Evaluation of four-wheel vehicle driven by lower limb with electric pedalling assistance for elderly people

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ABSTRACT

The idea of designing independent personalized mobility equipment for elderly is to improve the quality of life and improvised the care prevention system in the society. We proposed and designed a four-wheel type of electric power assistant for personal mobility in care prevention. The preliminary experiment was conducted consisted of twenty healthy elderly people (8 males and 12 female) recruited subjects to evaluate the performance of our mobile support equipment system. We examined the change of the physical workload with oxygen uptake amongst healthy subjects. The physical workload is recommended according to protocol suggested in exercise therapy. The purpose of our pilot study is to evaluate the relationship of elderly people specifically for physical workload with the oxygen uptake rate in the different tilted level of the surface route such as on a flat and 8% slope surface route. Although all of recruited subjects were able to safely travel on the flat surface route, yet three subjects interrupted the experiment because of their physical discomfort at 8% slope surface route. Maximum uptake of oxygen when running on the flat surface route with constant speed of 6 km/h travelled distance 1.2 km took durations of 12 minutes 30 seconds not indicated any significant difference in A mode and N mode. Our designed vehicle quantitatively presented the smooth traveling behaviour as possible

ISSN 1823- 5514, eISSN 2550-164X

Received for review: 2017-03-28
Accepted for publication: 2017-10-10
Published: 2018-04-15

with less physical workloads on the recruited subjects, even in the 8% slope surface route when using assisted force mode (A mode).Our mobility support equipment is beneficial as a daily outdoor support equipment for the elderly people who have deteriorated in gait function and people with motor impairment due to cerebrovascular disorder.

Keywords: *Personal mobility, transportation support, lower limb, motor impairment, physical load, exercise therapy*

Introduction

The physical deteriorates changes, especially at the lower limb part normally occur with aging can lead to personal mobility problems [1]-[3]. Mobility problems may be unsteadiness during walking, difficulty to stand up from a chair, or falls. Furthermore, common conditions in older people such as muscle weakness, joint problems, pain, disease, and neurological difficulties generally contribute to mobility problems. A crucial step in counter measure the problem with the technical approach to restore the functional impairment of the body which has arisen, utilization of the residual function, and assistive tools, thus the daily life can be go through as effective as possible [4].

There are many walking assistive devices such as wand, walker and wheelchair to support the daily mobility specifically for people with impairment at the lower limb function. They can select and use the suitable assistive tools matching with their degree of lower limb function disorder and their financial ability [5]-[6].

A walking stick or a walking aid is a tool to assist walking. However, the physical workload may be huge and in some cases, there is a risk of falling if walking for a quite long distance with the walking aid [6].

A wheelchair is a chair with wheels and usually used as a walking substitute tool by people who is difficult or impossible to walk due to illness, injury, or disability [10]-[14]. However, the wheelchair is a device that moves from one place to another without moving the lower limbs part. Movement of lower limbs in daily life activity plays an important role in maintaining lower limb function and our healthiness, thus it is not an optimal solution to select a wheelchair as personal mobility equipment [5].

In recent years, several wheelchairs, especially driven by foot have been developed and effective as a movement assistive tool for hemiplegic patients as well as for the device specifically to sustain the motor function [6]. However, these kind of devices actually designed assuming indoor use, and it is not suitable for outdoor usage like going out to the towns where there are different kind of the sloping surface of the streets.

In this study, we developed a novel four-wheel vehicle with electric assistance pedalling driven by the lower limbs. Our vehicle able to secure the safety of the user, and consumes a small physical workload to support the elderly and others who have deteriorated in walking function. Our system also capable of measuring the physical workload when traveling on a flat surface route and the roads with the inclines rate nearly 8% slanted degree for the elderly in the early and late aging. Besides, we also proposed the evaluation technique to describe changes in the levels of physical fitness measurement with estimation the maximum uptake of oxygen during the pedalling exercise (VO2max) in male and female, both young and old populations. Therefore, the measurement of the physical workload is an important indicator of physical fitness index to specify the physical strength [7]. Scientific researches already clarified as the total of physical activity increases, vascular conductivity also increases in generating energy for muscle contraction that create motion [8]-[9]. Since the generation of energy requires oxygen, the uptake of the oxygen into the body increases. Therefore, it is possible to evaluate the level of physiological workload as the exercise intensity proportionally increases in the oxygen uptake [15]-[17].

