Design and Evaluation of an Amplified Walking System for Elderly People

T. Ando, M. Nihei, T. Inoue, M. G. Fujie

Abstract — **The Tread-Walk, developed based on the needs of elderly people, is a vehicle designed to achieve mobility, maintain bodily function, and give the appearance of walking. In this paper, the Tread-Walk was designed taking the body size and characteristics of elderly people into consideration to determine the specification. Subsequently, the risks generated in driving the Tread-Walk were analyzed and actions to counter the risk were implemented. Finally, the test driving was conducted by healthy young and elderly subjects. Based on the gait analysis, it emerged that the gait on the Tread-Walk proceeded smoothly, like natural walking and based on the test driving, the three required functions had been met, as well as the universal specification and required functions having been fulfilled to some extent.**

I. Introduction

Of all advanced counties, Japan has the most aged society (21.5% of the total population), meaning the importance of support systems for elderly Japanese people will increase in future. To support the mobility activities of the elderly, the following methods are employed: improving physical ability by training or using power assist devices [1], [2], reducing loads by sustaining their weight [3], and expanding barrier-free [4]. As stated above, there are many intelligent robots capable of understanding human intentions. However, it is difficult to meet the needs of elderly people merely by facilitating movement and mobility alone. We have thus been developing a new walking-aid system called "Tread-Walk (TW)," as shown in Fig. 1. The initial phase of the development involved proving the concept that the system enables elderly people to move about comfortably on their own, without stressing their physical condition or health [5]. The second phase focused on a DC motor that controls the belt velocity by sensing the walking motion and adjusting the belt speed to match that of the user as he or she walks naturally on the belt [6]. We later developed a second DC motor system that controls the velocity of the Tread-Walk driving wheel, so that it is amplified by a predetermined factor in relation to

Fig. 1 Tread-Walk (TW-1)

the walking speed of the user [7].

In this paper, we focus both on the further design of the Tread-Walk, which was based on the bodily features of elderly people, and on the evaluations of the Tread-Walk, which involved both young and elderly subjects in developing a highly safe and easily maneuverable Tread-Walk system for elderly people. This paper is composed of the following sections:

Section 2 shows the concept and mechanism of the Tread-Walk, while Section 3 shows the design method based on the characteristics of body size and shape and so on. In addition, we extrapolated the risks of Tread-Walk. In Section 4 meanwhile, two experiments are conducted to analyze the gait on Tread-Walk and evaluate the realization of the required functions.

II. Tread-Walk System

A. Concept of the Tread-Walk

There is a psychological dilemma associated with a loss of physical independence. Many people do not want to be stigmatized by having to use canes, wheelchairs, or other equipment that makes them appear disabled. One of the most challenging problems is that the equipment decreases lower limb mobility, that is, restricts the distance a person can walk unassisted. Here we describe a hybrid mobility assistance device to address this issue. In the present study, the generation process of the psychological conflict obtained from qualitative data was revealed by modelling details and taking the movement, function and appearance of the body into consideration. Based on the model we have proposed and developed, a new mobility aid, "Tread-Walk," meets the following three requirements: "maintaining body function", "extending mobility activities", and "maintaining a natural walking appearance" [8]. A new concept of Tread-Walk is effective in reducing the resistance to mobility-aid machines. Here, the targeted individuals are those with the ability to walk unaided, although slowly

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B. Mechanism of the Tread-Walk

The Tread-Walk device, as shown in Fig. 2, is a four-wheeled vehicle that permits the user to walk naturally while a servo motor amplifies the normal walking speed of the user. Its main components are a treadmill and two front driving wheels and sensors in the treadmill detect the acceleration/deceleration forces applied to the surface while walking, from which signals control the rotational speed of the driving wheel motors. Computer software also monitors the walking pattern, as measured by the treadmill motor load, and the steering control detects the angle of the steering wheel and controls the speed ratio of the left and right wheels. The specification of a prototype is shown in Table 1.

Figure 3 shows the system flow of the functional overview of the treadmill and driving sections. The treadmill motor actuates the treadmill belt and acts as a sensor device at the same time. The entire mobility aid drive operates as follows:

1) The kicking force of the user rotates the treadmill belt.

2) The rotation force is directed to the shaft, and the load current is detected as the kicking and braking forces while walking.

3) An increase or decrease in the rotation speed is determined in the same manner as the kicking or braking force, based on the signal of the current load, which is derived by a computer program.

