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Development of a New Vehicle Based on Human Walking Movement with a Turning System

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1. Introduction

In engineering research and technology, a considerable amount of attention has recently been focused on developing devices to assist the elderly. For elderly persons, walking is one way of improving the functions of the mind and body, and is therefore effective in increasing the quality of life (J. Jutai et al., 1999). Among the techniques that can be used to assist mobility among the elderly are improvement in physical ability by training or by using power-assisted devices (Y. Sankai et al., 2000, C. J. Walsh et al., 2006), reducing loads on the lower limbs by sustaining the weight of the individual (R. Riener et al., 2000, T. Tani et al., 1996), and expanding the range of environments that can be accessed by users of mobility devices, for example, by the development of wheelchairs that are capable of climbing stairs (R. Morales et al., 2006, E. S. Boy et al., 2002). Furthermore, many intelligent robots can anticipate the intentions of humans (R. C. Simpson et al., 2005, Q. Zeng et al., 2006), but it is difficult to use this ability in meeting the needs of the elderly in terms of facilitating movement and mobility.

Fig. 1. Tread-Walk 1

Fig. 2. The target user of Tread-Walk1 and Tread-Walk2

We have designed and developed two new mobility-aid systems for the elderly that improve their walking speeds. These devices are called Tread-Walk1 (TW-1), which is shown in Fig. 1, and Tread-Walk2 (TW-2). They are mobile treadmill-like systems that are designed to meet the following three requirements: the maintenance of bodily function, the extension of mobility (based on a trend survey of elderly persons (M. Nihei et al., 2008)), and the maintenance of the appearance a natural gait (M. Nihei et al., 2007). The targeted users, as shown in Fig. 2, have the following characteristics: the ability to walk under their own power, but not quickly; the motivation to maintain or expand the geographical area in which they are mobile; and the wish to appear as though they are walking naturally.

The control of the system's belt velocity is based on the natural walking velocity of the user. The user's intended walking speed is detected by the kicking and braking forces applied by the user's feet as he or she walks on the treadmill belt, which in turn is connected to a dc motor. These forces are counteracted by the propulsion force of the belt.

To control this system more accurately, signals for rotational movement should also be derived directly from the walking motion. In this chapter, we focus on human rotational movement, and we describe a new system that uses two belts to derive separate signals from each foot during walking (M. Nihei, 2008).

There are types of two-belt treadmill system. One has force plates built into it (A. Belli et al., 2001) and is mainly used for the analysis of walking movement, because it can measure the reaction force from the floor during walking. The other has an impedance control system using an ac servomotor (T. Tani et al., 1995); in this system, the burden on the lower limbs during walking is controlled by the rotational velocity of the belt. The applications of this kind of system in rehabilitation and training to prevent falling have already been the subject of research (K. Hase et al., 2002).

In this chapter, we explain our developments and we describe our evaluation of a new system called Tread-Walk2 (TW-2), which effects changes in direction by using as an input signal the differences between the patterns of kicking and braking forces applied to the treadmill belt by the soles of the right foot and the left foot. To identify the advantages and disadvantages of the TW-2, we compared its functions with those of the TW-1.

2. Development Concept

2.1 The Functions of Tread-Walk1

(a) Natural walking (b) Walking on a treadmill system

Fig. 3. The system for detecting the forward and backward components of the reaction force of the ground

TW-2 is basically a functional enhancement of TW-1. TW-1, which is illustrated in Fig. 3, amplifies the velocity of the treadmill, based on the input signal, to drive a wheel that, in turn, moves the device along the ground (M. Nihei, 2008). In this way, the slow gait of the user is transformed into a more-rapid movement of the device in the same direction. In TW-1, the sum of the forward and backward components of the reaction force of the ground applied to both feet during the walking movement is used as an input signal to accelerate and decelerate the system, as shown in Fig. 3 (Y. Kaneshige et al., 2006). In addition, the angle of rotation of the handle is used a second input signal to allow the system to be steered to the right or left. Therefore, the rotational movement that controls the steering of TW-1 is performed by a movement of the user’s upper limbs. Other functions of TW-1 are discussed below.

