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Development of JARoW-II Active Robotic Walker Reflecting Pelvic Movements while Walking

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Abstract This paper addresses the problem of a novel walking assist scheme considering pelvic movements. Generally, pelvic motion includes pelvic tilt, pelvic rotation, and lateral pelvic displacement. When a human walks, the pelvis is meant to both tilt and rotate. Specifically, rotational movement on the pelvis' transverse plane and tilting movement on its coronal plane are related to stride length and step width in walking and center-of-gravity swaying in the left-and-right direction, respectively. With these considerations, we introduce the innovative design of our second generation assist robotic walker (JARoW-II) for elderly people in need of supervision. And, this paper proposes a pelvic based walking-support control technique employing JARoW-II. By facilitating pelvic movements while walking, we try to enhance and/or maintain ambulatory performances such as stride length. As another important feature, the scheme is realized without use of specific manual controls or additional equipment. In detail, JARoW-II allows to accurately generate both the direction and location of walking movement and the pelvic movement in a way that corresponds to the user's walking steps. In this paper, the implementation details based on the walking-support scheme are explained, and the effectiveness of the scheme by using JARoW-II is verified through extensive experiments in everyday environments.

Keywords Welfare robotics · Robotic walker · Human-robot interaction · Easy maneuverability · Walking intent · Reflecting pelvic movements

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1 Introduction

A declining birth rate and an aging population (aging society) continues to progress in Japan and other developed countries. An increase in a country's elderly population and a decrease in its younger population tend to reduce the overall ability of a society to provide adequate welfare services. Independent movement is often limited in the elderly due to degraded physical functions that accompany injuries and diseases and aging in general. This has the effect of contracting an elderly person's range of activities and the size of that person's community. Such limitations can produce a lack of motivation and other adverse effects on a person's mental state. Additionally, a drop in activity and loss of physical strength can lead to a downward spiral that ends up with the need for nursing care. Against this background, preventing deterioration of physical functions toward a state requiring nursing care is becoming increasingly important to reduce the number of elderly people under care. Leading an independent life is also important for elderly people in terms of a reason for living and self-esteem. To improve the quality of life for the elderly, ambulatory ability must be maintained and improved since it serves as an indispensable foundation for all sorts of movements and independent living.

The ambulatory ability of elderly people generally declines with age. To define their mobility status, gait assessment methods have been reported. For example, there include Performance-Oriented Mobility Assessment (POMA) [1], Functional Ambulation Classification (FAC) [2], and Berg Balance Scale (BBS) [3]. Among them, mobility status in FAC is rated on a 6-point scale from one, indicating a nonfunctional ambulator, to six, denoting an ambulator. Specifically, the scale means the degree of human assistance needed to ambulate on flat types of surfaces.

Based on an individual mobility status, walking aids such as canes, walkers, and rolling walkers are widely used to provide walking assistance. However, such aids can be difficult to handle for users with very little muscular strength. Moreover, some walkers that attempt to make handling easier such as by fixing the direction of a walker's wheels suffer a drop in turning performance, which can make them difficult to use in a daily routine. There have also been reports [4][5] about the risk of falling due to nonlevel surface conditions. Dealing with inclines or ramps can also be difficult with such walking aids.

To overcome these difficulties, robotic walkers have been studied and developed. The robotic walkers intend to be used by elderly people with declining muscular strength and impaired walking ability or patients with impaired walking ability due to an injury or physical disability. For example, there are passive robotic walkers that install motors in the wheel units of existing walkers [6][7]. Passive prototypes mounting special mechanisms such as servo brakes deal with ramps and prevent the user from falling were reported in [8][9]. Typical robotic walkers aim to enhance the ambulatory-assistance effect by using various types of actuators [10][11]. Moreover, the robotic cane uses no maneuvering apparatus with the objective of improving operability [12]. Like these examples, robotic walkers meeting a variety of needs have recently been developed to provide ambulatory assistance. However, to promote effective movements while providing physical assistance, there are still few robotic walkers for either elderly people in need of nursing care or relatively healthy elderly people.

Meanwhile, the first version of JAIST Active Robotic Walker (JARoW) [13][14] was developed to provide elderly people with two main functionalities. First, easy and reliable maneuverability for JARoW was presented to replace the burden of additional hardware, software, and heaps of hard-to-remember safety and operating rules. Secondly, from the viewpoint of the safe navigation of JARoW in a cluttered environment, the sensory assistance functionality was realized. Through early obstacle detection, this functionality helped the elderly be prevented from a balance problem caused by sudden velocity (and/or direction) changes. Our idea behind these features was that human walking within JARoW was regarded as movements on a 2-D plane. In detail, according to geometric relations between lower limbs, the human walking was defined as four walking states: stop, forward/backward movement, step left/right, and turning left/right. However, the human gait is nonlinear, and the centre of gravity of a human body during walking is expressed as a motion in a 3-D space. As another example, pelvic motion is represented as pelvic tilt, pelvic rotation, and lateral pelvic displacement. Thus, to support the smooth and accurate walking motions of elderly people, a more sophisticated robotic walker corresponding to their human gait is required.