In this preliminary experiment, we examined the change of the physical workload with oxygen uptake of the healthy recruited subjects. The experimental protocol is according to the physical workload recommended in exercise therapy and validated the tasks executed by the recruited subjects, which capable of safely travelled as our evaluation interest on the personal mobility device aimed at the elderly people.

System Overview

Figure 1 demonstrates the four-wheel electric power pedalling assisted for personal mobility vehicle, which developed and used in our study. We developed this novel vehicle to support the outdoor mobility of the elderly who weakened in muscular strength due to aging, which led to walking ability decreased as well as lack of the movement sensation and instantaneous power. Thus, the elderly can safely and comfortably go outdoors using our developed vehicle without dependent on other people. The vehicle operates like a normal bicycle driving system where the user need to drive it with their lower limb foot. Unlike the conventional two-wheel drive bicycles, this vehicle does not wobble even if it starts and runs slowly. It also invented to prevent the risk of falling when it stops, and has a feature where the user can rest if they tired during riding.

Figure 1 Four wheel electric power pedalling assisted for personal mobility

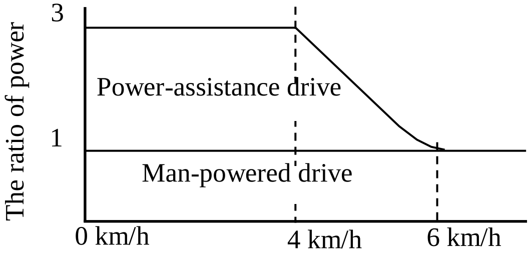


Figure 2 Control method of power assistance

The moving speed control of the vehicle based on the correlation method determined by the ratio of the pedalling force and the assisting force (assist ratio). The control system based on the standard electric wheelchair where the assist ratio tuned based on the standard criteria. In other words, in order to achieve the moving speed of 4 km/h from the departure, it is possible to boost up the pedalling force with double the assist force. Once the speed exceeds 4 km/h, the assist force gradually decreases until it reached zero with the constant moving speed of 6 km/h as illustrated in Figure 2.

There are three driving modes based on the assist force ratio can be selected according to the user's internal condition like motor function ability and outdoor environment. For example, when a user whose deteriorates in motor function chose a strong assist force, the user can still maintain the running speed as is he feels easier, even in unpredicted outdoor environments like as when climbing a steep slope route or when opposing the strong wind situation although the input of the pedalling force is weak. Moreover, our vehicle also has a potential as a training machine which using an Ergometer to change the running speed mode according to the comfortability of the user.

Mobility Experiment

Method of the experiments

The adjustment of the saddle height should be considered based on the nerve or physiological effect on the recruited subject‘s body posture as well as the mechanical effect on the joint during the pedalling movement training. Adjustment of lowering the saddle height will affect the pedalling movement achieved where the knee joint in a more flexion posture expected to increase the workload on the knee joint. We adjusted the saddle height to prevent complications, thus the body shape and posture of each recruited subject feel comfortable during the experiment. As presented in Figure 3 and Table 1, the height of the saddle needs an adjustment to ensure the knee joint of the subject was 60° or more.

The recruited subject requisite to fulfil two requirements of our preliminary study where they need to run on a flat surface route with a distance of 1.22 km at a speed of 6 km/h and 8% slope surface route with a distance of 120 m at a speed of 4 km/h. The running duration of the flat surface route was 12 minutes 30 seconds, whereas the 8% slope surface route took the running duration of 1 minute 50 seconds. During the pedalling movement training, the recruited subjects also verbally instructed to sustain a constant speed during the running. Under these conditions, the experiments carried out on two types of setup. Firstly, assisted force mode as a mode in which double the assist force added to a pedal rotational force hereinafter referred to A mode. Then, without assist force mode hereinafter referred to N mode. Moreover, the position of the handlebar was adjusted to sustain the trunk angle became constant, thus the subject could hold the same position of the handlebar under any condition during the experiment.

