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A Study on Energy Efficiency in Walking and Stair Climbing for Elderly Wearing Complex Muscle Support System

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Objective: This study was conducted to analyze the effect of wearable complex muscle support system on energy efficiency during walking in elderly.

Design: Cross sectional study

Methods: Twenty healthy elderly participated in this study. All subjects performed a 6 minuteswalk test(6MWT) and stair climbing test in dual, slack and no suit conditions. In each condition, oxygen consumption(VO_2), metabolic equivalents(METs), energy expenditure measures(EEm), physiological cost index(PCI), walking velocity and heartrate were measured. Through repeated measured ANOVA, it was investigated whether there was a statistically significant difference in the measurement results between the three conditions.

Results: In over-ground walking, VO_2, METs and EEm showed significant differences between no suit and slack conditions($p < 0.05$). In stair climbing, VO_2 showed significant difference between slack and dual conditions($p < 0.05$). Also, METs and EEm showed significant differences between no suit and slack, and between slack and dual conditions($p < 0.05$).

Conclusions: Wearing the wearable complex muscle support system for elderly does not have much benefit in energy metabolism efficiency in over-ground, but there is a benefit in stair walking.

Key Words: metabolic equivalent, technology, aging, aged

Introduction

Recent population data shows that the elderly population is increasing rapidly, and it is predicted that the number will continue to increase throughout the century[1]. According to this global population trend, the health problem of the elderly has emerged as an important individual and social issues. Also, most elderly experience inability to live independently, disability and illness, followed by high costs of health care and social welfare [2, 3]. South Korea is one of the countries with the most rapidly aging population over the world[4]. According to the Korea national statistical office, in 2021, the number of elderly people aged 65 and over is 8.537 million, accounting for 16.5% of the total Korean population. Since it exceeds 14%, it belongs to an aged society, and the future prospect is that it will become a super-aged society, exceeding 20% by 2025.

Older people lose muscle which is called

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sarcopenia, making it difficult to walk or climb stairs. This phenomenon limits the behaviors of the elderly, therefore, these restrictions continue to cause aggravation of sarcopenia along with secondary diseases[5]. Sarcopenia affects activities of daily living(ADL), which affects the quality of life of the elderly[6]. Structure changes such as muscle weakness due to aging impair functions such as balance and gait in the elderly[7]. Resistance exercise can be the most effective as a prevention of such muscle weakness[8], but it is practically difficult to perform such resistance exercise due to weakening of activity and cardiopulmonary capacity[9]. Therefore, intervention that the elderly can easily do in their daily life are required to overcome these limitations.

Type 2 muscle fibers are most affected by aging, and since functional electrical stimulation(FES) on these type 2 muscles first, applying FES to the elderly can improve functions such as balance ability[10]. Electronics and Telecommunications Research Institute (ETRI) developed electromyography – controlled FES (EMG-controlled FES) system, a device that can induce muscle contraction by external stimulation by simultaneously stimulating the corresponding muscle with an intensity proportional to the voluntary contraction force[11].

Clinical verification of the energy efficiency of this system has been conducted. Previous studies have shown that it allows the older adults to consume less energy when walking on stairs or over-ground with the system comparing to wearing the system turning it off. Recently, in order to upgrade this system, a complex muscle support system that adds a cable-driven method to the existing EMG-controlled FES has been developed. This study was conducted to verify the energy efficiency of a system that supports muscles in a complex form.

