biological joint power and have been shown to improve gait performance in people suffering from various diseases such as stroke [2], spinal cord injury [5], or multiple sclerosis [21].

Most of the lower limb exoskeletons for the support of impaired people are designed for level ground walking, and the kinematic, metabolic, and muscular effects of their support have been extensively studied [8]. Further studies have been published on the development and application of exoskeletons for assistance during stair-climbing. Depending on the disease and state of the users, these exoskeletons either act on all three [40] or two [42] joints of the lower leg, or only on the hip [19], knee [4], or ankle [41] joint separately. Complex exoskeletons such as the AIDER [40] or the Vanderbilt lower limb exoskeleton [5] enable people with a complete loss of motor (and sensory) function to walk and climb stairs without biological forces. These exoskeletons are capable to substitute the biological power of the user, but their design often adds mass and inertia to the limbs [10]. The added inertia can impede physiological walking and limit the usability in daily life for people with residual biological function of the legs [10]. Lighter and more versatile robots, such as the C-Brace [2], Keego [21], or Myosuit [12] have been designed to assist single joints or support the synergistic movements across multiple joints with one actuator [8]. These lightweight wearable robots provide assistive forces, for users with remaining function in the lower limbs that suffer for example from multiple sclerosis, cardiopulmonary restraints, or sarcopenia [40, 10].

Biomechanical analysis of the ankle, knee, and hip joint during stair-climbing, shows that peak ankle joint power is located at the end of the stance phase, whereas peak hip- and knee joint power are located at the beginning of the stance [35]. The ankle joint has an important role in gait symmetry, energy efficiency, and propulsion during ambulation [39, 17]. In studies with reductions in ankle power and prostheses, however, that power in the ankle joint is less important for maintaining an upright posture during stair-climbing, as the knee and hip joint can compensate for reductions in the ankle moment [39, 30, 10]. In stair-climbing, maximum knee power requirement during leg extension is increased compared to level walking, whereas power requirements in the ankle and hip joint only change slightly [35].

In a recent study, Kim et al. [19] have shown the positive metabolic effect of a single joint hip exoskeleton (GEMS, Samsung Electronics Co. Ltd., Korea) which supports hip flexion and extension of able-bodied users during walking and stair-climbing. Other exoskeletons for the support during stair-climbing exist and were tested for their feasibility and usability [18], for their mechanical and kinematic effects [2], and for their effects on functional outcomes [21] in impaired people. Little is known about the underlying metabolic and muscular effects of a lightweight wearable robot, that assists movements across the hip and knee joint, such as the Myosuit.

The Myosuit is a lightweight wearable robot that supports the synergistic extension of the hip and knee joint during ambulation. Previous studies have shown the capabilities of the Myosuit to improve functional outcomes and to reduce energy expenditure and muscular activity during level and uphill walking [13, 10]. The goal of this thesis is to assess the metabolic and muscular effects of assisted hip- and knee extension during stair-climbing in older adults. An improved understanding of these effects can help us to make evidence-based decisions on possible applications of wearable robots for older adults and deepen our knowledge of how stair-climbing is affected by the support during the synergistic extension of the hip and knee joint.

We hypothesized that energy expenditure and muscle activity in older adults during prolonged stair-climbing at fixed speed is reduced by robotic assistance extending the hip and knee compared to climbing stairs at the same speed without such assistance.

Chapter 2

Methods

2.1 participants characteristics

15 healthy older adults (five females, ten males, Table 2.1) were recruited to participate in this study. The inclusion criteria were: between 55 and 65 years of age, between 160 and 190cm tall, able to climb stairs without assistance and to walk at a moderate speed (0.6m/s) for at least four minutes. Subjects with acute or chronic lower back pain, ongoing systematic disease (such as high blood pressure, diabetes, arthritis, or multiple sclerosis), acute musculoskeletal injuries, cardiovascular or respiratory diseases, acute lower limb musculoskeletal diseases, or a Body Mass Index (BMI) above 30 were excluded from this study. The participants were asked to verbally confirm that they complied with these criteria on the day of the experiment.

Participants received a written information letter about the study prior to signing an informed consent form and could quit the experiment at any time without giving any reason. Approval for this study was granted by the ETH Zurich ethics commission under the number EK-2019-N-172.

The average age of the participants was 59.60 (sd ± 3.44) years, with a weight of 71.77 (sd ± 11.50) kg, a height of 176.13 (sd ± 7.29) cm, and an average sportive activity (such as hiking, running, playing tennis, gymnastics, or yoga) of 4.52 (sd ± 2.24) hours per week. The self-selected cadences on the stair-treadmill ranged between 45 and 60 steps per minute with an average of 51.33 (sd ± 4.81) steps per minute.

Table 2.1: Participants characteristics. mean (min|max) values

Gender	5 females, 10 males
Age	59.60 (55|64) years
Weight	71.77 (47|90) kg
Height	176.13 (165|190) cm
Activity	4.52 (2|9) h/week
Cadence	51.33 (45|60) spm

2.2 Wearable robot

2.2.1 Hardware design

For this study, we used the Myosuit (Myosuit Gamma, MyoSwiss AG, Zürich, Switzerland, Figure 2.1), a lightweight wearable robot for the lower. The Myosuit is a fabric-based, compliant exoskeleton and designed to support the user against gravity through active and passive elements aligned with the working direction of the major leg muscles. The active components of the Myosuit include a backpack-like compartment containing the motors, battery, and control unit of the exoskeleton (Figure 2.1) and knee orthoses attached to the thigh and shin for each leg. The orthoses provide anchoring points for the applied forces. Inertial measurement units (IMU) are integrated into the orthoses, to detect gait-events and time the assistance of the device. One cable per leg, called tendon, is routed from the motor at the back of the user over the hip, along the thigh, over a hinge at the knee, and is finally anchored at the shin interface. By winding up these tendons, the synergistic extension of the hip and knee joint is supported to help the user with the extension of the weight-bearing leg against gravity. The tension in the tendons can provide additional stability for the users during the stance phase of the gait cycle and in the standing position. Passive elements consisting of elastic rubber bands (Figure 2.1), are attached in front of the legs and connect the waist strap of the backpack to the thigh interfaces. These passive elements support the flexion of the hip and act in an antagonistic manner to the active elements described before. During hip extension and the stance phase of the gait, these elastics are stretched and store part of the energy which is eventually released in the swing phase of the leg. The underlying concepts and the detailed working principle of the Myosuit can be found in the work from Schmidt et al. [36] and Haufe [10].