1) The Basic Concept

The prototype of the TW-1 system is shown in Fig. 4. The prototype consists of a treadmill on which the user walks, a drive wheel, and a set of handlebars. Fig. 5 shows a diagram of the system, along with the walking and driving components. The control of the speed of the treadmill is activated by a dc motor that is attached to the treadmill belt. The driving system operates according to the following protocol. When the user starts to walk on the treadmill, the belt is rotated by the kicking force of the user. The resulting rotational torque is transferred to the shaft of the motor, where it is detected as a load current. A microprocessor control unit calculates the load current from the kicking/braking force and determines the walking speed; the treadmill then moves at the same speed so that the user stays in a position that is stationary relative to the treadmill base. At the same time, the walking speed is amplified by the driving wheels, so that the vehicle moves forward at a greater speed than that at which the user walks. The relationship between the walking speed and the driving speed is determined by the optional gain. In addition, the steering system controls the relative speeds of the right and left wheels.

Walking movement on TW-1 was analyzed kinematically by comparing it with the corresponding walking movement on flat ground (T. Ando et al., 2008). The angles of the joints of the lower limbs were found to be almost the same in these two walking movements; however, as shown in Fig. 6, 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 was higher when walking on the TW-1.

Fig. 4. Tread-Walk1

Fig. 5. A diagram of TW-1

Fig. 6. Toe trajectory in different walking movements. The driving wheels of TW-1 were fixed, each walking movement was conducted at a velocity of 2.0 km/h and a cadence 58 or 96 steps/min. Measuring system: 3D motion-capture system [Vicon 612 (Vicon, Los Angeles, CA, USA; 100 Hz; accuracy 1 mm)].

1) Steering system

We proposed a method for steering control that enables the user to turn the device safely and in a stable manner. The system is designed to allow the user to maintain his or her balance in a standing position during a turning operation; to achieve this, the rotational velocity at which a comfortable balance can be maintained in a standing position when the user is subjected to a centrifugal force was established, as shown in Fig. 7(T. Ando et al., 2008).

2) Slope

We developed a new system that facilitates walking up and down slopes, as well as walking on flat ground. Fig. 8 shows a trial of walking down a slope. To realize this, we detected the forward and backward components of the floor reaction force using a newly developed system for measuring the torque load on the motor. In addition, we developed a model that can express the relationship between the torque load during walking and the gradient angle of the slope. By considering the gradient angle as a feedback element, we demonstrated that it was possible for the user to walk straight on slopes as well as on flat ground. The results of a number of driving experiments using the prototype machine on slopes showed that a user can walk smoothly up or down a slope of up to $\pm 5.5^\circ$ in an interior environment and one of $\pm 7^\circ$ in an exterior environment without stopping (M. Nihei, et al., 2006).

Fig. 7. The relationship between the centrifugal force and the center of gravity: a is the distance from the wheel to the center of the vehicle, b is the distance between the center of the sole of either foot and the projection of the center of gravity onto the platform, h the height of the centre of gravity of the user above the platform, and F is the centrifugal force.

Fig. 8. Photograph showing the device being driven down a slope of 7°

However, to control this system more accurately, signals for rotational movement should be derived directly from the walking motion. Below, we focus on human rotational movement and describe a new system that uses two belts to derive a separate signal for each foot during walking.

2.2 Directional change by rotational movements

In the human gait, the swing phase occurs when one leg is brought forward, and the stance phase occurs when an external force is applied to the ground alternately by each foot. The rotational movement needed to adjust walking speed and to change direction is made by adjusting the force and moment between the foot and the ground.

Rotational movements can be divided into the spin turn, in which the movement that is required to change direction is made without moving forward, and the pivot turn, in which the movement required to change direction is made while the individual is moving forward. Such rotational movements are realized by adjusting the kicking and braking forces of the system.

As shown in Figs. 9 and 10, the rotational center of the human body is present on the front-horizontal axis. In the spin turn (Fig. 9), there is a rotation about the front-sagittal axis, corresponding to the center of the trunk, and about the spinning foot. In the case shown, the left leg is on the rotational axis, and the turn is realized when the left ankle and hip joint are adducted or the left leg kicks the ground strongly. On the pivot turn (Fig. 10), on the other hand, the rotational center is outside the body of the user and changes because of the rotational angle. This turn is performed when the kicking forces of the right foot and the left foot are different.

Fig. 9. Spin turn

Fig. 10. Pivot turn

2.2 Design and Required Specifications

The spin turn and pivot turn of TW-2 are realized by using the movements involved in changes in direction as explained above. The system detects the kicking force of each foot of the user, and a mechanism turns the vehicle in response to the detected spin turn or pivot turn movements made by the user.