Methods

Participants

20participants (7 male/13 female) between the ages of 69-80 years who are suitable for this study were recruited. Inclusion criterion for the participants were: (1) Elderly with no major problems with physical function (Short physical performance battery(SPPB) score of 7 or higher, minimal-mild limitations). (2) Elderly 65 years of age or older without a history of central nervous system disease within 6 months. (3) Elderly without problems of balance control with a berg balance scale (BBS) of 47 or higher[12]. (4) Elderly who are not taking drugs (benzodiazepines, antidepressants, neuroleptics) that affect balance or gait. Exclusion criterion for the participants were: (1) Elderly who have difficulty walking independently due to problems such as severe muscle paralysis, fracture, visual field defect. (2) Elderly with cardiopulmonary disease, claustrophobia or anxiety about wearing a mask. (3) Elderly who have difficulty to participate in this study due to adult diseases such as uncontrolled high blood pressure and diabetes. (4) Elderly with severe dizziness at risk of falls while walking. (5) Elderly who have difficulty understanding and performing the researcher’s instructions with a mini mental state examination (MMSE) score of 26 or less. (6) Elderly who are judged to be inappropriate by researcher for other reasons[13-16]. The subjects were recruited from senior citizen that met the selection criteria and lived in Seoul over the phone. The period of this study was from August 6, 2021 to September 31, 2021. The selected test subjects were calculated using G-power program (IBM Inc., USA). The effect size was set to 0.58, power value was set to 0.8 and 20 people were counted. For the effect size, reference was made to previous study[17]. In consideration of the dropout rate of 20% during the course of experiment, the number of participants was set to 24. 4 participants were dropped for the exclusion criterion and finally 20 elderly participated until the end of the study. This protocol was reviewed and approved by the Institutional review board at the Sahmyook University (IRB No. 2-1040781-A-N-012021103HR). Written informed consent was obtained from all subjects prior to participation in the study. 2021.8.6 - 2021.9.31

Procedures

First, all participants received a sufficient explanation of the contents of the experiment and signed a written consent to participate. And all subjects’ unique resting heart rate, oxygen consumption (VO_2), Metabolic equivalents (METs), and Energy expenditure measures

(EEm) were measured in a standing position for 3 minutes. After that, all participants put on the complex muscle support system and sufficient adaptation training was conducted for 5 minutes selecting the optimal electrical stimulation intensity for each subject. To measure energy efficiency, 6 minutes walk test (6MWT) was conducted for flat ground walking and stair climbing test was conducted for stair walking under three conditions. The first condition is not wearing the system(no suit), the second condition is wearing it but the power is turned off(slack), and the third condition is wearing it and the cable pulling method and FES electricity are on(dual). In order to minimize the influence of the precedence relationship, the order of the conditions and the two tests were randomized. In addition, sufficient rest time was provided for washing out between each condition and between the two tests.

Wearable complex muscle support system

Wearable complex muscle support system (Electronics and Telecommunications Research Institute, ETRI, Daejeon, Republic of Korea) was designed as a strategy to assist the elderly with walking. This system adopts and combines two biofeedback methods for walking assistance, one is an EMG-controlled FES and the other is a cable-driven method. EMG-controlled FES estimates the volitional EMG (vEMG) signal, which is a pure electromyography signal generated by voluntary contraction from EMG raw data which is contaminated by stimulation current. By the DESTD method[18, 19], the unnecessary noises such as FES artifact and M-wave were removed, and the remaining vEMG is utilized as a control intensity of FES stimulation. Therefore, the EMG-controlled FES system is suggested such that the FES intensity can be modulated proportional to the motion intention of user[20]. EMG-controlled FES consists of one FES channel and two EMG channel for one muscle and total four muscles (both sides of gastrocnemius and rectus femoris) are attached.The estimated vEMG is also utilized as a control input for tension force control algorithm of cable-driven system. The system can generate the active assistive force for plantar flexion of ankle joint, which is named Angel Suit – Ankle. Due to the gait pattern of the user can be estimated by the repetitive characteristics of vEMG, the assist time and peak force are modulated. Therefore, the cable-driven robot is designed to assist walking by keeping the tension in order to follow the human motion in idle stage, and providing a certain pattern of tension proportional to the motion intention of user at the required period while stance phase of walking.

