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# Kinematic Walking Analysis on a New Vehicle "Tread-Walk" with Active Velocity Control of Treadmill Belt

Takeshi Ando, *Student Member, IEEE*, Misato Nihei, *Member, IEEE*, Eiichi Ohki, Yasutaka Nakashima, Yo Kobayashi, *Member, IEEE*, and Masakatsu G. Fujie, *Member, IEEE*

*Abstract*—**The importance on walking for health is growing in elder dominated society. We have been developing a new mobility "Tread-Walk 1 (TW-1)" controlled by walking movement. The device uses active treadmill velocity control, which allows the user to walk on the treadmill at any desired velocity. In this paper, the walking movements on the TW-1 were kinematically analyzed and compared with the walking movements on a traditional constant-velocity treadmill and on flat ground. The results showed that the walking pattern on the TW-1 was somewhat similar to that on a constant-velocity treadmill and on flat ground; however, the flexion angle of the hip joint and the dorsiflexion and plantaflexion angles of the ankle joint during TW-1 walking were larger. It also was shown that the foot applied a stronger kicking force to the belt at toe-off and the foot clearance on the TW-1 was larger than that on the constant-velocity treadmill and on flat ground. Therefore, the walking patterns in the swing and stance phase on the TW-1 are little different. However, the walking movements based on the TW-1 active belt control are valuable from the viewpoints of motion training.**

## I. Introduction

### A. Mobility-aid device for the elderly

As of 2025, Japan will be a predominantly elderly society. Therefore, many mobility-aid devices for the elder such as canes and electric carts will be required. Many new devices already have been studied to support the mobility of the elder [1][2]. As shown in Fig. 1, we have also been developing a new mobility-aid vehicle called "Tread-Walk 1 (TW-1)". Target user of TW-1 is relatively healthy elder who has the ability to walk independently using canes and so on. TW-1 is controlled by walking movement and realizes both expanding the mobility area and keeping body function [3]-[6]. TW-1 is composed of two kinds of DC motor systems. The first DC motor controls the belt velocity by sensing the walking motion of the user and then adjusts the belt velocity to match that of the user as he or s he walks naturally on the belt [4]. The second DC motor controls the velocity of the TW-1 driving wheel, so that it is amplified by a predetermined factor in relation to the walking velocity of the user [5]. Therefore, TW-1 is able to amplify the user's walking velocity, and thus expands the user's mobility area.

Fig. 1 Tread-Walk 1 (TW-1)

### B. Related work on treadmill

Hitachi Ltd. has also studied on a treadmill system that is able to change the belt velocity depending on the user's intention [7]. This velocity changeable treadmill system realizes active walking, although the user walks passively on a conventional treadmill system. In this system, based on impedance control, the kicking force of the user rotates the motor and treadmill, and virtual braking force is generated by the viscosity parameter in the control algorithm. However, because the braking force cannot be set arbitrarily, it is difficult for the user to change the walking velocity on the belt with the same sense of ease experienced when walking unaided on flat ground. In contrast, in the TW-1, both the kicking and braking force of the user are used as input signals to control the treadmill velocity. Therefore, the velocity can be changed by a walking movement similar to the way velocity is changed in natural walking. In other words, TW-1 has more intuitive mobility control.

Many researchers have studied the differences and similarities between the walking movement on a traditional constant velocity treadmill and the natural walking movement on flat ground [8]-[13]. Some studies [10]-[12] on treadmill walking have reported an increase of the walking rate and time interval of the stance phase and of the double support phase (both feet contacting the ground). Although these studies do not exactly agree, the difference between the treadmill walking and that of flat ground walking is only approximately 1%. In effect, therefore, the walking movement on the constant-velocity treadmill is almost the same as that on flat ground. Nevertheless, walking movement on a treadmill such as the TW-1, whose velocity can be actively changed by the user, has not been analyzed.

### C. Purpose

Until now, elder subjects evaluated the degree of smoothness and comfort of the walking movement in test

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Takeshi Ando, Yo Kobayashi, and Masakatsu G. Fujie are with the Faculty of Science and Engineering, Waseda University, Tokyo Japan (Corresponding author, Takeshi Ando, e-mail: ando@aoni.waseda.jp).