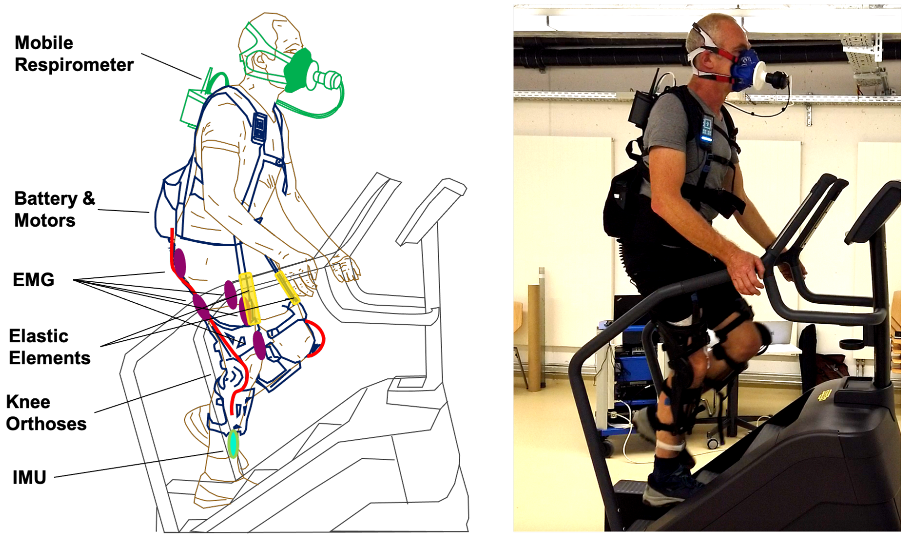


Figure 2.1: Experimental Setup: Participants walked on a stair-treadmill with the Myosuit (blue). A mobile respirometer (green) recorded oxygen and carbon-dioxide flow rates. Surface electrodes (purple) measured muscle activity on the right leg. An IMU sensor (turquoise) was placed on the shin of the right leg. The red lines indicate the routing of the tendons.

2.2.2 Control modes

For the purposes of this study, the outcomes between two different control modes, the Zero-Force mode and the Assistance mode of the Myosuit were compared. In Zero-Force mode, no active forces are applied to the user while the Myosuit only compensates for the added inertia, stiffness of the passive elements, and friction in the cables [10]. In Assistance mode, the Myosuit produces up to 400N of tension on each tendon and can thereby actively support the user in extending the hip and knee joints during the appropriate phase of the gait cycle. To assess the current gait phase and appropriate assistance, inertial measurement units are integrated within the thigh and shin interfaces of the Myosuit. A more detailed description of the control modes can be found in the work from [10].

2.3 Experimental protocol

The exoskeleton was fitted to the participants and was worn by the participants during the entire experiment. The experimental protocol (Figure 2.2) consisted of an initial familiarization task on flat ground and on the stair-treadmill (2.3.1), including a Timed Stair Test to assess the maximal speed and estimate an appropriate cadence for the stair-treadmill (B.1). The final task included a four-minute block of quiet standing to assess resting metabolic rate followed by four blocks of continuous walking at fixed speed on the stair-treadmill where we recorded metabolic and myoelectric data (2.3.2). A break of four minutes was granted between the different blocks, plus additional time for the placement and fitting of the electrodes and metabolic measurement system (Figure 2.1). Participants were instructed to walk as naturally as possible during the entire experiment and to only use the handrails if required for stabilization.

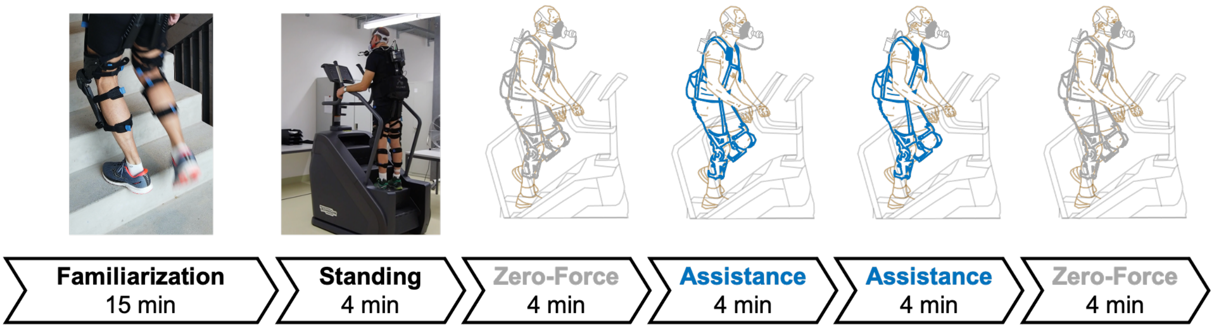


Figure 2.2: Experimental Protocol: After initial familiarization and a four minutes block of standing, participants walked during the first block in Zero-Force, followed by two blocks in Assistance, and a final block in Zero-Force mode. Each block had a length of four minutes.

2.3.1 Familiarization

Familiarization with the Myosuit was performed on level ground and on a staircase and followed by the familiarization with the treadmill. For initial familiarization with the exoskeleton, participants were asked to walk on flat ground with the Myosuit set to Zero-Force mode. After two minutes, the exoskeleton was switched to Assistance mode and participants continued to walk for another two minutes on flat ground before climbing six flights of stairs. After climbing the stairs, participants performed a Timed Stair Test (Appendix B.1) to identify their maximum speed to estimate an appropriate cadence for stair-treadmill walking.

For familiarization with the treadmill (described in 2.3.2), participants were instructed to start at slow cadences, to slowly increase and find a comfortable cadence within a range of 40% to 60% of the cadence that was reached during Zero-Force mode in the Timed Stair Test. An upper limit at 60 steps per minute (spm) was defined for walking on the treadmill. During the first two minutes of familiarization with the stair-treadmill, the Myosuit was set to Zero-Force mode. After the first two minutes, the Myosuit was set to Assistance mode and participants walked for another three minutes to familiarize themself with the support of the Myosuit on the stair-treadmill.

2.3.2 Stair-treadmill walking

Data for metabolic and myoelectric outcomes were collected on a stair-treadmill ergometer. (step height: 21, cm step depth: 28 cm, step width: 47 cm; Excite Advanced Climb LED, Technogym S.p.A., Cesena, Italy). The stair-treadmill was used because it made a theoretically infinite number of consecutive steps possible, without being interrupted by changes in direction or a finite number of floors. In addition, the stair-treadmill allowed precise control of the cadence during the entire experiment. Participants were asked to stand in a resting position for four minutes for the assessment of baseline metabolic rate. The task itself included four blocks of four minutes, one block in Zero-Force, followed by two blocks in Assistance, and one block in Zero-Force mode in the end. The mirrored design accounted for potential effects of order and time. A break of four minutes was granted between two consecutive blocks. During the entire experiment, the cadence remained constant at the preferred cadence that was chosen by the participants during familiarization.

2.4 Data collection

Before the assessment of energy expenditure and muscle activity, a respirometry system (described in 2.4.1) was fitted to the participants, and electrodes of the surface electromyography (EMG) system were placed on the right leg of the participants as described in 2.4.3 (Figure 2.1).