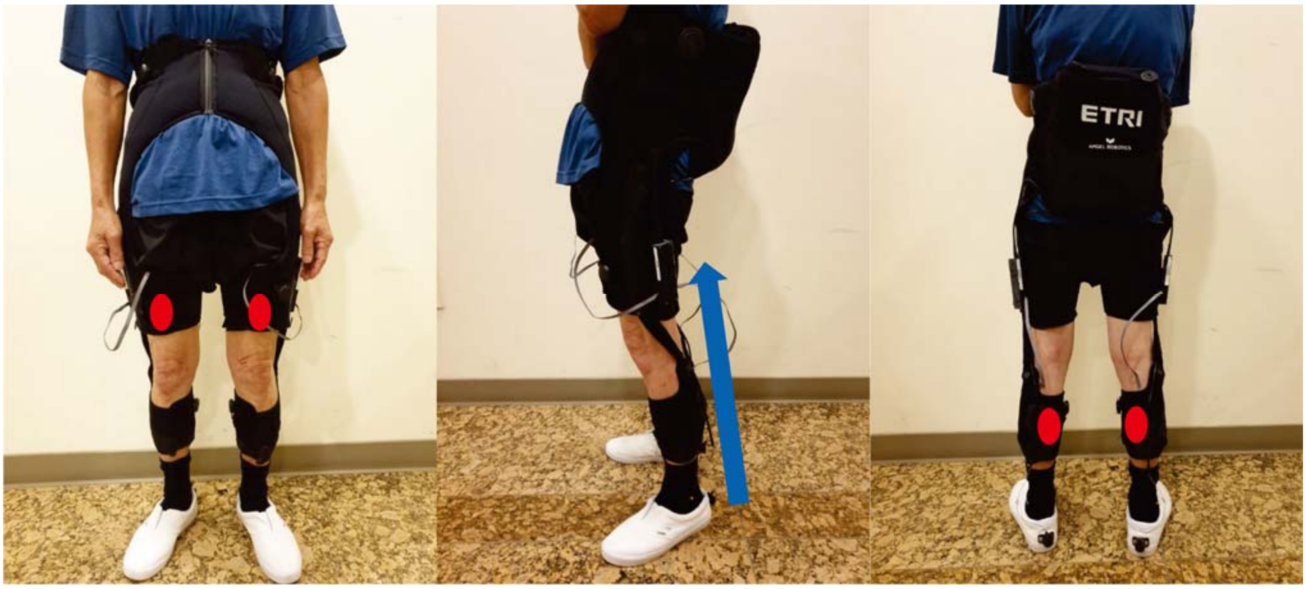


Figure 1. Wearable complex muscle support system
(Red point: EMG-controlled FES, Blue arrow: Cable pulling direction)

Outcome measure

Primary outcome

Cardiopulmonary metabolic energy cost

A K5(Cosmed, Italy) was used to measure VO_2, METs and EEm. To obtain the pure data value due to the task effect in 6MWT, the data value of the last one minute out of six minutes is used[21]. And in the stair climbing, to confirm pure oxygen consumption, metabolic equivalents and energy expenditure measures, statistical analysis was performed by subtracting each numerical value in a comfortable state evaluated at the beginning of the experiment from the value measured during task execution. To measure the heartrate, the average heartrate in a standing position for 3 minutes and data from the last minute were used as a baseline data and the average heartrate and maximum heartrate were measured in each condition using Polar H10 (Polar Electro Oy, Kempele, Finland)[22].

Secondary outcome

Functional evaluation

To evaluate functional outcome, we investigated the velocity during 6MWT and time required for stair climbing. To measure the walking speed over-ground, the speed was calculated by measuring the distance walked for 6 minutes at a high speed for 20m round-trip course. To measure the time taken to climb the stairs, the time taken to reach the third floor section using the stairs was measured using a stopwatch. All measurements were performed on 20 subjects in the same way in dual, slack and no suit condition.

Table 1. Characteristics of Participants (N=20)

Gender(male / female)	7 / 13
Age (year)	74.20 (3.25)
Height (cm)	160.92 (8.82)
Weight (kg)	63.30 (10.64)
Body mass index (kg/m^2)	24.38 (3.17)
Resting heartrate (beats/min)	70.85 (10.95)
Thigh circumference (cm)	51.60 (10.66)
Thigh length (cm)	79.38 (10.52)

Values are presented as number or mean(SD)

Statistical analysis

PASW statistics 18 (SPSS Inc., Quarry Bay, Hong Kong) was used for all statistical analysis. The Shapiro-wilk test was performed to confirm the normality of participants' characteristics. All data is expressed in mean (SD). A repeated measured ANOVA was used to compare the outcome between no suit, slack and dual condition. the statistical significance threshold was set at $P<.05$.