Eiichi Ohki is with the Graduate School of Advanced Science and Engineering, Waseda University, Tokyo Japan

Misato Nihei is with University of Tokyo, Tokyo, Japan.

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drives [6]. It was confirmed that walking movement on the TW-1 contains the basic elements of walking movement, such as the stance phase, heel contact. However, because this evaluation was based on our simple observations and the users' opinions, the kinematics of the TW-1 walking has not yet been analyzed quantitatively.

The focus of this paper is to kinematically analyze the walking movement on the TW-1, which is controlled by an active velocity change algorithm, and evaluate the differences between the movement on the TW-1 and on flat ground, with the ultimate goal of realizing a natural walking movement on the TW-1 without discomfort.

## II. Tread-Walk Mechanism

The TW-1 is a four-wheeled vehicle that permits the user to walk naturally while a servomotor amplifies the user's normal walking velocity. Its main components are a treadmill and two front driving wheels (See Fig. 2). The DC motor connected to the treadmill detects the acceleration and deceleration forces applied to the surface by the user through the load current values of the motor (See Fig. 3). The belt velocity is increased when the treadmill motor current value becomes smaller. On the other hand, the velocity is decreased when the current value becomes larger. The treadmill motor actuates the treadmill belt and acts as a sensor device at the same time. The TW-1 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 user's kicking and braking forces.
*3)* An increase or decrease in the rotation velocity is dependent on the kicking or braking force based on the signal of the treadmill motor current load.
*4)* The velocity of TW-1 is increased by the driving motors.

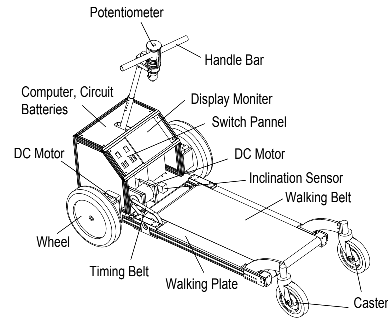
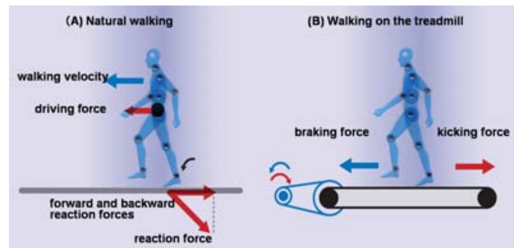



Fig. 2 TW-1 components




(A) Natural walking forces (B) Walking on the treadmill
Fig 3 Detection system of TW-1 walking forces

## III. Analysis of Tread-Walk Walking Movement

### A. Objective

The objective is to analyze the kinematic factors, such as the joint angle of the lower limb, of natural walking and walking on the TW-1. In this experiment, the healthy young (i.e., not disabled or elder) were the targeted subjects as a first step to study the influence on the walking movement on the TW-1.

### B. Experimental method

Three healthy young subjects walked on three ground conditions; natural ground, a constant-velocity treadmill system (Hitachi), and TW-1. Since the driving wheels of TW-1 were fixed, the effect of the treadmill, whose velocity was changed using the value of the motor load current, was considered; however, the effect that amplifying the walking velocity had on walking movement was not considered. When the subjects drove the TW-1 and constant-velocity treadmill, they held the handle and were careful not to tilt their trunks forward, so that they could better simulate the posture of natural walking. Each walking movement was conducted at velocity: 2.0 (km/h) and cadence: 58 or 96 (steps/min), and was measured for 20 walking cycles. This condition was determined based on the typical walking by the elderly. Ten body markers (DIFF format to analyze walking movement) were attached on right and left acrominon, great trochanter, epicondylus lateralis ossis femoris, lateral malleolus, and fifth metatarsal bone. The walking movements were measured by a 3D motion-capture system (Vicon612, sampling frequency 100 (Hz) and accuracy 1 (mm)). The subjects received a detailed account of the experimental objectives and we obtained their consent. Furthermore, they practiced the walking movement with a fixed cadence and walking stride for 5 min. in advance of the test to get used to the movement.