4) The velocity of the Tread-Walk is increased by driving motors.

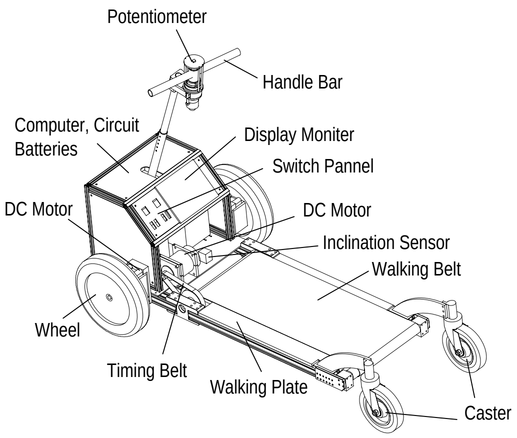


Fig. 2 TW-1 component

Table 1 The specifications of the prototype

Driving Components	**Size**	1520×760×1120mm
	Weight	55kg (without battery)
	System	Front-wheel drive (DC Motor×2), Rear caster
	Driving speed	6km/h (Max.)
Steering and Walking Components	**Size (walking interface)**	675×340mm
	Height	140mm
	System	Belt speed control (DC Motor)
	Belt speed	3km/h (Max.)
	Height of handle bar	850mm±50mm
	Handle angle	-45 ～45 deg

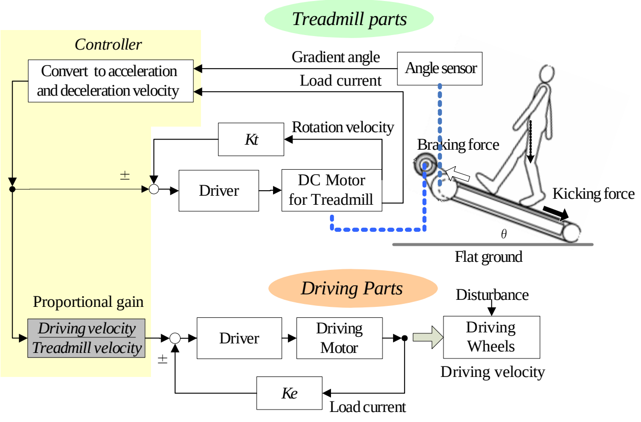


Fig. 3 A diagram of Tread-Walk system

III. Design of the Tread-Walk for Elderly Persons

A. Requested specifications

1) Environmental requirements

The Tread-Walk is envisioned to be used for short-distance outdoor rides. The specification of the Tread-Walk is based on that of an electric-motor-driven wheelchair with manual steering, because these two vehicles were used in the same area. Namely, the size and performance of the Tread-Walk conformed to JIS T9203 (Wheelchairs). Additionally, as for the outdoor steps and slope, the radius of the driving wheels and the vehicle structure were determined with the JIS T9203 hill-climbing test taken into consideration (Climbing the 10 (deg) slope), slope driving test (Driving the sigmate course with a 6 (deg) angle of gradient) and the step hurdling test (Hurdling 25 (mm) without a running start, and 40 (mm) with a running start 500(mm) before the step).

The usage environment was set as follows:

a) A large open space in- or outdoors (private property and public roads where allowed)

b) Maximum height of the step: 300 (mm) and maximum angle of the gradient: ±8 (deg) with minimal undulation

c) Asphalt or paved load

However, the size of the Tread-Walk was determined with consideration of the information in databases such as the Human Body Properties Database [9] – [12] to determine the characteristics of human movement and body size.

2) Physical requirements

(i) Vehicle driving section

The specifications of the driving wheel are significantly dependent on the usage environment, with the following items considered in the current study:

a) Space for the user to mount and dismount the vehicle easily

b) Arrangement of the driving wheel to bring the rotational center of the Tread-Walk close to that of the human trunk