2.4.1 Respirometry

For the assessment of energy expenditure, we used a mobile respirometer system (Cosmed K5 respirometer, COSMED Srl, Rome, Italy) and measured heart rate with a ANT+ chest strap (HRM Dual, Garmin, Kansas, USA). Participants were asked to fast for six to eight hours before the experiment to prevent any influences on metabolic exchange rates due to food digestion.

2.4.2 Rating of perceived exhaustion

Participants were asked to rate their perceived effort directly after each block on the Borg scale [3].

2.4.3 Electromyography (EMG)

Muscle activity of the musculus (M.) Gluteus, M. Biceps femoris, M. Vastus lateralis, M. Vastus medialis, and M. Rectus femoris were recorded by placing EMG electrodes (Hydrogel/Ag/AgCl, Kendall Arbo H124SG, Covidien, Ireland) in accordance with the SENIAM [15] guidelines. The electrodes were placed on the right leg after the skin was shaved, cleaned with alcohol wipes, and prepared with sand-gel. The Noraxon Ultium-EMG (NORAXON Inc., Arizona, USA) system with five electrode configuration was used to collect muscle activity with a frequency of 2000 Hz during this study. An additional inertial measurement unit (IMU) was placed on the right shin of the participants to collect acceleration- and gyroscopic data for step segmentation.

2.5 Data processing and analysis

Oxygen and carbon-dioxide breath-by-breath exchange rates were measured by the mobile respirometric system for the assessment of indirect calorimetry. Average energy expenditure during the last two minutes of each four-minute block was calculated based on the oxygen and carbon-dioxide rates as described by Péronnet and Massicotte [28]. Physical activity energy expenditure (PAEE) was calculated as the difference between total energy expenditure (TEE) during stair walking, minus resting energy expenditure (REE) measured during the last two minutes of the initial period of standing (Equation 2.1).

$$PAEE = TEE - REE \tag{2.1}$$

Heart rate values were calculated as the average heart rate over the last two minutes of each block.

Raw EMG data were filtered by a Parks-McClellan 20 - 400 MHz band-pass filter and the moving root-mean-square (RMS) over a time-window of 50ms was calculated. EMG data were normalized to the uppermost 5% values of EMG activity during the Zero-Force conditions [9]. The data were segmented into single gait cycles based on the local minimum of gyroscopic rate change of the right shin in the sagittal plane [6]. Steps with a dynamic-time-warping distance above twice the average dynamic-time-warping distance from the previous steps of the same block were discarded. The placement of electrodes was limited by space-constraints posed from the Myosuit so that electrodes could not always be placed at the primary location of the muscle belly. For some participants, signals from the M. Gluteus medius were recorded, while for others, the signals of M. Gluteus maximus were recorded. Based on the EMG patterns presented by Lyons et al. [20], the data from the M. Gluteus site were separated into M. Gluteus medius data and M. Gluteus maximus data. The data were separated based on a histogram-plot from the EMG activity data at 40% of the gait cycle divided by the maximum EMG activity (Appendix A.2). The lower group counted to the M. Gluteus medius and the higher group to the M. Gluteus maximus.

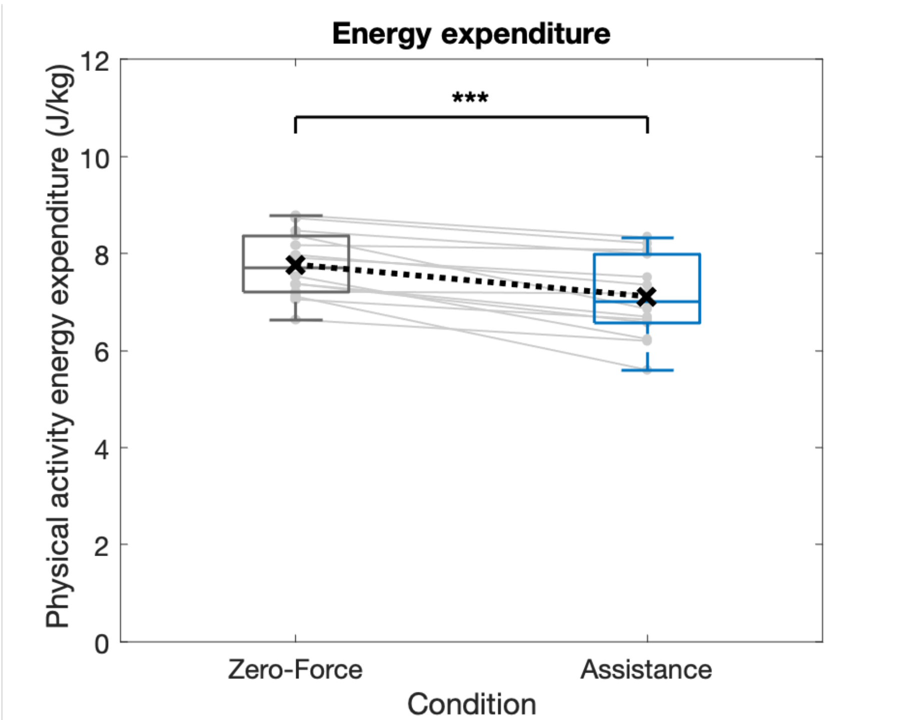
Data-distribution of the measured data was analyzed by the Shapiro-Wilk Test. Normally distributed data were analyzed with a Paired T-Test, while the Wilcoxon Signed-Rank Test was applied to data that violated the assumption of normal distribution. Statistical significance was accepted at $\alpha < 0.05$. All data processing was performed in MATLAB (MATLAB R2020b, MathWorks Inc., Massachusetts, USA).

Chapter 3

Results

3.1 Reduced physical activity energy expenditure

With the support of the Myosuit, a significant reduction in average physical activity energy expenditures per unit mass of 8.5% (sd ± 6.3%) between Zero-Force and Assistance mode was observed, with a mean physical activity energy expenditure of 7.75 J/kg (sd ± 0.65 J/kg) and 7.10 J/kg (sd ± 0.81 J/kg) respectively ($p < 0.001$; n = 14; Figure 3.1). Metabolic data for one participant (SWP 09) had to be removed, due to systematic errors in the volume flow, presumably caused by leakage of the mask from the metabolic measurement system.