### C. Qualitative analysis of joint angle

Figures 4, 5 and 6 show examples of the time-series changes of the flexion and extension angles of the hip joint and knee joint as well as the dorsiflexion and plantaflexion angles of the ankle joint in the walking movement (20 walking cycles) of a subject. The walking patterns of all three subjects showed the same tendencies. The horizontal axis is the walking phase (%). Heel contact is defined as 0% and the next heel contact of the same foot is defined as 100%. Comparing the results for each joint angle in constant-velocity treadmill walking and natural walking with the results of related work on treadmill walking [14]-[17], we confirmed that these walking patterns were almost the same. Moreover, the lower limb joint angles in TW-1 walking, constant-velocity treadmill walking and natural walking had almost the same pattern for both the 58 and 96 cadence for all subjects, as described in the following.

*1) Hip joint:* After heel contact, the hip joint continues to extend and reaches maximum extension before toe-off. The flexion starts at the early swing phase, becomes about 0 (deg) in toe-off and reaches the maximum flexion angle just before heel contact.

*2) Knee joint:* In the early stance phase, the knee joint flexes to absorb the impact of the heel contact. After that, the joint extends completely at toe-off. Then, the joint flexes maximally in the mid-swing phase.

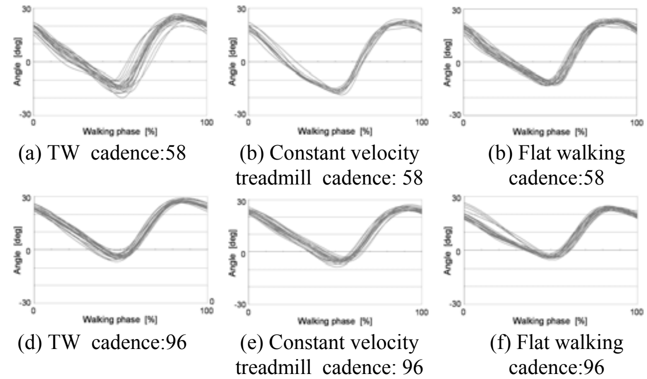
*3) Ankle joint:* The ankle joint has the plantaflexion condition in heel contact and continues plantaflexing in the early stance phase. After heel-off, the joint starts dorsi-flexion and reaches it maximally just after toe-off. In the swing phase, the joint plantaflexes to approximately 0 (deg).

### *D. Quantitative analysis of joint angle*

In this section, we define some important features of the joint angles and discuss the quantitative analysis of the differences among TW-1 walking, typical treadmill walking, and natural walking. The selected features are shown in Fig. 7: the maximum flexion angle ${}_h\theta_f$ and maximum extension angle ${}_h\theta_e$ in the hip joint, the maximum flexion angle ${}_k\theta_f$ in the knee joint, and the initial dorsiflexion angle ${}_a\theta_{d1}$, maximum plantaflexion angle ${}_a\theta_p$, and second dorsiflexion angle in the ankle joint ${}_a\theta_{d2}$. The features in each walking movement were analyzed by the *t*-test. As a result, the maximum extension angle ${}_h\theta_e$ in the hip joint, the maximum plantaflexion angle ${}_a\theta_p$ and second dorsiflexion angle ${}_a\theta_{d2}$ in the ankle joint of the TW-1 walking movement and natural walking movement at a cadence of 96 (steps/min) showed significant differences ($p<0.01$) in all subjects. The averages of these features in TW-1 walking were larger than those in natural walking. In addition, the maximum flexion angle ${}_k\theta_f$ in the knee joint in the TW-1 walking movement and the natural walking movement at a cadence of 96 (steps/min) showed significant differences ($p< 0.01$) in two of the three subjects, and the averages of these features in TW-1 walking were larger than those in natural walking.

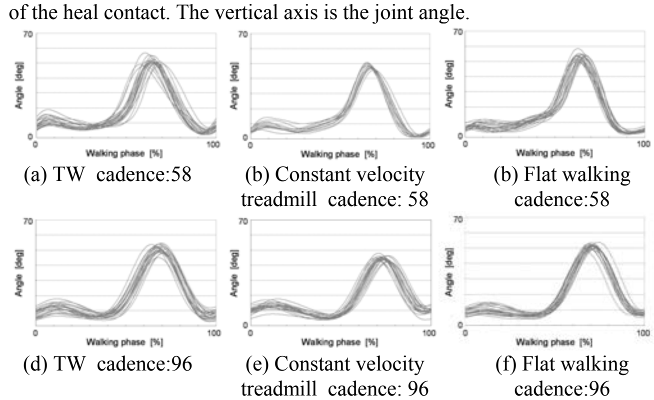
### *E. Foot trajectory and clearance on the Tread-Walk*