Results

The averages of the participants' general characteristics are shown in Table 1.

Primary outcome

In each condition, the average heart rate measured in the stair climbing test and the average heart rate and PCI value measured in the 6MWT are shown in Table 3 (Figure 2). Table 3 shows the average values for VO_2, METs and EEm which are other energy efficiency variables measured during stair climbing test and 6MWT (Figure 3). Between the no suit and slack

Table 2. Cardio Metabolic Energy Cost (N=20)

	No suit	**Slack**	**Dual**
Over-ground Average Heartrate (beats/min)	1.12 (0.2)	1.07 (0.21)	1.06 (0.21)
Over-ground Maximal Heartrate (beats/min)	44.43 (8.75)	49.23 (13.88)	49.16 (12.62)
PCI (beats/meter)	0.47 (0.15)	0.49 (0.18)	0.47 (0.16)
Stair Average Heartrate (beats/min)	100.7 (14.69)	100 (12.86)	100.7 (13.39)
Stair Maximal Heartrate (beats/min)	119.15 (16)	118.85 (15.03)	119.3 (16.26)

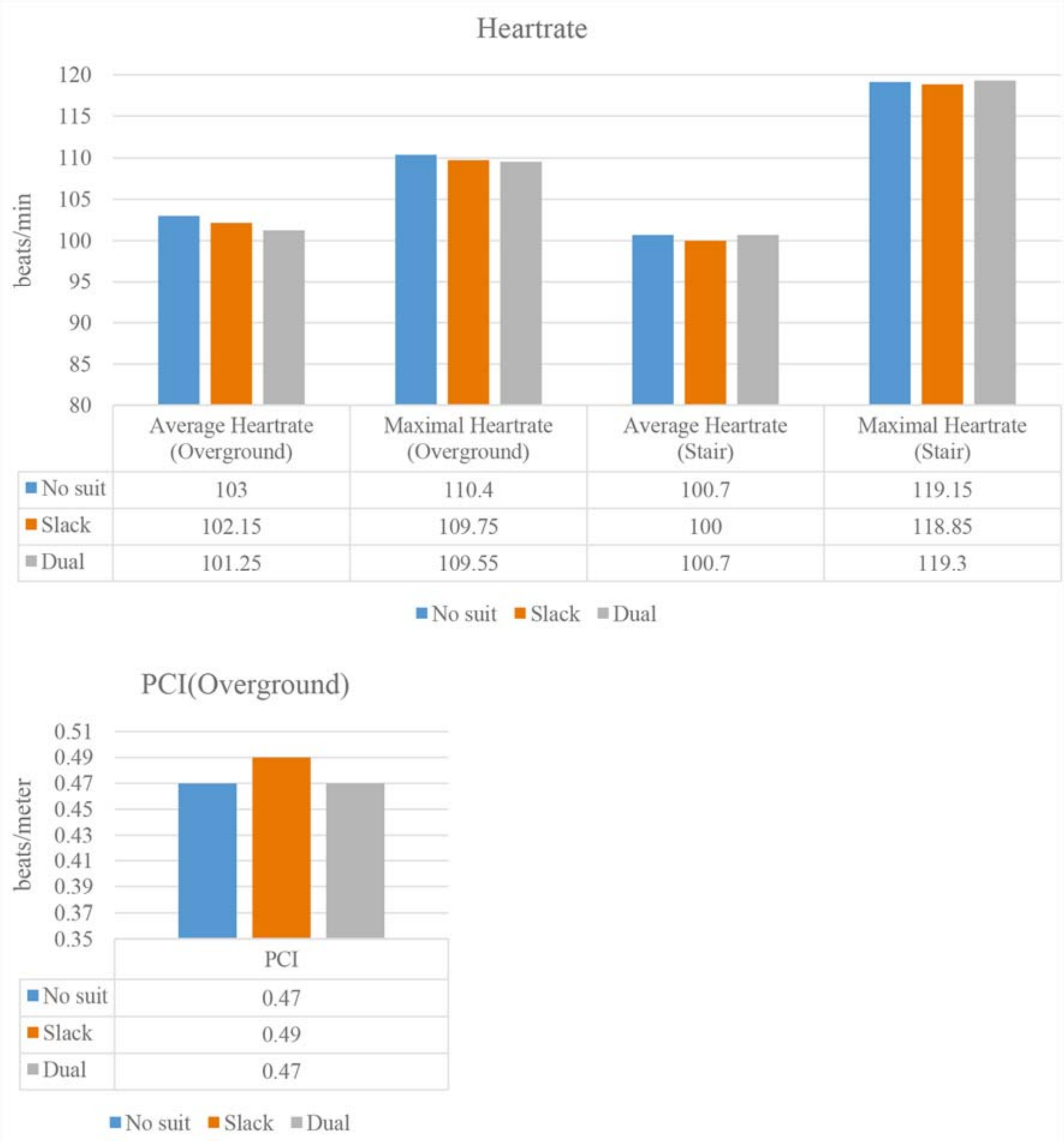
Abbreviation: PCI=Physiological Cost Index