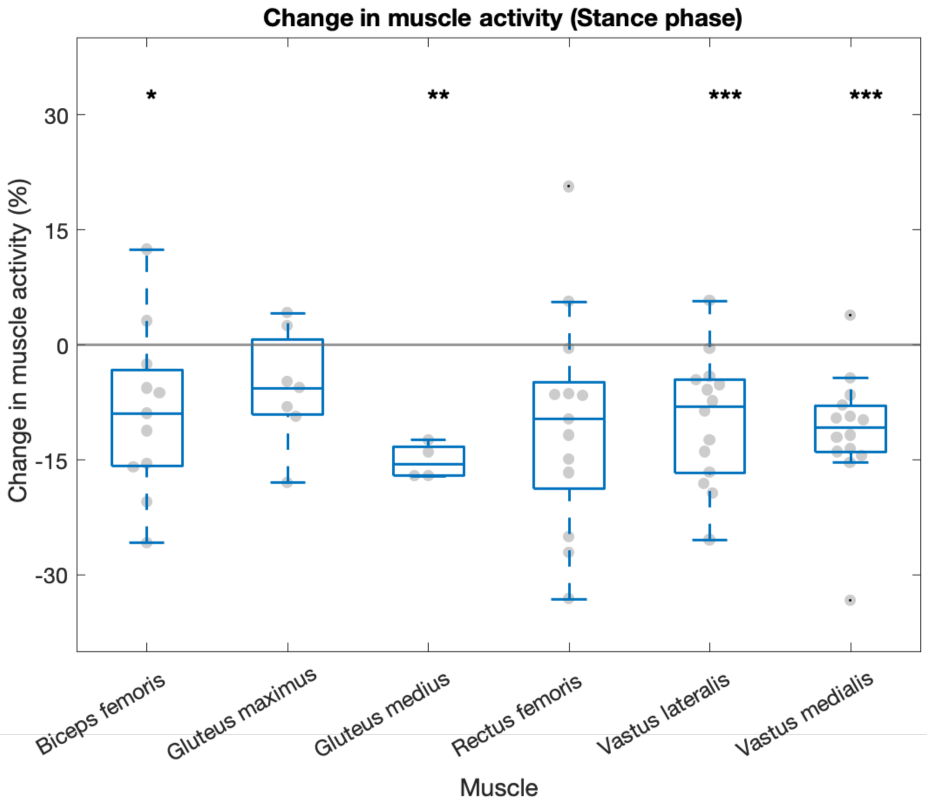
***: $p < 0.001$; n = 14

Figure 3.1: Physical activity energy expenditure for each participant in Zero-Force and Assistance mode. Each data-point represents the average over both measurements in the same conditions with and without the assistance of a wearable robot.

3.2 Changes in average muscle activity during stance phase

Average muscular activity of the stance phase was reduced during stair-climbing with the assistance of the Myosuit, compared to Zero-Force mode. Figure 3.2 shows the relative change of mean muscular activity for the Assistance condition, compared Zero-Force condition. Statistical analysis showed a significant reduction of average myoelectric activity during stance phase in Assistance mode, compared to Zero-Force mode for the M. Gluteus medius, M. Biceps femoris, M. Vastus lateralis, and M. Vastus medialis. No significant reductions for the M. Gluteus maximus and M. Rectus femoris were observed (Table 3.1).

Some of the EMG data-sets were missing or excluded from the data analysis due to data losses or artifacts caused by the moving parts of the Myosuit. These excluded data-sets are listed in the Appendix (Table A.2).



*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$

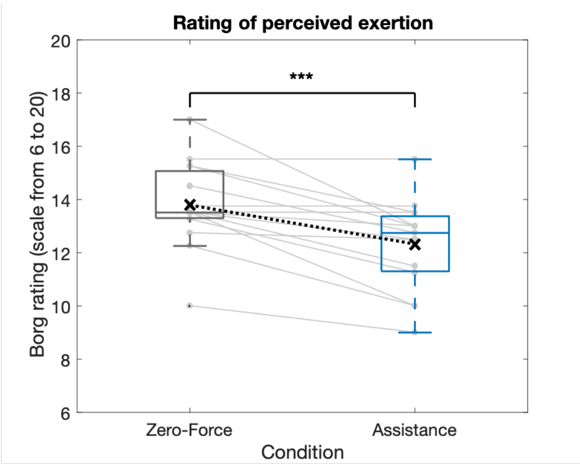
Figure 3.2: Changes in muscular activity from Zero-Force mode to Assistance mode.

Table 3.1: Changes in average muscle activity during stance phase from Zero-Force to Assistance mode

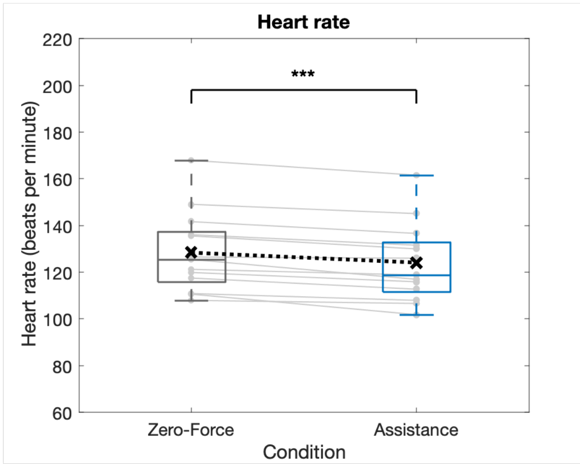
Muscle	Change	Standard-deviation	p-value	n
M. Biceps femoris	-8.2%	± 10.9%	0.04	11
M. Gluteus maximus	-6.0%	± 7.5%	0.10	7
M. Gluteus medius	-15.2%	± 2.3%	< 0.01	4
M. Rectus femoris	-8.4%	± 14.3%	0.07	13
M. Vastus lateralis	-9.2%	± 8.4%	< 0.001	14
M. Vastus medialis	-11.3%	± 8.1%	< 0.001	14

3.3 Decrease in perceived effort and heart rate

A significant decrease in the Borg rating of perceived exertion was observed, with a range from 10 to 17 in Zero-Force mode (mean 13.6; sd ± 1.4) and from 9 to 16 (mean 12.3; sd ± 1.7) in Assistance mode of the Myosuit (Figure 3.3). On average, the Borg rating was reduced by 1.5 points (sd ± 1.2 points; $p < 0.001$; n = 15). Mean heart-rate decreased by 3.5% (sd ± 2.1%) from 128.3 beats per minute (bpm) (sd ± 17.3 bpm) without assistance to 123.8 bpm (sd ± 16.9 bpm) with assistance of the Myosuit ($p < 0.001$; n = 13). Heart rate data for two participants (SWP 03 and SWP 13) were missing, due to connection and recording problems with the heart rate belt.



A: Borg rating (n = 15)



B: Heart rate (n = 13)

***: $p < 0.001$

Figure 3.3: Borg rating **(A)** and heart rate **(B)** for each participant in Zero-Force and Assistance mode. Each data-point represents the average over both measurements in the same conditions with and without the assistance of the Myosuit.