1) The system detects the kicking force of the user's feet

As with TW-1, TW-2 detects the kicking force of both feet by detecting the forward and backward component of the ground reaction force applied to each foot by the load current of the dc motors connected to the walking belts. The treadmill of the TW-2, however, consists of two walking belts to detect the kicking force of each foot independently.

2) *Vehicle turns based on the user’s movements*

To conduct the turn movement with a similar sensationnatural walking, the center of rotation of the TW-2 should be close to that of the human user. Therefore, as shown in Fig. 9, the two driving wheels are arranged under the center line of the twin-belt treadmill. In addition, two passive casters are positioned to the front and two more are positioned to the rear to improve stability. So that the TW-2 can be used on sidewalks, its size must conform to the JIS (Japan Industrial Standardization) standards for motored wheelchairs (JIS T9203, 2003), that is, a maximum length of 1200 mm, a maximum width of 700 mm, a maximum height of 1090 mm, a maximum speed of 6.0 km/hr, and sufficient rotational performance that the TW-2 can make a right-angle turn in a 1.2-m-wide intersection. Moreover, the weight must be less than 100 kg, the same as that of a standard electric cart.

3. Development of the TW-2

3.1 Mechanism

1) *The overall design*

TW-2 is composed of three subsystems: *the walking (treadmill) subsystem*, which extracts the walking pattern, controls the velocity of the treadmill belt, and extracts the rotational movement; *the driving subsystem*, which moves the vehicle along the ground; and *the operation-lever subsystem*, which supports the trunk of the user and recognizes the kind of rotational movement that is being made. The prototype is shown in Fig. 11, and Table 1 list the specifications for the TW-2.

2) *The walking (treadmill) subsystem*

As shown in Fig. 12, the walking subsystem consists mainly of the walking belts and a walking board; the latter supports the user’s weight. The size of the walking board is 460 × 720 mm, which takes into account the typical walking stride length of older people. In addition, a tape is used to decrease the friction on the upper surface of the walking board.

Fig. 11. Tread-Walk2

Fig. 12. Walking subsystem

Fig. 13. Driving subsystem

The width of each belt is 140 mm, which is wider than the average foot width of 100 mm (NEDO database). The height of the walking subsystem (140 mm) is as low as possible to

minimize the chances of falling off and to reduce the burden of mounting and getting down from the TW-2.

		TW-2	TW-1
Size (mm)		1340 × 840 × 1120	1520 × 760 × 1120
Minimum rotational radius (mm)	Spin turn	840	
	Pivot turn	1120	
Weight (kg) (including battery)		90	75
Max. vehicle velocity (km/h)			6
Max. walking belt velocity (km/h)			3
Continuous use time (h)		~3	~6
System motors		2 wheel-driving motors 2 treadmill-driving motors	2 wheel-driving motors 1 treadmill-driving motor

Fig. 14. System structure

The forces applied to each walking belt are transferred to a dc motor that connects with the corresponding belt through a gearbox (gear ratio: 5:1). The dc motor, motor drive, and tacho-generator were selected for use in the walking subsystem on the assumptions that the maximum load would be 80 kg and the maximum velocity is 4.0 km/h.

3) Driving subsystem

As shown in Fig. 13, the size of TW-2 is 1340 × 840 mm, which takes into account the typical width of a sidewalk in Japan. The driving subsystem includes six wheels: two central or driving wheels, and four front and rear wheels that are omnidirectional to improve the performance of translatory and rotational movements. There are two dc-geared driving motors that are controlled by a velocity control driver (Curtis Inc.). The right and left driving wheels are aligned with the center of the treadmill belt to match the centre of

rotation of the user with that of the TW-2. The front wheels are set 630 mm ahead of the driving wheels, and the rear wheels are placed 480 mm behind the driving wheels.

4) Operational lever subsystem

The operational lever subsystem consists of a supporting column, a gas spring, and a potentiometer. The height of the lever is adjustable from 770 to 1120 mm to accommodate users of various heights without affecting their walking movements. In addition, the lever is placed about 100 mm in front of the center of the walking belt to maximize the likelihood that the user will walk on the center of the belt.