Fig. 1 Conceptual design of JAIST Active Robotic Walker ver. 2 (JARoW-II) facilitating pelvic rotation in users

In this paper, we attempt to promote pelvic motion while walking by using a robotic walker to improve ambulatory ability for elderly people. The pelvic motion indicates a significant involvement in human walking [15]. In other words, the motion is coupled with lower-limb movements during walking. Specifically, when the human walks, the pelvis is meant to both tilt and rotate. From these, it is expected that pelvic rotational movement and tilting movement contribute greatly to an increase in stride length. However, there are few robotic walkers allowing to enhance walking behaviors by facilitating the pelvic movements autonomously. With this considerations in mind, the second version of our JAIST Active Robotic Walker (JARoW-II) highlighting walking and pelvic movements is designed and developed toward delaying needs for nursing care. Moreover, we expect to prevent relatively healthy elderly people from needing nursing care. Fig. 1 shows the conceptual design of JARoW-II for elderly people corresponding to the Category-5 [1] and Category-6 [2] in FAC [2].

The remainder of this paper is organized as follows. Section 2 summarizes the walking characteristics of el-

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[1] (Independent, Level surfaces only): Patient can ambulate independently on level surfaces, but requires supervision or physical assistance to negotiate any of the following: stairs, inclines, or nonlevel surfaces.

[2] (Ambulator, Independent): Patient can ambulate independently on nonlevel and level surfaces, stairs, and inclines.

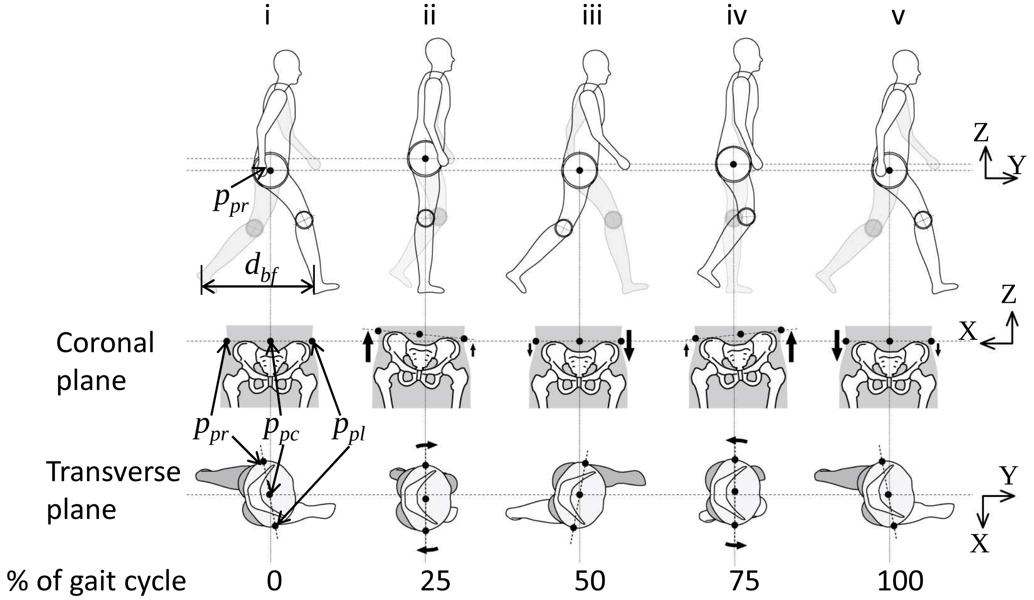


Fig. 2 Successive phases of pelvic movements in one gait cycle

derly persons and defines the problem to be solved in relation to robotic walkers. Section 3 analyzes human gait and pelvic movements in a gait cycle and introduces a simplified model. It then proposes a mechanism based on this model to reproduce pelvic movements. Section 4 describes the design of JARoW-II and system configuration. In JARoW-II system development, our aim is to read the user's foot movements with mounted range finders, and based on that data, to reproduce pelvic motions applicable to the direction and speed of walking and the user's gait at that time. Section 5 describes a working experiment to assess the developed system functions for facilitating pelvic motions while walking. The experiment also checks whether the JARoW-II system can be used for any elderly person with any gait by having several elderly subjects with different step lengths and walking rates use the system. Finally, Section 6 summarizes the paper and discusses the future outlook for this technology.