c) Load capacity for elderly people

d) Long time and distance usage

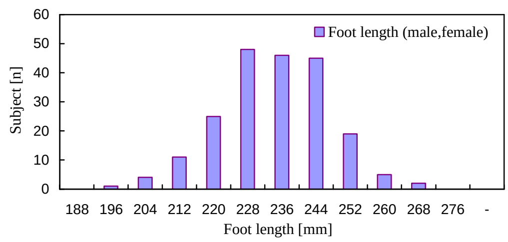


Fig. 4 Foot length

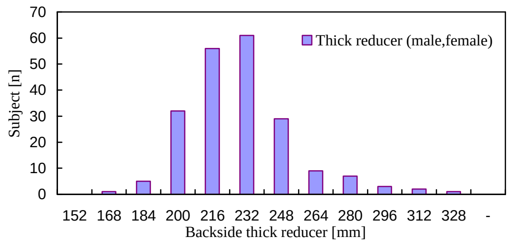


Fig. 5 Backside thick reducer

a) Space to mount and dismount l_{go}: The foot length and backside thick length were selected as the basis of the space in which to mount and dismount the vehicle, while Figs. 4 and 5 show the statistical data concerning the distribution of the foot and backside thick lengths. The space for users to mount and dismount the Tread-Walk easily was set at 300 (mm).

b) Arrangement of the wheel: The behavior of the vehicle is determined by the position of the driving wheel. In this study, it is expected to realize similar rotational radius with that in human rotation, because the posture on the Tread-Walk is similar to that of human walking. The driving wheels need to be arranged at the midpoint of the vehicle (mid-wheel driving system), so that the rotational center of the vehicle matches that of the trunk. However, as shown in Fig. 6, the mid-wheel driving system lacks sufficient space, l_{go}. Therefore, the front driving wheels and rear caster wheel were set to bring the rotational center of the vehicle in front of that of the gravity center of a human.

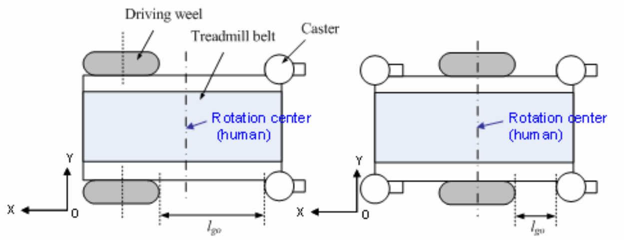
c) Load capacity W_h: The average weight of Japanese elderly people is 61 kg for males and 55 kg for females respectively, similar to that of normal healthy people. The load capacity is set as 80 (kg), because 80 (kg) is often used as the basis for load capacity in designing and testing vehicles.

d) Continuous usage time: The lead storage battery, which was used in the general electric wheelchair and chair, was selected for continuous use for 15 (km) or 4 hours.

(ii) Steering parts (handle)

There are certain methods used to control the vehicle, such as a joystick, lever, directional switch and handle. A rotational handle whose center is a rotational center was selected, because it is easy to visually understand the relation between the rotational angle of the vehicle and the handle angle.

a) Handle length l_{hd}: Considering the distances between the left and right acrominon of elderly males and females, l_{hd} is 440 (mm), to which 400 (mm) is added, the maximum of the average distance, to 20 (mm), representing the right



(a) Front wheels and platform space (b) Middle wheels and platform space

Fig. 6 Position of the driving wheels

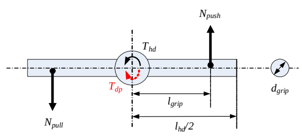


Fig. 7 Grip position and handle torque

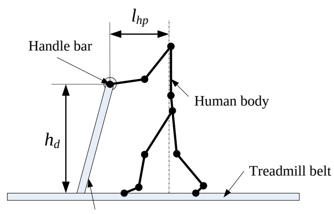


Fig. 8 Handle height and standing position

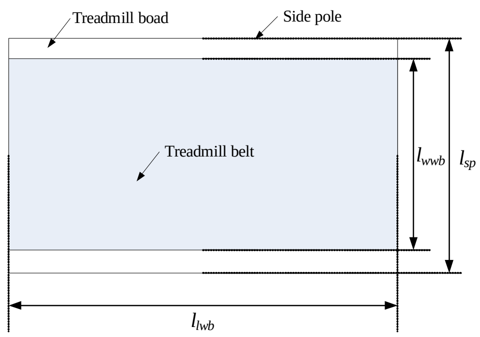


Fig. 9 Treadmill board and belt size

and left margins. Additionally, the handle length was designed to be within the width of the walking belt, in order not to come into contact with the external surroundings and other humans.

b) Handle radius d_{grip}: Considering the test to grip the cylindrical column [10], the maximum radius, d_{grip} shown in Fig. 7, of the cylindrical column is less than 40 (mm).