3.2 System structure

Figure 14 shows the structure of the TW-2 electronics system. Power is supplied from a 24-V Ni-H battery that actuates two dc motors that rotate the two treadmill belts, and another two dc motors that turn the driving wheels. The control microprocessor is powered by a 5-V dc source provided from the power supply via a dc-dc converter. Encoders are used to measure the number of rotations made by the two driving wheels. The continuous operating time of the TW-2 is about two hours.

4. Rotational Movements of Humans and the System

4.1 Rotational Method

The parameters for determining the direction of travel from rotational movements made by the user are the point of application of the floor reaction force, the magnitude of the force, and its moment. In TW-2, however, the only detected signal that is used to conduct rotational movement is the forward and backward component of the ground reaction force. This can cause problems. First, it is possible that the translatory performance will be decreased because differences between the walking patterns of the right and left feet may occur at the start of the walking movement and/or when the walking velocity is low. Secondly, it is difficult to recognize the pattern when a rotational movement is conducted at the first step of a walking motion.

Therefore, in the TW-2, there is a component in the lever subsystem that solves this problem by allowing the user to go straight or to turn.

4.2 Sensing the Walking Pattern of Each Leg

An examination was conducted to measure the pattern of the forward and backward components of the ground reaction force. In this examination, only the treadmill subsystem was actuated, and the walking pattern was detected by measuring the load current values of the right and left belt-driving motors during the walking movement. In particular, it was important to detect the value of the current when the treadmill motor was controlled at a constant velocity. The relation between the load current value of a motor and the forward and backward reaction force applied to its belt is shown in Equation 1.

$$f = A \times K_t \times i / r \quad (1)$$

where f is the forward or backward component of the ground reaction force, A is the measured current value, K_t is the torque constant, i is the reduction ratio, and r is the shaft radius.

The kicking and braking force of each leg during walking movement on the treadmill belt is transferred to a dc motor connected to the belt for the appropriate leg, and the load torque that is generated by the kicking and braking force is detected as a load current value.

Fig. 15 shows the load current values for a period of 20 seconds of constant walking at a velocity of 2 km/h. As shown in the Fig. 15, the right foot and the left foot currents alternate at constant frequencies. It should be added that the frequency of the vibrations corresponds to a walking cadence of 58 steps/min, which we set as a typical value of the walking cadence for an elderly person.

Fig. 15. Load current values for the left and right feet during walking movements

Therefore, this figure confirms that the right and left walking patterns can be independently estimated from the frequency and the peak value. Moreover, the figure also confirms that the braking force applied to the walking belt on contact of the heel raises the load current value, because the resulting braking force is in the direction of deceleration of the rotational velocity of the motor. On the other hand, the kicking force applied as the toe lifts off decreases the current value, because the kicking force accelerates the rotational velocity of the motor. Thus, it is certain that the peaks shown in Fig. 15 correspond to braking forces, whereas the valleys correspond to kicking forces.

4.3 Operating Movement

Movements of the TW-2 system can be divided into a spin-turn mode, a pivot-turn mode, and a straight mode. Table 2 shows the relation between each of these modes and the lever manipulation and walking movements.

Operation of lever switches P1 & P2	Walking movement	TW-2 movement
ON and ON		Straight

ON and OFF or OFF and ON		Pivot turn
OFF and OFF		Spin turn

Table 2. TW-2 Operations

1) Straight Movement

In straight movement, the belt velocity is controlled in the same manner as it is controlled during the walking movement, even if the forward and backward components of ground reaction force of the right and left legs are different. The increasing and decreasing values of the right and left treadmill velocities, $Tr_{Straight}$ and $Tl_{Straight}$, are calculated by multiplying a constant by the sum of the integral value of the forward and backward components of the ground reaction force of the right and left legs, $r(t)$ and $l(t)$, from a time t_0 to the current time t .

$$Tr_{Straight} = Tl_{Straight} = \alpha \left\{ \int_{t_0}^t r(t)dt + \int_{t_0}^t l(t)dt \right\} \quad (2)$$

Acceleration or deceleration is performed when this value reaches a threshold value for acceleration or deceleration. The value of t_0 is reset every time the vehicle accelerates or decelerates.

2) Turning movement

The forward and backward components of the ground reaction forces of the right and left legs are used independently as input signals for altering the velocity of the control belt. Therefore, the values for recognizing the increasing and decreasing velocities of the right and left belts Tr_{Turn} , Tl_{Turn} are defined as follows:

$$Tr_{Turn} = \beta \int_{t_{r0}}^t r(t)dt, Tl_{Turn} = \beta \int_{t_{l0}}^t l(t)dt \quad (3)$$

where β is a constant.