Flat surface route driving trials conducted at physically handicapped driving training site in Hyogo Prefectural General Rehabilitation Centre. Running trials carried out outside of the driving training site course with the small effect of the slope surface route. The distance of a complete lap is 245 m as illustrated in Figure 4.

The slope surface route running trial carried out on the evacuation route as demonstrated in Figure 5 and Figure 6 with facility the 8% longitudinal slope at the Sports Exchange Centre (Gymnasium) of Hyogo Prefectural General Rehabilitation Centre.

In both of the trials, the steering wheel type electric wheelchair (SUZUKI LT 4 F) was led in front of the subject to sustain the constant moving speed, and the subject orally instructed to follow the leading vehicle as demonstrated in Figure 7.

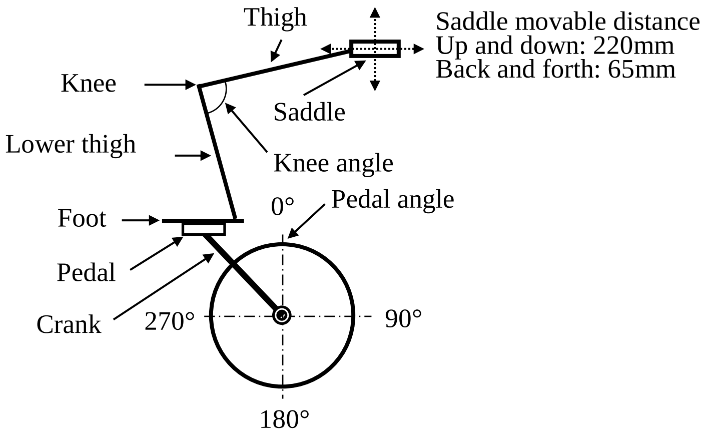


Figure 3 Saddle height adjustment based on the knee angle when rowing on a pedal

Table 1 Relationship of pedal angle and knees angle joint adjustment of the subject during seating position

Pedal angle	Left knee angle	Right knee angle
0°	60°	90°
90°	60°	90°
180°	90°	60°
270°	90°	60°

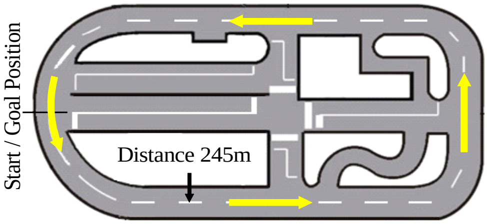


Figure 4 Overview of flat surface route

Figure 5 Overview of slope surface route

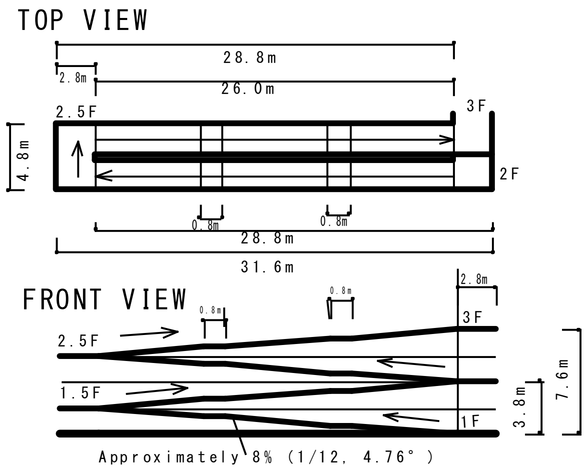


Figure 6 Specification profile of slope surface route course

(a) Flat surface route (b) Slope surface route

Figure 7 Overview image of experiment set

Recruited subjects

We obtained approval from our institute ethics review board before conducted any trials in our study. Furthermore, we explained entire contents of the trial to recruit subjects and obtained their consent.

The elderly subjects in our pilot study involved of 8 men and 12 women (average age 73.6 ± 6.3 years old, average weight 56.4 ± 10.4 kg, average height 155.7 ± 8.7 cm) without any medical history.

Oxygen uptake Measurement

In this experiment, measurement of oxygen uptake was carried out using a portable respiratory metabolism measuring apparatus (MedGraphics® VO2000). The measurement accuracy of oxygen analyzer within ± 0.01%, average oxygen uptake measured in every 10 seconds. Data on oxygen uptake also collected during resting for 5 minutes before and after the running experiments for each route course trial.