c) The Pushing handle force N_{push} and Pulling handle force N_{pull} : The force required to pull the handle exceeds that required to push it at a height of 0.8 (m) ~ 1.0 (m), while the maximum pulling force is 103.5 (N) [10]. In the Tread-Walk system, a variable damper was arranged at the rotational center of the handle to ensure safety and steady control. In case the maximum force at 160 (mm) from the supporting point of the handle was 103.5 (N), a torque of 16.6 (Nm) is generated, meaning a swing damper (Torque adjustability: 0 (Nm) ~ 8 (Nm), Maximum angle: More than 90 (deg)) needed to be selected.

d) Handle height h_d: Fig. 8 shows the position relation between the treadmill and human from the sagittal plane perspective. The distance from the handle to the human trunk, l_{hp}, is about 350 (mm), while the handle height is set at a level at which it is easiest for the user to push and pull the handle. The handle height, h_d, is 950 ± 50 (mm) from the walking surface, using a retractable structure to match the differences in the individual property.

Table 2 Risk analysis of the mobility aid, Tread-Walk

Situation	Danger source and condition	Risk estimation	Essential safety design	Action in TW
User and TW	Stumbling in mounting and dismounting TW	Injury	Lowering height to step over	Lowering the height of the walking surface
	Stumbling or falling down on walking	Injury	Safety control of the walking belt / Emergency stop brake	Control of the walking belt / Stop switch
	Body shifting with sudden start and stop	Injury	Safety control of the walking belt / velocity limit	Control of the walking belt / Limitation of walking and vehicle velocity
	Bumping to handle	Injury	Safety control of the walk velocity and vehicle velocity	Limitation of ratio vehicle velocity to walking velocity
	Falling down due to vehicle tilt	Injury	Emergency stop brake	(No consideration of rough road)
TW and Third person	Contact with a third party	Injury	Emergency stop device / blockage sensing / Velocity limit / Rounding projection	Stop switch / Soft cover
	Compressing third person	Injury	Velocity limit / weight saving	Velocity limitation / Weight saving
	Electrification	Injury / death	Low voltage operation	(No consideration)
	Vehicle moving and stopping	Injury	Solenoid brake	Setting solenoid brake
TW and External environ-ment	Short, heating and ignition by rain or snow	Injury	Waterproof	(No consideration in case of rain)
	Failure or breakage of mechanical parts on a rough road	Injury	Dustproof and vibration-proof	(No consideration of rough road)

(iii) Treadmill belt part

As shown in Fig. 9, the size of the belt and walking board and the height of the walking surface were determined to fix the specification of the treadmill belt part. These items were determined based on the following conditions:

a) Belt length to stop the foot falling from the belt
b) Belt width to retain a comfortable stride
c) Height of walking surface to avoid stumbling when stepping over
d) Height of the bottom part of the walking surface to avoid coming into contact with the floor at the steps.

a), b) Belt size l_{lwb}, l_{wwb}, l_{sp}: The length of the walking belt was based on the free walking stride of elderly people [10]. The stride of individuals aged 60 – 80 years was about 600 – 680 (mm) in males and 560 – 650 (mm) in females. Therefore, the maximum length was about 680 (mm) to minimize the size of the Tread-Walk. On the other hand, the width of the belt is longer than 300 (mm), which is an additional 200(mm), namely twice the step width of 100 (mm), the foot width, and shorter than 400 (mm), which is the average distance between the left and right acrominon. Additionally, the maximum belt velocity was set as 3.0 (km/h).

c) Height of the walking surface h_{wb}: The height of the walking surface was designed to take the position of the wheel into a consideration and a height sufficient to avoid any contact with the floor on the step. The distance from the ground to the center of the shaft was 158 (mm), because the tire radius of the driving wheel was 317 (mm), meaning the maximum height of the walking surface was 158 (mm).

d) Size of the walking board: The length of the walking board was about 680 (mm), because it depended on the length of the belt. Additionally, the width of the walking board, l_{sp}, was determined as a distance equivalent to the width of side columns added to that of the belt.

B. Consideration of the minimized risk

1) Characteristics of the new device (Tread-Walk)

The characteristic of the Tread-Walk is a robot that supports the mobility of elderly people out of doors. Therefore, the usage scenario is an elderly person using Tread-Walk alone. Additionally, actions such as avoiding the false operation of the handle, falling of the Tread-Walk device and so on are important. Moreover, the risk of accidents and other people and objects in the external environment becoming potential risks needs to be considered.