4.4 Rotational Movements and Rotational Angles

1) Spin-turn mode

(a) Spin turn

The relation between each kicking force and the rotational angle is as follows: TW-2 turns to the right when the left foot applies the kicking force and turns to the left when the right foot applies the kicking force. On the basis of the values of kicking forces for the right and left feet, the turn direction is decided by means of threshold recognition. For example, when the kicking force is applied by the right foot, a braking force is simultaneously generated by the

left foot. When the generated kicking and braking forces are above arbitrary threshold values, the rotational angle is calculated by using an angular acceleration function. On the basis of the relation between the impulse of the rotational movement and the momentum during the walking motion, the angular acceleration function is selected to make the relation between the kicking force during rotational movement and the rotational angular acceleration linear. The angular acceleration function is derived as follows:

$$\ddot{\theta} = k_s \cdot l / I \cdot f(t) \quad f(t) = \begin{cases} f_R \\ -f_L \end{cases} \quad (4)$$

where $\ddot{\theta}$ is the angular acceleration of the person and the TW-2, k_s is a correction coefficient, l is the distance between the right and left feet of the user, I is hypothetical inertia moment, and f is the kicking force of the right or left foot. In this case, the values of l , I , k_s are constant and K_s (the correction coefficient between the angular acceleration and kicking force) is defined as follows.

$$K_s = k_s \cdot l / I \quad (5)$$

Therefore, the following equations are derived.

$$\ddot{\theta} = K_s \cdot f(t) \quad (6)$$

$$\theta = \iint K_s \cdot f(t) \cdot dt \cdot dt \quad (7)$$

That is, the angular acceleration is generated from the impulse produced by the kicking force. Hence, it is possible to adjust the rotational angle depending on the kicking force in a way that is similar to adjusting the rotational movement of a rigid body. In other words, it is easy for the user to control the rotational operation of the TW-2.

Furthermore, when K_s is large, a small kicking force can result in a large angle of rotation, whereas when K_s is small, a large kicking force can result in a very small angle of rotation. Additionally, K_s is adjustable for each user, because K_s is set to an arbitrary value that is matched to the user's physical condition. In TW-2, the corrective coefficient K_s is set by trial and error until the user feels it is easy to operate the rotational movement of the system.

In the spin-turn mode, the thresholds for the kicking and braking force of each leg are set as f_{thk} and f_{thb} , to recognize the spin turn and pivot turn, and the spin turn is conducted when the forces simultaneously exceed f_{thk} and f_{thb} . These thresholds can be adjusted by trial and error to recognize even small kicking and braking forces, so the user feels it is easy to control the rotational movement of the vehicle. Additionally, the maximum angular velocity $\dot{\theta}$ is set at a comfortable level for the user.

(b) *Spin turn operation in the TW-2*

As shown in Fig. 16, the angular velocity of TW-2 is determined by the rotational velocities of the right and left driving motors and the distances between the right and left driving wheels.

$$\dot{\theta} = (v_R - v_L) / 2d \quad (8)$$

where $v_R = -v_L$, $\dot{\theta}$ is the angular velocity of TW-2, v_R is the rotational velocity of the right motor, v_L is the rotational velocity of the left motor, and $2d$ is the distance between the right and left driving wheels.

Fig. 17 shows the measured rotational angles and kicking forces during a spin turn ($f_{thk} = 0.42\text{ A}$, $f_{thb} = 3.0\text{ A}$). It was found that TW-2 rotated 92.9° to the left when the kicking force of the left foot was large (less than 0.42 A). Similarly, it was confirmed that right and left rotations of the TW-2 are controlled by the right and left kicking and braking forces.

Fig. 18 shows the trajectories of the right and left driving wheels and the center point between them, which is equal to the rotational center of the human body under the same experimental condition, as shown in Fig. 10. The right and left driving wheels are rotated around the center point of the TW-2. When TW-2 turns 92.9° in the spin-turn mode, the displacements of the midpoints of the right and left driving wheels are about 36 mm along the x -axis and 38 mm along the y -axis from the original points, that is, about 4.3% of the overall width and 2.8% of the overall length. Thus, it was confirmed that the amount of vibration of the rotational axis is small.