Experimental results

The data of the experimental results of 20 recruited subjects participated in this experiment where we secured the safety of the subjects as they performed the running tasks in both routes as revealed in Table 2. All recruited subjects accomplished both A mode and N mode of the flat surface route.

In the A mode of the slope surface route, 19 subjects were able to complete the running course. However, due to the physical discomfort, subject H interrupted the experiment after running on 60 meters.

Thus, in N mode of the slope surface route, subject H discontinued the running course due to the reason of the interruption in the A mode running. Subject E has withdrawn the experiment after traveling 8 m and subject I halted after traveling 90 m. However, another 17 recruited subjects were accomplished to complete the running course, even without of the assistance mode.

We analysed the running speed and the VO_2 data to quantitatively evaluate the running movement workload. In this paper, we only discussed and explained in detail the behaviour and characteristic as representative data for one recruited subject, which exposed the running speed, and the data of VO_2 during both surface routes of each assistance mode and non-assistance mode condition setup.

Figure 8 illustrates the moving speed of the recruited subjects when traveling in both types of surface route at the car driving training site. The moving speed recorded and measured at the time of the subjects followed the steering wheel-type electric wheelchair led in front of the subjects. At flat surface route, the recorded and measured data demonstrated a constant speed of 6 km/h. Besides, the recorded and measured data also illustrated the constant moving speed of 4 km/h at the 8% slope surface route. In both cases, we measured the speed of the wheelchair leading was almost at the same moving speed.

Table 2 Experimental result of recruited subjects'

Subject	Sex	Age	Flat Surface Route		Slope Surface Route	
			Non -assistance (time)	Assistance (time)	Non -assistance (time)	Assistance (time)
A	F	70	12:23	12:21	2:08	2:03
B	M	87	12:22	12:20	2:03	2:01
D	M	72	12:20	12:19	1:52	1:51
E	F	75	12:25	12:28	－(8m)	12:05
F	F	75	12:28	12:27	2:01	2:59
G	M	70	12:29	12:28	2:07	2:02
H	F	84	12:38	12:34	－	－(60m)
I	F	75	12:30	12:29	－(90m)	2:05
J	F	79	12:26	12:25	1:58	1:56
K	F	68	12:27	12:27	1:55	1:52
L	F	66	12:25	12:23	1:53	1:51
M	F	75	12:23	12:22	1:55	1:54
N	F	67	12:29	12:28	1:57	1:55
O	M	67	12:28	12:26	1:55	1:53
P	M	71	12:27	12:26	1:50	1:49
Q	F	65	12:28	12:27	1:52	1:51
R	F	66	12:27	12:27	1:49	1:48
S	M	82	12:29	12:28	1:53	1:52
T	M	80	12:22	12:22	1:48	1:47
U	M	79	12:23	12:22	1:47	1:47

Figure 9 demonstrates the oxygen intake (Oxygen uptake hereinafter referred to VO_2) by the recruited subjects when traveling on a flat surface route. The A mode behaviour as illustrated in Figure 9 (a), and the N mode behaviour is demonstrated in Figure 9 (b). The VO_2 clearly indicated that the physical workload of the subjects with the assistance mode and non-assistance mode at rest condition was around 0.3 (ml / 10 sec), it began to run at the same time and increased to 0.8 (ml / 10 sec), then it showed almost constant VO_2 until the end of the running region. The time taken of VO_2 during the rest condition almost same if compared after running.

Figure 10 illustrates VO_2 at 8% slope surface route during running at constant speed of 4 km/h. The A mode behaviour of the a recruited subject as illustrated in Figure 10 (a), and N mode behaviour as shown in Figure 10 (b).

In A mode, VO_2 gradually increases in the duration of 40 seconds with the mileage of about 45 m. Later, VO_2 increased about twice from the rest condition, and then it demonstrated as increased about the same level as during the running on a flat surface route. The time taken of VO_2 for at rest is almost the same as during running on a flat surface route.

In N mode, VO_2 proportionate and rapidly increased from the start of running and continued to increase until it finished 120 m. VO_2 at the time of complete running increased more than 3 times compared to the VO_2 at rest. The time taken to recover the VO_2 at rest is almost doubled in A mode.