Values are presented as mean (SD)

Table 3. Pulmonary Metabolic Energy Cost (N = 20)

	No suit	Slack	Dual
Over-ground VO_2 (ml/min/kg)	12.98* (4.3)	14.05* (3.37)	13.84 (3.9)
Over-ground METs	3.7* (1.23)	4.01* (0.96)	3.95 (1.11)
Over-groundEEm (kcal/min)	3.98* (1.23)	4.32* (0.96)	4.26 (1.11)
Stair VO_2 (ml/min/kg)	10.92 (2.26)	11.39* (2.26)	10.66* (2.51)
Stair METs	3.09* (0.69)	3.25* (0.65)	3.04* (0.72)
Stair EEm (kcal/min)	3.28* (0.67)	3.47* (0.66)	3.2* (0.77)

Abbreviation: VO_2 = Oxygen Consumption, METs = Metabolic Equivalents, EEm = Energy Expenditure Measures
Values are presented as mean (SD)
*: $p < 0.05$



	Average Heartrate (Overground)	Maximal Heartrate (Overground)	Average Heartrate (Stair)	Maximal Heartrate (Stair)
■ No suit	103	110.4	100.7	119.15
■ Slack	102.15	109.75	100	118.85
■ Dual	101.25	109.55	100.7	119.3