2) Envisioned risk

Table 2 shows the analysis of risks generated during the use of Tread-Walk and countermeasures taken. The situations were divided into three types; the User and the Tread-Walk, Tread-Walk and a Third person, and Tread-Walk and the External environment. According to these categories, the danger source and condition were isolated and their risks determined. Risk countermeasures were then proposed as part of the essential safety design. However, actions which could be realized were implemented because the Tread-Walk developed in this study was a functional prototype Tread-Walk model.

IV. Evaluation of the Tread-Walk System

A. Test drive to confirm the movement (in a healthy young subject)

It was objectively confirmed by a user using a video whether the lower limb movement in the walking on the Tread-Walk was natural. The subject was a healthy female in her 30s, who received a detailed account of the experimental objectives. In addition, we explained that she was entitled to stop the experiment whenever desired and obtained her consent. Furthermore, she practiced walking on the belt and driving the Tread-Walk in advance of the test to get used to controlling the Tread-Walk.

1) Double stance phase 2) Push off [L] 3) Foot off [L] 4) Stance phase [R] 5) Heel contact [L]

Fig. 10 The gait pattern during walking and driving on the Tread-Walk

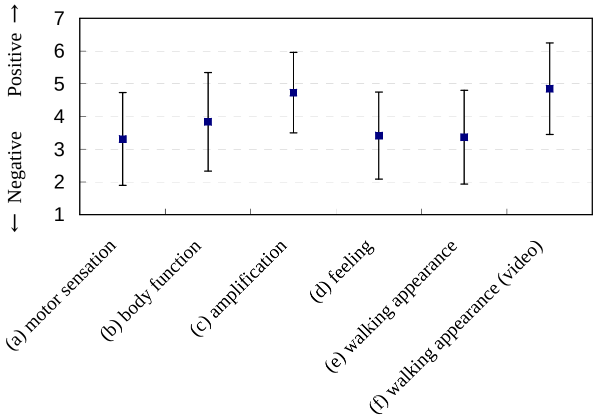


Fig. 11 Driving test and evaluation, subjects (healthy and young)

Table 3 Physical profile of healthy older subjects

Subject	Sex, Age	Height in cm	Weight in kg
A	Male, 63	170	62
B	Male, 65	171	55
C	Female, 62	154	46

(a) Subject A (b) Subject B

Fig. 12 Driving test and evaluation by healthy elder subjects

Subsequently, the subject drove Tread-Walk 10 (m) straight over a flat and spacious area. During this test, the driving velocity of Tread-Walk was set as twice the velocity of users walking on the belt.

Fig. 10 shows the continuous pictures showing the user gait on the Tread-Walk. The movie shot was divided into 5 pictures, each taken every 0.2 (s). As the gait was analyzed by each picture, *1) Double support phase*, *2) Kicking* by the right foot, *3) Swing phase* of the left foot and *Stance phase* of the right foot, *4) Starting swing* of the left foot in the stance phase of the right foot, and *5)* Left *heel contacting* were confirmed. Therefore, it emerged that the gait on the Tread-Walk was implemented smoothly, like natural walking.

B. Test drive to evaluate the function of the Tread-Walk (in a healthy young subject)

1) Method of experiment and driving condition

The basic function was evaluated by 10 healthy young people (167±10 (cm), 58±10 (kg)) who were first time drivers. The subjects received a detailed account of the experimental objectives. In addition, we explained that they could stop the experiment whenever they desired, and obtained their consent. Furthermore, they practiced walking on stopped Tread-Walk in advance of the test. The subjects drove straight at an arbitrary velocity for 10 meters in an open, flat area, with two amplification factors (driving wheel speed/walking speed), 1.2 and 1.5. The driving tests were conducted twice for each amplification factor. The driving scene was shot using a video camera from a sagittal plane to record the gait.

After the driving test, the following six specific items were investigated in seven stages, and the general feeling with regard to controlling the Tread-Walk was also determined.

a) Could you perceive a motor sensation such as that of flat walking?
b) Did you feel you were using your body function on the gait?
c) Did you feel your walking velocity accelerate?
d) Did you feel comfortable with the amplification of walking?
e) Did you think that third parties would have viewed you as walking normally?
f) Did you feel that you portrayed the impression of walking? (by video)

2) Result of experiment and driving condition

The evaluation result is shown in Fig. 11, with the error bar indicating the standard deviation.