2 Walking Characteristics of the Elderly and Problem Definition

The following characteristics can be observed in elderly persons with diminished ambulatory ability, the target of this research [16][17]. To begin with, a decrease in walking speed owing to a shortening of stride length is conspicuous. This is induced by a shift in the person's center of mass associated with walking behavior. In addition, there is a tendency for step width to increase and walking rate to decrease due to a diminished sense of balance, which in turn causes an increase in the double support phase, increase in back-and-forth swaying in the upper body, decrease in joint angle range, and increase in the forward-leaning angle, respectively.

Walking takes on special significance for elderly persons. In particular, research targeting the elderly has shown that a decrease in walking speed can be a predictor of a decline in daily functioning and of the occurrence of falls and can even contribute to a life and death prognosis [18]. This is because walking itself requires support from various parts of the body such as cardiopulmonary functions, the circulatory system including internal organs, and the musculoskeletal system. In other words, a decrease in walking speed reflects a decline in physical functions. Accordingly, maintaining walking speed through efforts at maintaining health with the idea of preventing nursing care is important as a health-related index. There are various techniques for maintaining walking speed, and in recent years, the number of elderly persons involved in sports activities and muscle training as means of maintaining one's health has been increasing. Of course, having the ability of engaging in such health-maintenance activities is desirable, but at the same time, making walking into a routine activity should naturally help to maintain ambulatory ability.

In general, elderly people walk slower than young people. When making a conscious effort at increasing walking speed, a young person will tend to increase stride length while an elderly person will tend to increase walking rate while hardly changing stride length. Similarly, on analyzing walking behavior in terms of stride length, walking rate, and other factors, it was found that, for subjects walking at a speed at which walking is easiest, the amount of required energy per step is the same regardless of physical features such as height [19]. Consequently, when walking a certain distance, an elderly person will tire easily compared with a young person due to individual walking behavior dependent on walking rate. In other words, walking generates a bigger load for an older person.

Maintaining walking speed by increasing stride length without increasing walking rate is necessary as an ambulatory assistance technique that aims to prevent the need for nursing care. In this regard, it is said that a decrease in the stride length of an elderly person originates in the swaying of the person's center of mass associated with walking behavior [20]. For this reason, we focused on pelvic movements in walking that are considered to have an effect on stride length and center-of-gravity swaying. We observed, in particular, rotational movement on the pelvis' transverse plane and tilting movement on its coronal plane, which are related to stride length and step width in walking and center-of-gravity swaying in the left-and-right direction. These walking-associated pelvic movements are not being performed appropriately in the elderly, and we considered that improving them could improve their overall walking behavior.

In this paper, we describe the development of a walking-assist system facilitating pelvic movements to see what kind of effects stimulating the pelvis while walking can have on the walking behavior of elderly people. First, however, we analyze the relationship between walking and pelvic movements and propose a mechanism for facilitating pelvic movements based on the results of that analysis.

3 Pelvic Movements in Walking and Proposed Mechanism

3.1 Analysis of Pelvic Movements

Walking, in general, consists of cyclic movements having a periodicity that can be expressed by a sine wave [21]. The simplified flow of both ends of the pelvis when dividing one gait cycle into four segments (five phases of pelvic movements) is shown in Fig. 2. Here, the left and right endpoints of the pelvis are denoted as p_{pl} and p_{pr} respectively, and the center point lying between those two points as pelvis center point p_{pc}. In the figure, phase [i] shows the instant at which the heel of the right foot touches the ground (0%), phase [ii] the mid-stance (25%), phase [iii] the instant at which the heel of the left foot touches the ground (50%), phase [iv] the midswing (75%), and phase [v] the instant at which the heel of the right foot again touches the ground (100%). First, in the transverse plane, each pelvis endpoint rotates about p_{pc}, one moving forward in the direction of the swing leg and the other moving backward in the direction of the standing leg. The resulting angle of rotation is maximum in phases [i], [iii], and [v]. Next, in the coronal plane, one of the pelvis endpoints rises on the side of the standing leg in the single support phase while the pelvis tilts laterally from the standing leg to the swing leg. Then, in the double support phase, the same pelvis endpoint drops vertically. This vertical drop is maximum in phases [i], [iii], and [v] and the vertical rise on the standing leg is maximum in phases [ii] and [iv].

The movement of each pelvis endpoint in the above gait cycle can be approximated as follows. At time t, denoting the movement in the transverse plane of right pelvis endpoint p_{pr} as y_r and that of left pelvis endpoint p_{pl} as y_l, we get the following equations:

$$y_r = k_1 \sin(\omega_1 t + \frac{\pi}{2}), \tag{1}$$

$$y_l = k_1 \sin(\omega_1 t - \frac{\pi}{2}). \tag{2}$$

Here, k_1 is the amplitude of the pelvis endpoints at the time of maximum rotation and ω_1 is the angular speed of the pelvis endpoints in the Y direction (direction of travel).