Table 3 shows the calculation results of the average value and the standard deviation of VO_2 during the flat surface route and the slope surface route of 17 recruited subjects, and Figure 11 illustrates a graph of this calculation result.

The average VO_2 standard deviation at rest is 1.37 ± 0.4 (l / min) as exposed in Table 3. VO_2 when running on a flat surface route with constant velocity of 6 km/h in A mode is 2.96 ± 0.7 (l / min), whereas VO_2 in N mode is 3.25 ± 0.6 (l / min). The average value in N mode is slightly larger value than the A mode.

In the case of slope surface route, it is clearly indicated that VO_2 in N mode significantly increased. VO_2 has increased about 1.6 times than the A mode.

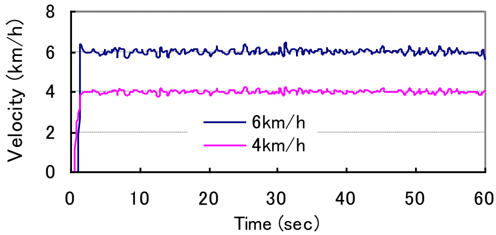
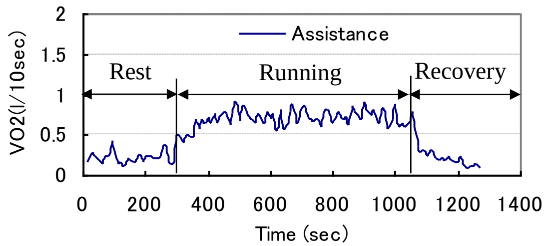
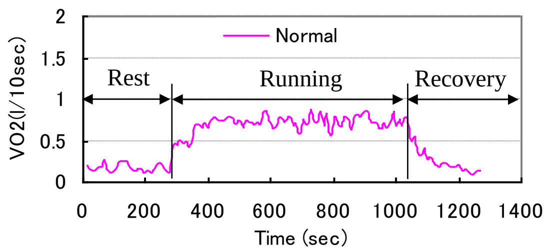


Fig. 8 Running velocity of flat (6km/h) and slope (4km/h) surface route



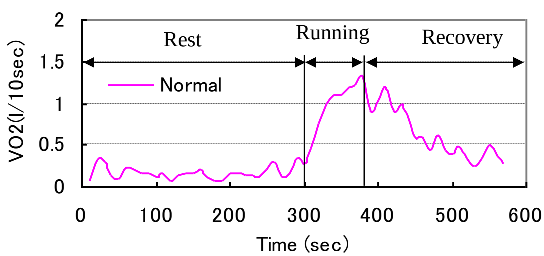
(a) Assistance mode



(b) Normal (non-assistance) mode

Figure 9 Oxygen uptake on flat surface route

(a) Assistance mode



(b) Normal (non-assistance) mode

Figure 10 Oxygen uptake on slope surface route

Table 3 Oxygen uptake data of subjects (n=17)

Experimental condition		Oxygen uptake (VO_2)
Rest		1.37±0.4
Flat surface Route	Assistance (A mode)	2.96±0.7
	Normal (N mode)	3.25±0.6
Slope surface Route	Assistance (A mode)	2.72±0.4
	Normal (N mode)	4.31±0.6

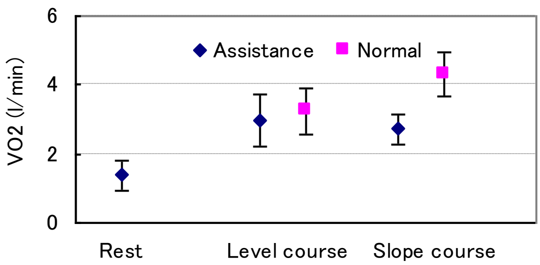


Figure 11 Oxygen uptake on rest, flat and slope surface route course

Discussion

Based on the data collection VO_2, we observed the physical workload of healthy elderly people aged between 65 to 87 years old involved of male and female using our developed mobile assistance vehicle on a flat surface route and 8% slope surface route.