As shown in Section III *D*, the maximum hip extension angle ${}_h\theta_e$, maximum knee flexion angle ${}_k\theta_f$, and maximum ankle plantaflexion angle ${}_a\theta_p$ tended to be larger when the cadence was large in the TW-1 walking movement. Therefore, it was estimated that the trajectory of the foot tip from toe-off to heal contact in the TW-1 walking movement would be larger in the direction opposite to the traveling direction and higher than that in constant-velocity treadmill walking and flat walking. Figure 8 shows examples of the trajectory of the fifth metatarsal bone in the sagittal plane when the three subjects walked on the TW-1, constant-velocity treadmill, and flat ground. It was confirmed that the foot tip kicked about 0.05-0.08 (m) more to the back side in TW-1 walking. The cause of this stronger kick to the back side is that the same strength of the frontward and backward components of the kicking force is needed to maintain constant velocity in both high-cadence walking and low-cadence walking. This is because the belt velocity of the TW-1 is determined using the values of the frontward and backward direction components of the kicking force. Namely, the relation between kicking force and the velocity change rate in the TW-1 was determine ed based on the same relations in the natural walking of young subjects on flat ground. When the walking stride of



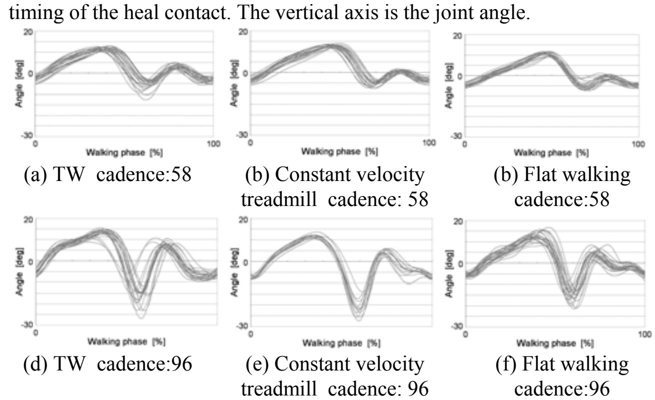
(a) TW cadence:58 (b) Constant velocity treadmill cadence: 58 (b) Flat walking cadence:58
(d) TW cadence:96 (e) Constant velocity treadmill cadence: 96 (f) Flat walking cadence:96

Fig. 4 Hip joint angle (+:flexion, -:extension). Note that the horizontal axis is walk phase (%). 0% is the timing of heal contact and 100% is the next timing of the heal contact. The vertical axis is the joint angle.



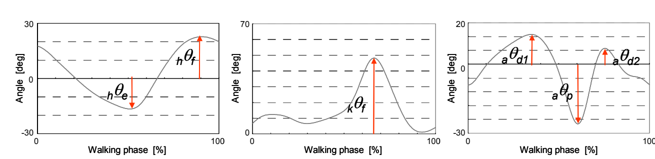
(a) TW cadence:58 (b) Constant velocity treadmill cadence: 58 (b) Flat walking cadence:58
(d) TW cadence:96 (e) Constant velocity treadmill cadence: 96 (f) Flat walking cadence:96

Fig. 5 Knee joint angle (+:flexion, -:extension). Note that the horizontal axis is walk phase (%). 0% is the timing of heal contact and 100% is the next timing of the heal contact. The vertical axis is the joint angle.



(a) TW cadence:58 (b) Constant velocity treadmill cadence: 58 (b) Flat walking cadence:58
(d) TW cadence:96 (e) Constant velocity treadmill cadence: 96 (f) Flat walking cadence:96

Fig. 6 Ankle joint angle (+:dorsiflexion, -:plantaflexion). Note that the horizontal axis is walk phase (%). 0% is the timing of heal contact and 100% is the next timing of the heal contact. The vertical axis is the joint angle.