Chapter 4

Discussion

The influences of the mechanical assistance of a wearable robot during stair-climbing on the metabolic and muscle activity of fifteen healthy older adults were investigated during this study. The presented results show that assistance of a lightweight, wearable robot can reduce energy expenditure, heart rate, and perceived effort. Our results show also a significant decrease in muscle activity for all measured muscles, except the M. Gluteus maximus and M. Rectus femoris.

4.1 Reduction in energy expenditure

A reduction in energy expenditure by 8.5% was observed with the assistance of the wearable robot during this study. This reduction reflects a decrease in the biological energy demand for a given mechanical work in climbing stairs. It was shown that the assistance of a wearable robot can reduce the required cardiopulmonary effort of older adults during stair-climbing. This reduction in the required cardiopulmonary effort can make the negotiation of stairs for older people with cardiopulmonary limitations easier and help to compensate for the higher energy demands, that older adults experience during stair-climbing.

The observed reduction in energy expenditure is consistent with findings from previous experiments from our group, where the effects of the Myosuit for walking on an inclined treadmill and inclined overground walking on an outdoor path reduced energy expenditure by 7.4% and 9.5% respectively [11]. A similar result was reported by Kim et al. [19], with a reduction in energy expenditure of -10.2% for the use of a hip-exoskeleton compared to a no exoskeleton condition. These results indicate a slightly bigger change in energy expenditure than shown in our study, however, as reductions in energy expenditure for overground walking are larger compared to treadmill walking [11], a similar reduction in energy expenditure to the findings from Kim et al. can be assumed.

Haufe et al. [14] showed that using the Myosuit reduced energy expenditure for a participant with incomplete spinal cord injury by -17%, compared to not using it. Whereas smaller reductions in energy expenditure for healthy participants were reported [14]. Therefore, we assume that the observed effects of a wearable assistive robot during stair-climbing will transfer and result in larger benefits for more severely impaired participants.

4.2 Reduced muscle activity

Muscle activity was reduced between -6% and -15% for all measured muscles with the assistance of a wearable robot. A significant decrease in muscle activity was found for all, except the Gluteus maximus and Rectus femoris muscle. The general trend for reduced muscle activity shows that the assistance of a wearable robot can decrease the required muscular effort in older adults. By a decrease in required muscle effort, the assistance of a wearable robot can presumably compensate for age-related decreases in muscle efficiency, power, and strength and thereby support older people during the negotiation of stairs.

In-depth analysis from the patterns of muscle activity (Appendix B.2) showed significant changes for all measured muscles, except for the M. Gluteus maximus and medius. Significant decreases in muscle activity patterns have been observed during the initial stance-phase between 6% to 25% gait cycle and smaller increases at the end of the stance phase between 47% and 48% and at 62% gait cycle (Appendix B.1). The initial decrease in muscle activity aligns well with the corresponding peak in power requirement of the hip and knee-joint during extension of the leg [35]. Therefore, we assume that the reduced muscle activity with the assistance of a wearable robot is a result of a reduction in biological power requirement for the hip and knee joint during leg extension. The increase in muscle activity during the final phase of the gait cycle and shortly before toe-off was observed for all three measured muscles on the anterior side of the leg. A contribution to early hip-flexion for the muscles of the anterior leg muscles, as well as adaptations in gait patterns for pronounced use of assisted joints, are possible explanations for the transient increases during the late phase of the gait cycle. Similar changes with a reduction in muscle activation during the weight acceptance phase and increased muscle activity shortly before the release of assistive forces have been found in a previous study from our group, investigating the effects of the Myosuits assistance during uphill walking. [10]

4.3 Perceived effort

The results show a reduction in the rating of perceived exertion by 1.3 points on the Borg scale, meaning that the participants felt less exhaustion when assisted by the wearable robots. It is therefore shown that the assistance condition did not only reduce energy expenditure and heart rate but was also perceived as less exhausting by the participants. However, the observed reduction in energy expenditure was below the threshold of 25.2%, which was claimed as the just noticeable difference in energy expenditure for walking with a wearable robot by Medrano et al. [23]. Even if the reductions in Borg rating, that was found in our study, did not originate from a change in energy expenditure, we assume that participants rather rate the overall experience for the different conditions and it, therefore, may still indicate that participants did not perceive the Assistance mode as harder or worse compared to the Zero-Force mode.

4.4 Study limitations

One of the limitations of our study was that all of our participants had very good functional status and most of our participants performed sportive activities for multiple hours per week. People above the age of 65 or with impairments could not be included, as originally planned, due to the COVID-19 pandemic. Therefore, it remains open to further studies, to investigate the effects of supported hip and knee extension during stair-climbing for people above the age of 65, with impairments or reduced functionality of the lower limbs. Furthermore, there were no means of blinding the participants for the different conditions, meaning that the subjective outcome in perceived exhaustion is possibly biased.

Another limitation is the comparison to a Zero-Force condition instead of a No-Exoskeleton condition. We choose the comparison to a Zero-Force condition as it allowed us to separately investigate the technical effects of assistance by a lightweight wearable robot on stair-climbing, without being confounded by the physical effects of the added weight or complexity. It also allowed us to conduct the entire experiment without re-positioning of the EMG electrodes, which could have lead to higher variability in the recorded EMG data. In a single case study, investigating the effects of the added weight and complexity of the Myosuit during stair-climbing, the differences in cost of vertical transport between the switched-off condition of the Myosuit and a No-Myosuit condition were analyzed. An increased cost of vertical transport of 11.6% for the switched-off condition in healthy participants was observed (Appendix, C). These results indicate that the reported benefits in reduced cost of vertical transport for Assistance condition may be nullified for healthy participants by the added weight and complexity of the suit.

With the space-constraints posed by the Myosuit, electrode placement was restricted and placement at the center of the muscle belly and recommended location was not always possible. Therefore noise and artifacts from the robot and additional signals from nearby muscles could have an important influence on the EMG recordings. The exact placement of the electrodes on the muscle belly of the M. Biceps femoris was not possible due to the space-constraints by the Myosuit. Different activation patterns for this location have been observed and a clear separation to different muscle patterns was not possible. Therefore, it is plausible that multiple hamstring muscles, most likely the M. Semitendonosus and the short- and long head of the M. Biceps femoris were measured across different participants.

4.5 Future work

With the restrictions due to the COVID-19 pandemic, we were not able to include people above 65 or more severely impaired participants in our study. Additional measurements in the future with older and more severely impaired participants will help us to understand the effects of robot-assisted hip and knee extension during stair-climbing.

Currently, it is not clear, if larger assistive forces would further reduce energy expenditure and muscle activity during stair-climbing. For level walking, Quinlivan et al. [31] reported a linear reduction in energy expenditure, if assistive forces are increased. As the maximum level of assistive forces from the Myosuit is limited (Appendix A.4), it remains an open question to future studies, if energy expenditure during stair-climbing could be further reduced with a wearable robot, that can produce higher assistive forces.