2) Pivot-turn mode

(a) Rotational movement in the pivot turn

As in the case of the spin turn, the relation between the kicking force and rotational angular velocity is expressed as:

$$\ddot{\theta} = k_p \cdot l / I \cdot f(t) \qquad f(t) = \begin{cases} f_R \\ -f_L \end{cases} \tag{9}$$

where $\ddot{\theta}$ is the angular acceleration of the person, and TW-2, k_p is a corrective coefficient, l is the distance between the right and left feet or belts, I is the hypothetical inertia moment of a human body, f_R is the kicking force of the right foot, f_L is the kicking force of the left foot. In this case, l , I , and k_p are constant, and K_p (the correction coefficient for the angular acceleration and the kicking force) is defined as:

$$K_p = k_p \cdot l / I \tag{10}$$

Therefore, the following values are derived:

$$\ddot{\theta} = K_p \cdot f(t) \tag{11}$$

$$\theta = \iint K_p \cdot f(t) \cdot dt \cdot dt \tag{12}$$

As is the case of the spin turn, an angular acceleration is generated from the impulse of the kicking force. It is therefore possible to adjust the rotational angle depending on the kicking force. In other words, pivot-turn operation of TW-2 is also easy.

Furthermore, the larger the value of K_p , which is the corrective coefficient between the angular acceleration and the kicking force, the larger will be the angle of rotation, even if the kicking force is small. On the other hand, when K_p is small, it becomes possible to control a minute rotational angle by a large kicking force. Therefore, because K_p is set to an arbitrary value matched to the user's physical condition, control of rotational movement is easily adjustable. In TW-2, the corrective coefficient K_p is set by trial and error until the user feels that it is easy to control the rotational movement of the system.

In the pivot-turn mode, the threshold of the kicking force is set to f_{th} , so that the pivot turn is executed only when the arbitrary kicking force exceeds f_{th} . This threshold is adjustable by trial and error, so that rotational movement can be executed even by a small kicking force that can be easily applied by the user. Additionally, the maximum angular velocity $\dot{\theta}$ is set at a level that is comfortable for the user.

In our system, the rotational velocities of the right and left motors are adjusted to correspond to the rotational centers of the wheels.

(b) Pivot-turn operation

As shown in Fig. 19, the angular velocity of TW-2 (v is the translational velocity of TW-2) is determined by the rotational velocities of the right and left driving motors and the distances between the right and left driving wheels.

$$\dot{\theta} = (v_R - v_L) / 2d \quad (13)$$

$$\rho = 2d \cdot (v_R + v_L) / (v_R - v_L) \quad (14)$$

where $\dot{\theta}$ is angular velocity of TW-2, v_R is the rotational velocity of the right motor, v_L is the rotational velocity of the left motor, $2d$ is the distance between the right and left driving wheels, and ρ is the distance from the rotational center to the center of TW-2.

Fig. 20 shows the rotational angles and load current values corresponding to the right and left kicking forces when the TW-2 makes a right-angle turn at an arbitrary angular velocity. The load current values for the right and left motors are alternately detected during straight movement. As shown in the figure, the kicking force of the left foot increases at around 3 seconds. The threshold of the kicking force was set to be 0.2 A, after user trial and error indicated that it was easy to operate TW-2 with this force. Therefore, it was confirmed that TW-2 starts to turn by 94.6° when the kicking force falls below a threshold of 0.2 A. (Fig. 13 includes data for the right foot as a reference.)

Fig. 21 shows the trajectories of the right and left wheels of TW-2 and the midpoints of the right and left wheels. It was found that TW-2 is rotated by making the left driving wheel the center of rotation.

Fig. 19. Pivot turn model

Fig. 20. Walking pattern and pivot-turn mode

Fig. 21. Trajectory of TW-2 in pivot turn

5. Driving Evaluation for a Right-Angle Intersection

5.1 Method and Conditions

In this experiment, which is based on the JIS T9023 Rotational Performance Test, the subjects each drove the TW-2 into a 1.2-m-wide virtual right-angle intersection (defined by plastic tape). The subjects were 10 young people and 5 elderly people, all of whom were healthy. The subjects practiced controlling the TW-2 in advance. After that, they repeatedly drove the TW-2 until they were able to control it without contacting the intersection plastic tape. The test drives were conducted in spin-turn and pivot-turn modes.