Based on *a)*, 3 out of 10 people responded that it was easy to walk to a certain extend, although 3 people found it difficult to some extent. Based on *b)* and *d)*, it was confirmed that the user used the walking function and felt the amplification of walking velocity. Moreover, *c)* revealed that the amplification of walking velocity was comfortably conducted to a certain extent. The responses to *e)* and *f)* showed the tendency that the subjects felt the walking appearance on the Tread-Walk was more natural than they imagined. Consequently, it has been proved that three developmental requirements; (A) Maintaining body function, (B) Extending the activity area by the amplification of walking velocity and (C) showing the walking appearance were simultaneously met.

C. Test drive (healthy elderly)

1) Method of experiment and driving condition

Three subjects drove straight at an arbitrary velocity for 10 meters in an open, flat area, with two amplification factors (driving wheel speed/walking speed), 1.2 and 1.5 and with the driving tests conducted twice for each amplification factor. The subject received a detailed account of the experimental objectives. In addition, we explained that they could stop the experiment whenever they wished, and we obtained their consent. Furthermore, they practiced walking on a stopped Tread-Walk in advance of the test. The driving scene was recorded using a video camera from a sagittal plane to record the gait.

After the driving test, the six aforementioned specific items were investigated in seven stages, and the general feeling with regard to controlling the Tread-Walk was also determined.

Table 3 shows the physical profile of healthy older subjects. The subjects did not exercise so much in daily life, but did maintain themselves to some extent with dancing and so on, and did not feel any pain or injury in the body.

2) Result of experiment and driving condition

Fig. 12 shows the scene of the driving test with the elderly people. As a result of the questionnaire survey, every subject answered that they could definitely walk naturally based on *a)* and felt that they were using their body function to walk on the Tread-Walk based on *b)*. As regards the responses to *c)* and *d)*, the subjects perceived an amplification of the somesthetic velocity, while some subjects answered that they wanted to drive the Tread-Walk with an amplification factor greater than 1.5. Therefore, it was confirmed that the Tread-Walk was a comfortable system to increase and decrease the walking and driving velocities. The responses to *e)* and *f)* showed a tendency whereby the subjects felt the walking appearance on the Tread-Walk was realized more than they had imagined.

Consequently, the driving test carried out on the healthy elderly subjects proved that the three developmental requirements; (A) Maintaining body function, (B) Extending the activity area by amplification of the walking velocity and (C) Showing the walking appearance were simultaneously met. However, some subject tended to walk on the belt while looking down (Subject B shown in Fig. 12).

D. Summary of the test drive result

The result of the driving test by healthy elderly people is almost the same as that obtained with the test on healthy young subjects. The development of the Tread-Walk realized the required functions. Consequently, there were no negative opinions concerning the driving velocity amplifying the walking velocity. Moreover, it was confirmed from opinions that the subjects wished to drive Tread-Walk faster and make the amplification factor larger and that the subjects drove the Tread-Walk without any discomfort with an amplification factor of 1.5. However, considering that the subjects who cooperated with this test had high athletic ability, the realization of the required functions needs to be confirmed by those with the average athletic ability of elderly people.

V. Conclusion

In this paper, firstly, the Tread-Walk, which is a vehicle for elderly people, was designed to take consideration of the body size and characteristics of elderly people when determining the specification. With this in mind, the risks generated in driving the Tread-Walk were analyzed and countermeasures implemented. Finally, the test driving was conducted by healthy young and elderly subjects, whereupon it emerged that:

1) From the gait analysis, the double support phase, stance phase, kicking, swing phase and heal contacting were confirmed. Therefore, it emerged that the gait on the Tread-Walk was smoothly conducted like natural walking.

2) Based on the test driving conducted by ten young subjects, the three required functions were met.

3) Based on the test driving by three elderly people, the required functions were realized and operability in terms of straight driving was confirmed.

4) Those who were 153 – 177 (cm) height and 43 – 68 (kg) in weight were able to drive Tread-Walk. The universal specifications and required functions were fulfilled to some degree.

In future, a control system sensing the kicking force, with an improved control motor and handle operation would facilitate the more comfortable use of Tread-Walk without looking down.

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