The current control mechanism of the Myosuit leads to an abrupt release in assistive forces [10]. The anticipated loss of the assistance could lead to higher muscle co-contractions for stabilization. We would therefore recommend testing different force profiles in future studies, to investigate the influence of different force profiles on muscle activity.

Chapter 5

Conclusion

This study aimed to investigate the metabolic and muscular effects of assisted hip and knee extension against gravity during stair-climbing in older adults. It was shown that the assistance of a lightweight wearable robot decreased energy expenditure and reduced muscle activity in the main muscles that contribute to leg extension against gravity during stair ascent. Our results suggest that assistance of a lightweight wearable robot during stair-climbing can be beneficial for older adults, by mitigating the effects of limitations in the cardiopulmonary effort and decreased muscle strength. Additional research with more severely impaired participants is needed to fully understand how assisted hip and knee extension affects people with muscular weakness or cardiopulmonary limitations during stair-climbing.

Appendix A

Additional Information

A.1 Detailed participant information

Table A.1: Detailed participant information

Participant	Age years	Weight kilograms	Height cm	Activity h / week	Cadence spm	Gender male / female
SWP 01	61	78	181	2	60	m
SWP 02	55	75	179	4.5	55	m
SWP 03	62	90	176	2	45	f
SWP 04	57	79	187	6	60	m
SWP 05	57	71	175	9	50	m
SWP 06	57	83	180	5	50	m
SWP 07	56	64	168	3	50	m
SWP 08	62	73	177	4	50	m
SWP 09	57	78	178	7	50	m
SWP 10	55	82	190	5	55	m
SWP 11	60	47	167	2.5	45	f
SWP 12	64	70	165	2	45	f
SWP 13	64	71	171	2.75	50	f
SWP 14	64	52	168	5	50	f
SWP 15	63	63	180	8	55	m

A.2 Rejected EMG data

Table A.2: Excluded data in the analysis of muscular activity

	M. gluteus	M Biceps femors	M. vastus lateralis	M. vastus medialis	M. rectus femoris
SWP 01	all	all	TR1	TR1	all
SWP 02	all				
SWP 03	all	all	all	all	all
SWP 04	all	all	AS2		
SWP 05		AS1			
SWP 13					all

A.3 Placement of EMG electrodes

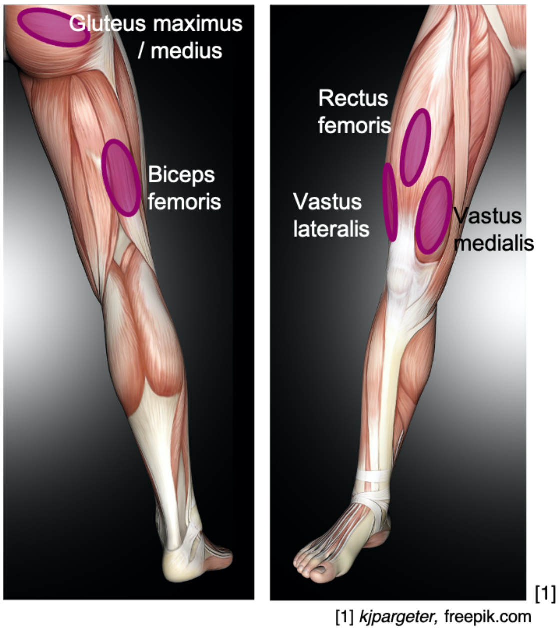


Figure A.1: Placement of EMG electrodes on the right leg

A.4 Seperation into Gluteus medius and Gluteus maximus

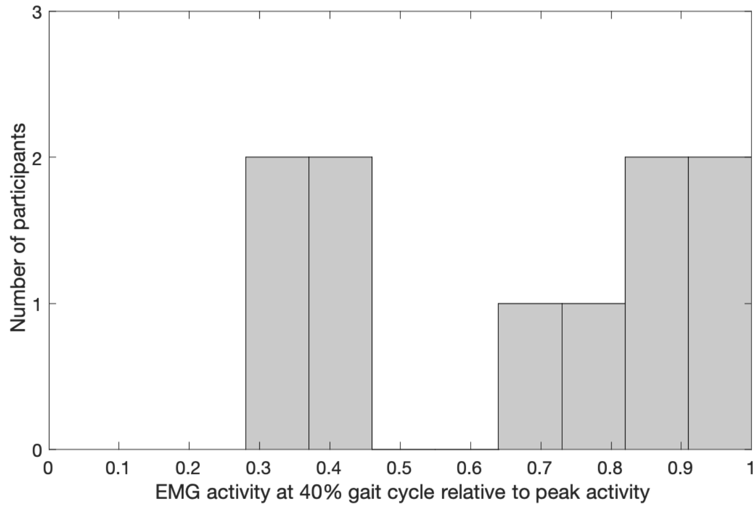


Figure A.2: Histogram plot to separate the data from the M. Gluteus site into M. Gluteus medius and M. Gluteus maximus.

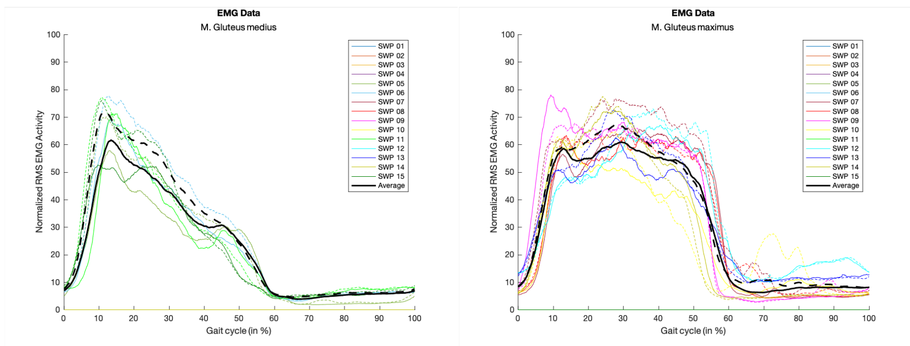


Figure A.3: Patterns of muscle activity of the M. Gluteus medius and M. Gluteus maximus. Assistance condition is represented by solid lines, while dashed lines represent Zero-Force condition.