As shown in Fig. 22, markers were placed at the outside front tip of the right front wheel [A: front wheel (R)], at the outside center of the left driving wheel [B: middle wheel (L)], at the outside rear tip of the right rear wheel [C: rear wheel (R)], and at the midpoint of the right and left driving wheels (O: TW-2 center). The trajectory of TW-2 while being driven through the right-angle intersection was measured by using a three-dimensional position sensor (Vicon 612).

Fig. 22. Marker positions

Fig. 23 The trajectory of spin turn

Fig. 24 The trajectory of pivot turn

5.2 Experimental Results

Table 3 shows the numbers of trial times needed before the subjects could successfully control the TW-2 at the right-angle intersection without contacting the virtual edges of the intersection. In the spin-turn mode, all the subjects succeeded within three trials. On the

other hand, in the pivot-turn mode, all the young subjects succeeded within three attempts, whereas it took one elderly subject five attempts to achieve successful control. Some examples of the results of the experiments are shown in Fig. 23 and Fig. 24. The left front and rear wheels rotated in a ragged fashion around the intersection in the spin turn mode, as shown in Fig. 23. On the other hand, it was confirmed that the right front and rear wheels rotated smoothly around the intersection in the pivot-turn mode, as shown is Fig. 24. In both modes, it was found that TW-2 did not contact the edges of the virtual intersection.

Attempt Number		1	2	3	4	5
Spin turn	young person	7	1	2		
	elderly person	2	2	1		
Pivot turn	young person	4	2	4		
	elderly person	0	2	1	1	1

Table 3. Experimental Results Showing Numbers of Successful Navigations at Each Attempt

5.3 Discussion

It was found that both young and elderly people were able to steer the TW-2 successfully using the rotational operation method developed in this research. This experimental result shows that the vehicle motion in the pivot turn is smoother than that in the spin turn. The spin-turn trajectory shows that when the vehicle turns a narrow corner, the user has to operate two patterns of motion: straight driving and a spin turn. On the other hand, it was also found that more trials were needed to control the TW-2 at the right-angle intersection in the pivot turn mode than in the spin turn mode. Therefore, the spin turn mode is more suitable than the pivot turn mode for narrow sidewalks or roads where subtle operation is needed. Moreover, it was found that it is more difficult for elderly people than for young people to manipulate TW-2 in the pivot turn. This is because the pivot turn is more difficult to execute as it requires both subtle movements and complex lever operations (as shown in Table 2). In addition, it is assumed that the motion of the pivot turn is easier to understand because the center of rotation is located near the rotational center of the human body. To sum up, we found that the rotational movement of TW-2 can be realized by using the forward and backward components of the ground reaction force during the rotational walking movement. In addition, we found that the system requires a new operating method for easier operation than is provided by the current system.

6. Functional Comparison of the TW-1 and the TW-2

We developed a treadmill system with one or two belts (one for each foot) that are used to detect the forward and backward component of the ground reaction force, which is the kicking force during walking movement. Additionally, we developed a new vehicle, called TW-2, that could conduct rotational movements based on the pattern of the kicking forces applied by the right and left feet of the user as he or she walks on a two-belt treadmill. As a result, the operations for both straight movement and rotational movement are realized directly by using the human gait.

Because the driving movement can easily be matched to the user’s physical condition, and an arbitrary driving velocity can be set in the system, it is expected that elderly people could use TW-2 to maintain their walking function while improving their overall mobility.

	TW-1	TW-2
Overall	Weight: lighter Driving time (lead battery); long but heavy Center of rotation: similar to that of a bicycle	Weight: heavier Driving time (Ni-H); light but short Center of rotation: similar to a human turning
Steering subsystem	Handle: user-friendly; similar to that of a bicycle	Switching lever: Safe, but not user-friendly
Walking subsystem	One motor: fewer parts	Two belts: permits measurement of the force for each leg and enables the walking phase to be analyzed.
Driving subsystem	Front drive: simple	Center drive and omni-wheel: similar to human turning, but requires many parts
Target person and purpose	Young to healthy elderly with a functional ability to walk; prevention of need for care; amusement and sport	Young to healthy elderly with functional ability to walk; prevention of need for care; amusement and sports. Possibly adaptable for paraplegic patients (if safety measure are adopted)

Table 4. Comparison of Characteristics

It became clear from the functional evaluation of the two prototypes that such systems show merits and demerits. Table 4 shows a comparison of characteristics for various function performed by the TW-1 and TW-2.