	PCI
■ No suit	0.47
■ Slack	0.49
■ Dual	0.47

Figure 2. Cardio Metabolic Energy Cost

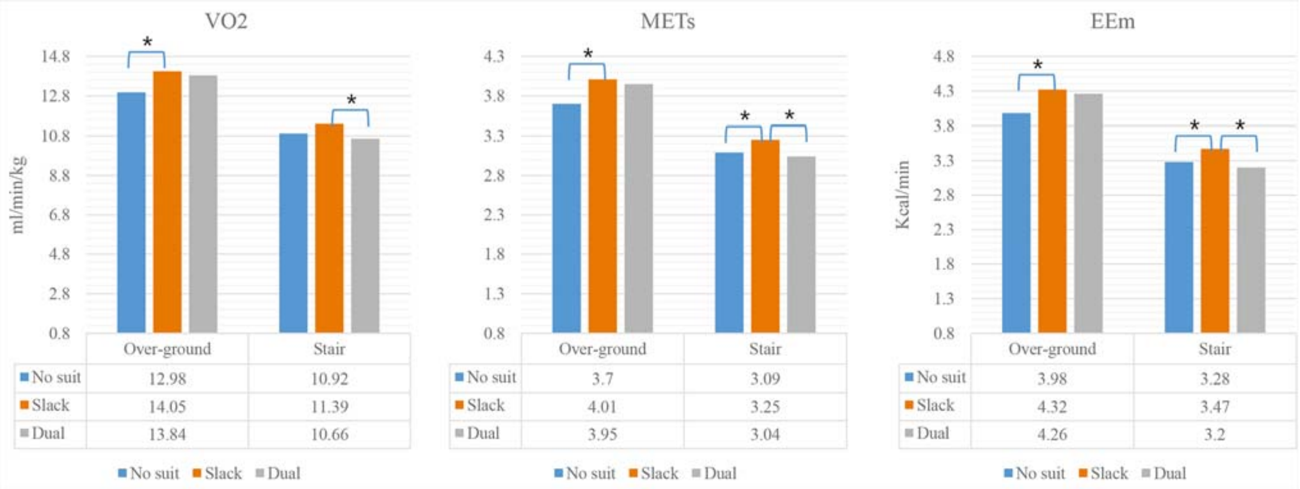


Figure 3. Cardio Metabolic Energy Cost

conditions, the results of VO_2, METs and EEm were statistically significantly different at 6MWT ($p < 0.05$). In the stair climbing test, VO_2 was significantly different between slack and dual condition ($p < 0.05$). And METs, EEm were significantly different between no suit and slack conditions, between slack and dual conditions ($p < 0.05$).

Secondary outcome

Table 4 shows the measured walking speed on flat ground during 6MWT and the time required for the evaluation of stair climbing for each of the three conditions. Compared to no suit condition, dual and slack condition were lower in both over-ground and stair climbing in terms of speed(Figure 4).

Table 4. Functional evaluation (N=20)

	No suit	Slack	Dual
Over-ground velocity (m/s)	1.12 (0.2)	1.07 (0.21)	1.06 (0.21)
Time required for stair climbing (sec)	44.43 (8.75)	49.23 (13.88)	49.16 (12.62)

Values are presented as mean (SD)

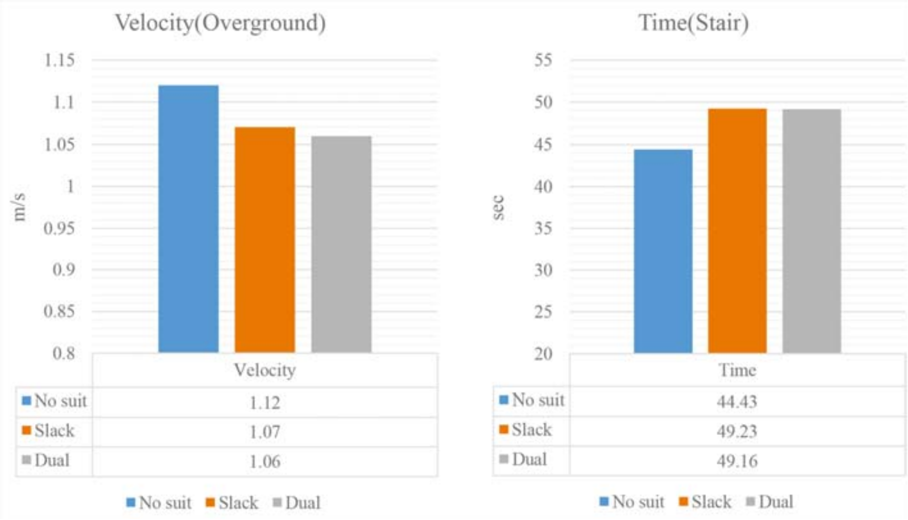


Figure 4. Functional evaluation

Discussion

The purpose of this study was to investigate the effect of the wearable complex muscle support system on cardiopulmonary metabolic efficiency in walking and stair climbing in the elderly. The results of this study revealed that the application of wearable complex muscle support system during climbing stairs for elderly is more effective than when not applied. Energy efficiency can be investigated by measuring cardiopulmonary capacity which consists of heart and lung capacity. Cardiopulmonary metabolic energy efficiency is being studied continuously because it is an important variable in daily life[23]. The dual condition was the lowest in both average and maximum heartrate when walking on over-ground. This is because in dual condition, assistance increased energy efficiency. But there was no significant change in heartrate variables in the three conditions at over-ground and stair climbing.

This result is presumed to be because the load was not sufficient to affect the heartrate of the 6 minute walk test and the stair climbing test. PCI means the physiological consumption index with the calculation formula as (average heart rate – resting heart rate) average speed(meter/min). In over-ground walking, the lower the physiological consumption index, the more economical walking. Over-ground walking in no suit condition and dual condition can be seen as more economical walking than slack condition.