A.5 Force profile of the Myosuit assistance

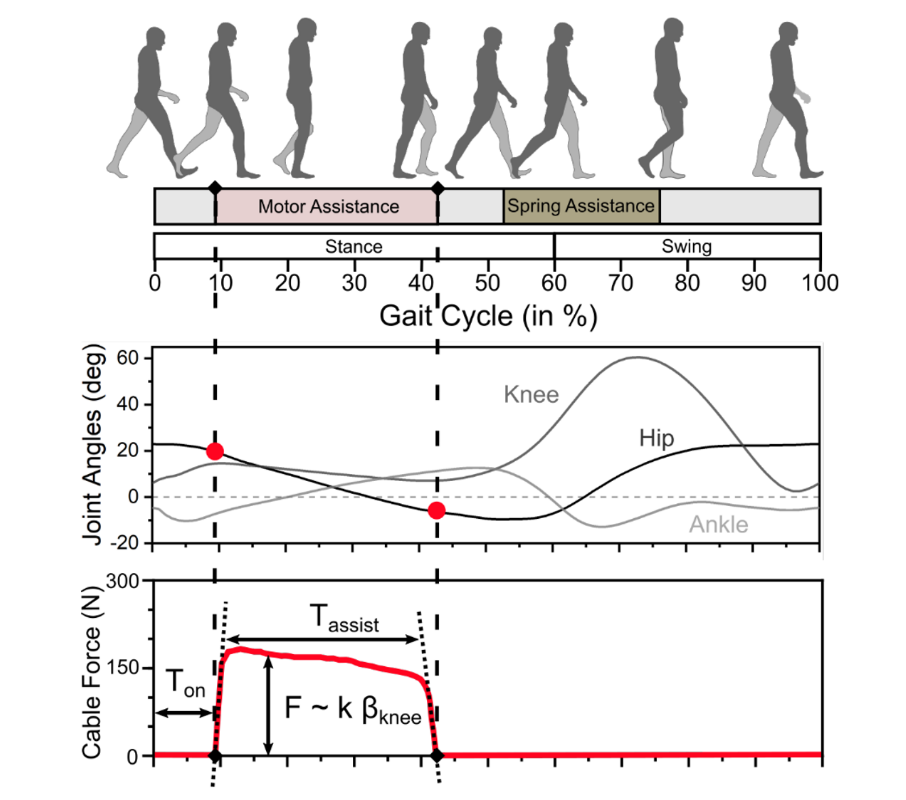


Figure A.4: Schematics of tendon forces in Assistance mode and corresponding joint angles of the lower limb during different phases of the gait cycle; reproduced from [10]

Appendix B

Additional measurements

B.1 Timed Stair Test (TST)

B.1.1 Methods TST

The Timed Stair Test was performed as part of the familiarization on a twelve-step staircase (each step 18 cm in height, 27.5 cm in depth, and 122.5 cm in width details B.1). The maximal cadence in stair-climbing was assessed by the Timed Stair Test as described by Nightingale et al. [24], in which participants were instructed to climb a flight of stairs with twelve steps as fast as possible while staying safe and without using the handrail. Before the start of the actual measurement, participants performed two test runs of the Timed Stair Test (first run in Zero-Force, second run in Assistance mode). The participants had to climb one flight of stairs four times (details 2.3) with the first run in Zero-Force mode, followed by two blocks in Assistance mode and a final block in Zero-Force mode. Between two consecutive runs, a break of one minute was granted for returning to the starting position and to reduce the effects of fatigue.

Participants were instructed to start the test in the resting position, in which both feet are placed in front of the first stair and to then perform the test in a walking manner, without skipping steps or using the handrails. Time for the Timed Stair Test was manually measured using a stopwatch, starting from first movement after the resting position and stopped when both feet were placed beside each other on top of the last step.

The time for the Timed Stair Test was manually measured with a stopwatch.

B.1.2 Results TST

No significant changes in the cadence during the TST were found between Zero-Force (124.9 spm; sd $\pm$ 27.4 spm) and Assistance mode (120.8 spm; sd $\pm$ 27.0 spm) (Average change -3.2%; sd $\pm$ 6.1%; p-value = 0.07; n=15).

B.1.3 Discussion TST

As shown in Chapter B.1.2 no significant changes in cadences were observed during the Timed Stair Test. Even though not significant, cadences during stair climbing tended to be slower with the assistance of a wearable robot. For healthy participants, walking with the assistance of a wearable robot does not seem to increase cadences during stair-climbing and the assistance is possibly perceived as a disturbance to the normal gait pattern.

This result is consistent with the study from Kim et al., where participants were free to select their cadence to climb a staircase of 128 steps, no significant difference between Assistance and a No-Exoskeleton condition was observed with a wearable robot for the support of the hip. [19].

Another result was presented by the study from McGibbon et al. [22], where the functional changes for the assistance of an exoskeleton acting on the knee joints in participants with Multiple Sclerosis were investigated and a significant decrease in performance during the Timed Stair Test was reported for the use of the exoskeleton compared to not using it.

For assessing the cadence, a stopwatch was used to manually measure the time needed for a twelve-step TST.

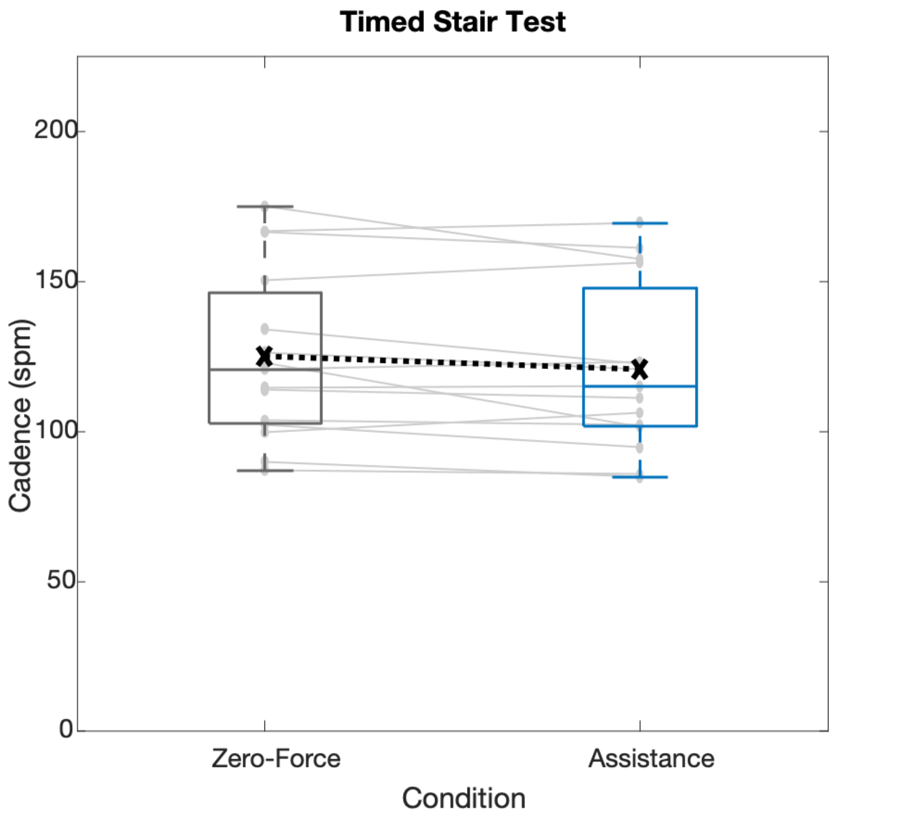


Figure B.1: Results of the timed stair test

B.2 Patterns of muscle activation

B.2.1 Data processing patterns of muscle activation

EMG activation patterns were compared using statistical parametric mapping as a one-dimensional extension of the paired t-test [27].