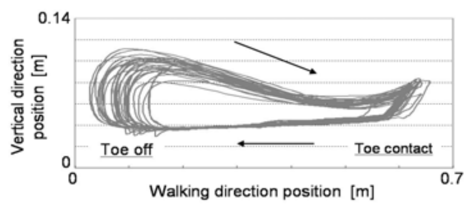

(A) hip joint angle (B) knee joint angle C) ankle joint angle
Fig. 7 Example joint angles as a function of walking phase

young subjects on the TW-1 is shorter (the cadence is higher) than that in natural walking, the kicking force is also smaller. The-refore, in the TW-1, the belt velocity becomes slower than user's desired velocity. To keep the velocity from becoming too small, the user makes the kicking force larger.

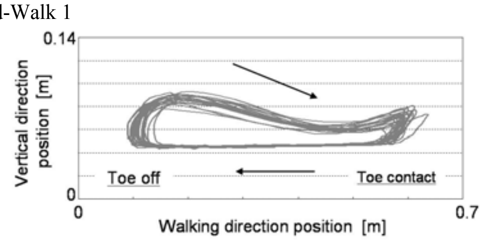
It was also predicted that foot clearance in the later part of the swing phase became greater, because the second dorsiflexion angle in the ankle joint, $_a\theta_{d2}$, became larger. Figure 9 shows the foot clearance, which is the maximum height of the fifth metatarsal bone, in TW-1 walking (32±5 (mm)), constant-velocity treadmill walking (24±5 (mm)), and flat walking (27±3 (mm)). The clearance in TW-1 walking is significantly larger ($p < 0.01$).

## IV. CONCLUSION

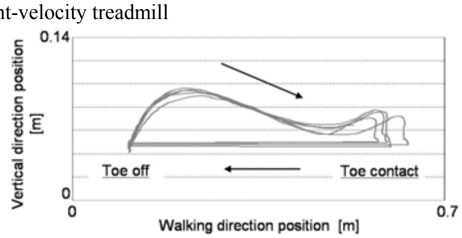
The walking movement on TW-1 was kinematically analyzed by comparing it with the walking movements on a traditional constant-velocity treadmill and on flat ground. The joint angles of the lower limb in these three walking movements were almost the same. However, the maximum extension angle in the hip joint and both the maximum plantaflexion angle and the second dorsiflexion angle in the ankle joint were significantly different between the TW-1 walking and natural walking when the cadence was high.




(A) Tread-Walk 1




(B) Constant-velocity treadmill




(C) Flat walking

Fig. 8 Toe trajectory in different walking movements. Note that the foot tip was kicked about 0.05- 0.08 (m) more to the back side in TW-1 walking

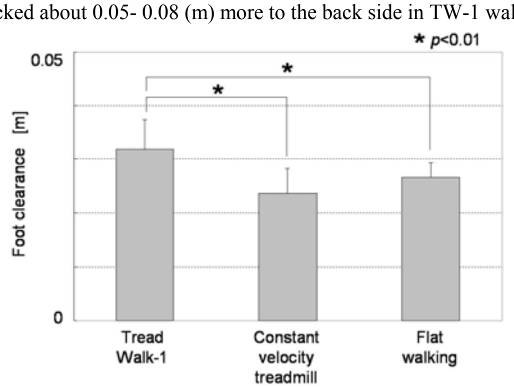



Fig. 9 Foot clearance in different walking movements. Note that the foot clearance in TW-1 walking (32±5 (mm)), constant-velocity treadmill walking (24±5 (mm)), and flat walking (27±3 (mm)). (Mean±S.D.)

Specifically, the foot kicked backward more strongly and the trajectory of the foot after toe-off became higher and larger in the direction opposite to the travel direction because of the belt velocity control algorithm of TW-1. In addition, the clearance before heel contact became higher in TW-1 walking. Therefore, the use of muscles in the later stance phases and swing phase on the TW-1 is probably different from their use on flat ground. These characteristics of TW-1 walking, that is, higher clearance, are beneficial from the viewpoints of training to avoid the falling.

In the future, TW-1 walking will be kinetically analyzed using the floor reaction force and EMG signal. In addition, the change of walking movement will be analyzed as the velocity of the driving wheels of TW-1 is amplified. Also, we will design a controller with a new algorithm that will detect the walking pattern on the TW-1 so that the user can perceive the same feelings as those felt during natural walking.

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