The average value and standard deviation of VO2 during rest condition of 17 recruited subjects as presented in Table 3 were 1.37 ± 0.4 (l/min), however VO_2 when running on a flat surface route at constant velocity of 6 km/h in A mode was 2.96 ± 0.7 (l/min), and VO_2 in the N mode was 3.25 ± 0.6 (l/min). On the flat surface route, although there is a slight difference in the average value of VO_2 between A mode and N mode, there is no significant difference with risk rate about 5%.

More precise quantitative data on VO_2 can obtained by included the experiment conditions with constant exercise intensity, especially while running experiment of 8% uniform slope at a constant speed of 4 km/h [9].

In the 8% slope surface route experiment, VO_2 gradually increased in A mode during the start of running until accomplished a distance of 45m, and it doubled from the rest condition and showed a tendency to gradually increase afterward as illustrated in Figure 10 (a). We considered that the pedal revolution per unit distance is 66% when running on a flat surface route at constant speed of 6 km/h. From the experiments, we recognized that the external disturbance factor is more influenced the increased in VO_2 than on the internal body workload [10]. Running at a constant speed with constant exercise intensity produced a constant load, thus VO_2 exhibited a continuous and linear increase trend [11] until it reached the stable range.

Besides, the VO_2 continues to increase linearly in the N mode until it finished the mileage of 120m as illustrated in Figure 10 (b) and finally the VO_2 has increased triple of the rest time. When traveling at 8% slope surface route (about 4.5°) with our developed vehicle, the physical workload reaches a very hard level if there is no assisting force. In the case of elderly people or people with cardiovascular disease, it is not necessary to involve in the experiments due to the safety point of view [7].

Since the slope surface route running with the electric assist force is the same workload as running on a flat surface route, thus it will be a low-intensity aerobic exercise beneficial during the both experiments [12]. Aerobic exercise training has strong grounds for maintaining and improving health as well as improving cardiovascular disease and walking ability of cerebrovascular disorder [13-14], and a suitable training method to improve aerobic ability [15-16].

It is necessary to decide type of exercise, exercise intensity, frequency and duration of the training specifically suitable for the individual based on their physiological for instance, physical exercise and the training exercise recommended to the elderly and those with cardiovascular disease [17]. A low intensity exercise load of about 40% of the physical workload used VO_2 and heart rate is appropriate exercise intensity, especially in high risk exercise for people such as a patient who has cardiovascular disease, low physicality and frailty in elderly people [12].

The mobile support equipment proposed in this re-search objectively demonstrated that during both experiments of flat and 8% slope surface route, the physical workload of the subjects was small and could run smoothly as possible. Furthermore, it seems to be beneficial as a daily use outdoor support tool for elderly people whose deteriorated in walking function and people with the motor impairment disorder because of cerebrovascular disorders. Moreover, during outdoor activities, it becomes a sufficient exercise for the lower limb, especially legs and it can contribute to maintain and improve the physical function.

Conclusions

In this study, we proposed four wheel vehicle driven by upper limb with electric pedalling assistance to support outdoor mobility of the elderly as well as patients with motor impairment disorder that can move their legs but their walking ability became difficult due to a decline in motor function. We also measured and analysed the oxygen uptake behaviour during mobility at the flat and 8% slope surface route as the evaluation scale of the physical workload. We summarized the results obtained as mentioned below.

1) Although all of recruited subjects were able to safely travel on the flat surface route, yet three subjects interrupted the experiment because of their physical discomfort at 8% slope surface route.
2) VO_2 when running on the flat surface route with constant speed of 6 km/h travelled distance 1.2 km took durations of 12 minutes 30 seconds not indicated any significant difference in A mode and N mode.
3) Our developed personal mobility assistive vehicle quantitatively presented the smooth traveling behaviour as possible with less physical workloads on the recruited subjects, even in the 8% slope surface route when using assisted force mode (A mode).
4) Our mobility support equipment is beneficial as a daily outdoor support equipment for the elderly people who have deteriorated in gait function and people with motor impairment due to cerebrovascular disorder. Moreover, the outdoor activities become a moderate exercise of the legs to maintain and improve the physical function.

Acknowledgement

The authors would like to express deep gratitude to the experts who cooperated in promoting this research and deeply appreciate the cooperation of Kawamura Co., Ltd. in the development of prototype for experimental equipment.

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