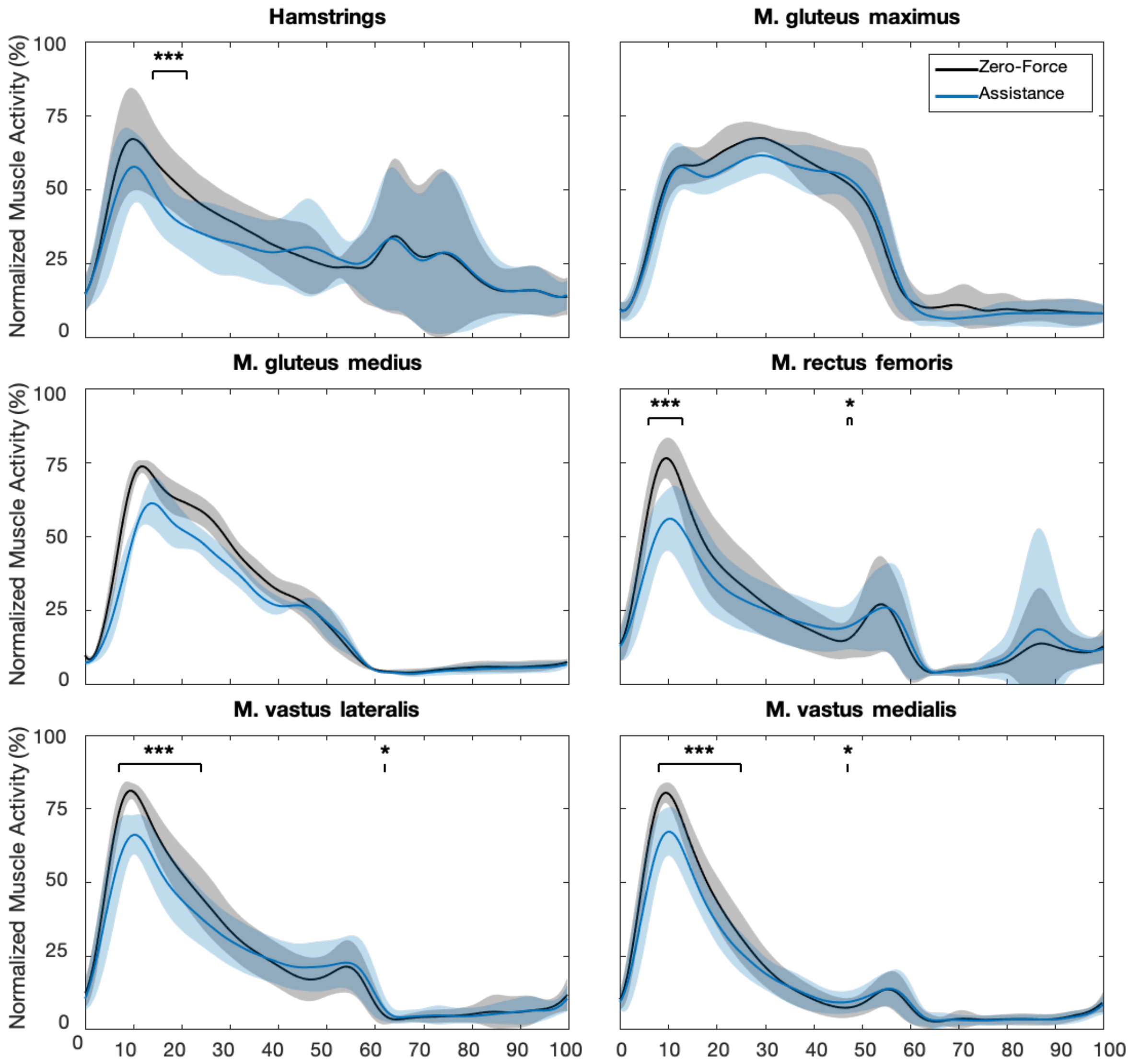
B.2.2 Results patterns of muscle activation

The mean pattern of muscle activation during Zero-Force and Assistance condition were similar for the majority of muscles and time (Figure B.2). However, some muscles (M. Biceps femoris, M. Rectus femoris, M. Vastus lateralis, and M. Vastus medialis) showed clusters of significantly reduced actvity during Assistance condition compared to Zero-Force condition in the range between 6% and 25% gait cycle. Additional clusters of significantly increased activity in Assistance condition compared to Zero-Force mode were observed for the M. Rectus femoris and M. Vastus medialis in the range between 47% and 48% gait cycle and at 62% gait cycle for the M. Vastus lateralis. The analysed region was limited to the stance-phase (0% to 64% gait cycle) (Table B.1). The probability that the reported clusters of this size would be observed in repeated random samplings was below the significance level of $\alpha < 0.05$. Some of the EMG data-sets were missing or excluded from the data analysis due to data losses or artifacts caused by the moving parts of the Myosuit. The excluded data-sets are listed in the appendix (Table A.2).

B.2.3 Exact cluster locations and changes

Table B.1: Clusters of significant change in muscle activation pattern between Assistance and Zero-Force mode

Muscle	Cluster location (in % gait cycle)	Change for cluster location	p-value for cluster	n
M. Biceps femoris	14% to 21%	-3.10%	< 0.001	11
M. Gluteus maximus	-	-		7
M. Gluteus medius	-	-	-	4
M. Rectus femoris	6% to 13%	-9.13%	< 0.001	13
	47% to 48%	+26.84%	0.02	
M. Vastus lateralis	7% to 24%	-12.34%	< 0.001	14
	62% to 62%	+22.29%	< 0.04	
M. Vastus medialis	8% to 25%	-14.33%	< 0.001	14
	47% to 47%	+21.84%	< 0.03	



*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$

Figure B.2: Normalized muscle activation pattern during Zero-Force and Assistance condition for four minutes of stair-treadmill walking: Each curve represents the mean and shaded standard deviation over all participants. Muscle activity is normalized to uppermost 5% values during Zero-Force condition. The stance-phase (0 to 64% gait cycle) was analyzed with statistical parametric mapping as a one-dimensional extension of the paired t-test.

Appendix C

Comparing the No-Myosuit and Off condition

Table C.1: Energy expenditures for No-Myosuit condition and Switched-Off Myosuit condition for one single participant, walking for four minutes on the treadmill in each condition. (Participant characteristics: age: 25years, heigth: 180cm, weight: 85kg)

Condition	PAEE (J/kg)
Off	8.89
No	7.96

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