There were significant differences in oxygen consumption, METs, EEm in both over-ground and stair climbing. There was a significant difference between no suit and slack in over-ground test, but there was no significant difference with dual condition. The reduction in oxygen consumption of no suit than slack is a result of the weight of thewearable complex muscle support system. According to previous study, as the weight of the wearable robot increases, the energy efficiency decreases[24].

The wearable complex muscle support system's weight is 3.8kg and this weight led to the use of oxygen as 1.07(ml/min/kg)more than the no suit condition in over-ground. Because the slack condition was simply worn without operating the robot, it was possible to confirm the rate of decrease in energy efficiency due to the weight of the robot. When checking the results in the dual condition, the condition in which the robot was operated, there was no significant difference from the slack condition in oxygen consumption. This means that even the robot works, it does not show

A significant effect on energy efficiency in over-ground was produced. METs and EEm also show energy efficiency as a result of methematical calculations based on oxygen consumption. VO_2, the amount of oxygen consumption, increases with more intense exercise, and METs is also the intensity of exercise that the person feels, and the stronger the exercise, the higher the level of METs[25].

Because the participants' motor function was good, it is necessary to apply the system to the elderly of gait problems in the future. Also, compared to the system's weight of 4kg including shoes and 3.8kg without shoes, the assist method is less powerful than other exoskeleton robots. In particular, if the user's muscle strength itself is bad, the FES electrical stimulation is reduced by the system algorithm, which lowers the energy efficiency. If the weight of the system reduced, a significant difference can be expected even when walking in over-ground.

However, in stair climbing test, the dual condition was significantly different when compared with the other conditions. It was judged that more assistance was provided by the system algorithm because it was a task with a higher intensity than at over-ground when walking on stairs. In the slack condition, it can be seen that the energy consumption rate and exercise intensity are increased due to the weight. Energy efficiency and exercise intensity were significantly improved in the dual condition than in the slack condition, and there was no significant difference compared to the no suit condition. If the burden of weight can be reduced in the future, it is judged that it will be helpful in high-intensity tasks such as stair climbing.

In the case of METs, in general, 3.0 or less is interpreted as light intensity, 3.0-5.9 as moderate intensity, and 6.0 or more as vigorous intensity[26]. The reason for the lower oxygen consumption and exercise intensity of stairs than in over-ground is that the stairs have a strong load but since walking on over-ground at a high speed for 6 minutes, it seems that the 6-minute walk has higher intensity and oxygen consumption in the last minute. This is because the analysis of variables in the 6 minutes walk test is done by the last 1-minute data.

In over-ground walking velocity, dual and slack condition were slow and no suit condition was able to achieve high speed because there was no weight and various auxiliary stimuli. In walking, tension of the triceps surae muscle is generated during the ankle rocker – forefoot rocker and the swing phase is started using the tension generated in the swing phase(27). The wearable complex muscle support system uses a method to induce swing by simply assisting knee flexion. It is expected that natural gait can be derived if a suspension device that can generate tension like a rubber band during an ankle rocker – forefoot rocker and an auxiliary force that presses against the ground during a forefoot rocker are added in the future.In terms of speed in stair climbing, since the cable driven method assists knee flexion, it was expected that the speed would increase in stair climbing rather than over-ground walking by supporting upward thrust rather than forward thrust.

However, in the absence of stimuli and weight, it seems that the user felt most comfortable and was able to move quickly in no suit condition. But there was no significant difference in velocity in over-ground and stair climbing.The limitations of this study are: 1. The number of samples is too small to generalize the results of this study. 2. The optimal FES stimulation frequency for each subject was not considered.

Conclusion

There was no effectiveness of electrical stimulation compared to no suit condition using the wearable complex muscle support system for elderly in walking over-ground and climbing stairs. And the weight (about 4kg) issue for the system appeared clearly. Solving the weight issue and the method of electrical stimulation(such as addition of appropriate stimulation to enhance ground reaction, etc.) should be approached to multiple angles. Therefore, in further studies, it is necessary to conduct clinical studies of appropriate for cases in which efficacy has been shown and to verify the positioning that requires electrical stimulation and cable pulling method assistance among seniors.

Conflict of interest

The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this paper.

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