Three functions of TW-1 were modified in TW-2. The steering subsystem has a two-switch lever for selection of a spin turn or a pivot turn; however, this switching system is a little complex and requires some skill on the behalf of the operator. The walking subsystem has two belts and two motors; this system realized the requirement for turning the vehicle by measuring the force differential between each leg during walking. However, because this system requires one more motor than is used in the TW-1, it adds weight to the system and requires additional power. The driving subsystem adopted a center drive and an omni-wheel system; this system realized the requirement to be centered on the center of the human operator. However, the design requires two more casters than is the case for the TW-1. Overall, the TW-2 was adequate for its required function, but some problems, such as weight and usability, emerged. Therefore, to improve the TW-2 system, we suggest that the handle of the steering system requires adaptation to be more user friendly, and the structure requires modifications to achieve weight savings. For the walking subsystem, we suggest that there needs to be improvements in the system for evaluating the walking ability of users in clinical use.

7. Conclusion

In this chapter, we describe that the development of Tread-Walk2 (TW-2), which effects changes in direction by using the difference between the patterns of kicking and braking

forces applied to the treadmill belt by the soles of the right and left feet of the user as an input signal. TW-2 can conduct rotational movements that are based on the pattern of the right and left kicking forces applied by the feet of the user as he or she walks on the two-belt treadmill. As a result, the operations for both straight movement and rotational movement are realized by using the human walking movement. Furthermore, on the basis of a comparison of the functions of the three subsystems of TW-1 and TW-2, the advantages and disadvantages of each were clarified. From the result of this comparison, TW-2 was found to be adequate for its required function; however, we recognize that some problems remain, and it is necessary to make improvements in the weight of the vehicle and in the usability of the steering system.

In future, more work is needed to improve the TW-2 so that it is more useful and easier to operate than the other vehicles that elderly people use daily. Specifically, the walking subsystem of TW-2 needs to be developed so that it accommodates people whose right-leg and left-leg walking patterns and performances differ, e.g. as in the case of hemiplegia; in such case, it will be necessary to consider and improve the assistance parameters for each leg individually.

8. Acknowledgements

This work was supported in part by the 21st Century Center of Excellence Program "The innovative research on symbiosis technologies for human and robots in an elderly dominated society", Waseda University, Tokyo, Japan, the "Establishment of a Consolidated Research Institute for Advanced Science and Medical Care", Encouraging Development Strategic Research Centers Program, the Special Coordination Funds for Promoting Science and Technology, Ministry of Education, Culture, Sports, Science and Technology, Japan, the robotic medical technology cluster in Gifu prefecture," Knowledge Cluster Initiative, Ministry of Education, Culture, Sports, Science and Technology, Japan and KAKENHI 207004600.

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Robotics 2010 Current and Future Challenges

Edited by Houssem Abdellatif

ISBN 978-953-7619-78-7

Hard cover, 494 pages

Publisher InTech

Published online 01, February, 2010

Published in print edition February, 2010

Without a doubt, robotics has made an incredible progress over the last decades. The vision of developing, designing and creating technical systems that help humans to achieve hard and complex tasks, has intelligently led to an incredible variety of solutions. There are barely technical fields that could exhibit more interdisciplinary interconnections like robotics. This fact is generated by highly complex challenges imposed by robotic systems, especially the requirement on intelligent and autonomous operation. This book tries to give an insight into the evolutionary process that takes place in robotics. It provides articles covering a wide range of this exciting area. The progress of technical challenges and concepts may illuminate the relationship between developments that seem to be completely different at first sight. The robotics remains an exciting scientific and engineering field. The community looks optimistically ahead and also looks forward for the future challenges and new development.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Misato Nihei, Takeshi Ando, Yuzo Kaneshige, Takenobu Inoue and Masakatsu G. Fujie (2010). Development of a New Vehicle Based on Human Walking Movement with a Turning System, *Robotics 2010 Current and Future Challenges*, Houssem Abdellatif (Ed.), ISBN: 978-953-7619-78-7, InTech, Available from: <http://www.intechopen.com/books/robotics-2010-current-and-future-challenges/development-of-a-new-vehicle-based-on-human-walking-movement-with-a-turning-system>

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