Next, at time t, denoting the movement in the coronal plane of right pelvis endpoint p_{pr} as z_r and that of left pelvis endpoint p_{pl} as z_l, we get the following equations:

$$z_r = \{ \begin{array}{cc} k_2 \sin(\omega_2 t) & (0 < t \leq \pi) \\ -k_3 \sin(\omega_2 t) & (\pi < t \leq 2\pi) \end{array} , \tag{3}$$

$$z_l = \{ \begin{array}{cc} k_3 \sin(\omega_2 t) & (0 < t \leq \pi) \\ -k_2 \sin(\omega_2 t) & (\pi < t \leq 2\pi) \end{array} . \tag{4}$$

Here, k_2 is the amplitude of the pelvis endpoint on the standing leg, k_3 is the amplitude of the pelvis endpoint on the swing leg, and ω_2 is the angular speed of the pelvis endpoint in the Z direction (up/down direction).

3.2 Pace and Pelvic Movement Mechanism

In this paper, with the aim of developing a mechanism to facilitate pelvic movements adaptable to the gait of the user, we propose a technique for estimating pelvic movement from distance data between both feet. From

Eqs. (1)-(4), the relationship between displacement in the Y direction d_{py} and displacement in the Z direction d_{pz} of the pelvis endpoints is as follows for the standing leg and swing leg:

$$d_{pz} = \begin{cases} k_2 \cos(\frac{\pi}{2} \cdot \frac{d_{py}}{k_1}) & \text{(stance phase)} \\ k_3 \cos(\frac{\pi}{2} \cdot \frac{d_{py}}{k_1}) & \text{(swing phase)} \end{cases} . \quad (5)$$

Next, as shown in Fig. 2, we denote the distance between both feet in each phase as d_{bf} and stride length as d_{sl}. Here, d_{bf} and d_{py} have a positive correlation. The positional relationship between the distance between both feet and the pelvis endpoint is therefore as follows taking into account the acceleration/deceleration interval of the users pace:

$$d_{py} = \begin{cases} k_1 \sin(\frac{\pi}{2} \cdot \frac{d_{bf}}{d_{sl}}) & \text{(stance phase)} \\ -k_1 \sin(\frac{\pi}{2} \cdot \frac{d_{bf}}{d_{sl}}) & \text{(swing phase)} \end{cases} , \quad (6)$$

$$d_{pz} = \begin{cases} k_2 \cos(\frac{\pi}{2} \cdot \frac{d_{bf}}{d_{sl}}) & \text{(stance phase)} \\ k_3 \cos(\frac{\pi}{2} \cdot \frac{d_{bf}}{d_{sl}}) & \text{(swing phase)} \end{cases} . \quad (7)$$

Based on the above equations, we treat rotational movement in the pelvis transverse plane as yawing motion and tilting movement in the pelvis coronal plane as rolling motion. In this way, we develop a drive mechanism for transferring such motion to the pelvis and implement the mechanism as the JARoW-II robotic walker.

4 Design of JARoW-II

4.1 Configuration of JARoW-II

The JARoW-II robotic walker features a system for improving walking behavior by supporting the user's weight and facilitating pelvic movements while walking. When the JARoW-II user takes a step forward in a certain direction, the role of this system is to read that movement with range finders and facilitate walking based on user intent. The appearance of a JARoW-II prototype that we constructed for implementing this concept is shown in Fig. 3. The JARoW-II frame consists of a base frame and upper frame. The upper frame is supported by the base frame and is positioned at the center of the base frame. As shown in Fig. 3 (a), the base frame consists of a leg frame having a front leg (R), front leg (L), and rear leg extending in three directions from frame center at 120° intervals. The tip of each leg features an omni-wheel unit for a total of three wheels. These three equally spaced omni-wheel units enable JARoW-II to move in all directions. Total length, width, and height of JARoW-II are 766 × 850 × 740-922 [mm]. As shown in Fig. 3 (b), the user walks with the buttocks set at the edge of the seat. The upper frame has a mechanism for adjusting height relative to the base frame according to user leg length. As shown in Fig. 3 (c), it can accommodate users having a leg length of 67-85 [cm]. The upper frame is also equipped with a pelvis control unit for reproducing ideal pelvic movements while walking. (The pelvis control unit is described in detail later.) In addition, the rear leg is equipped with an interface for measuring user foot movements and the main controller and battery unit are installed at the rear of the base frame, as shown in Fig. 3 (d).

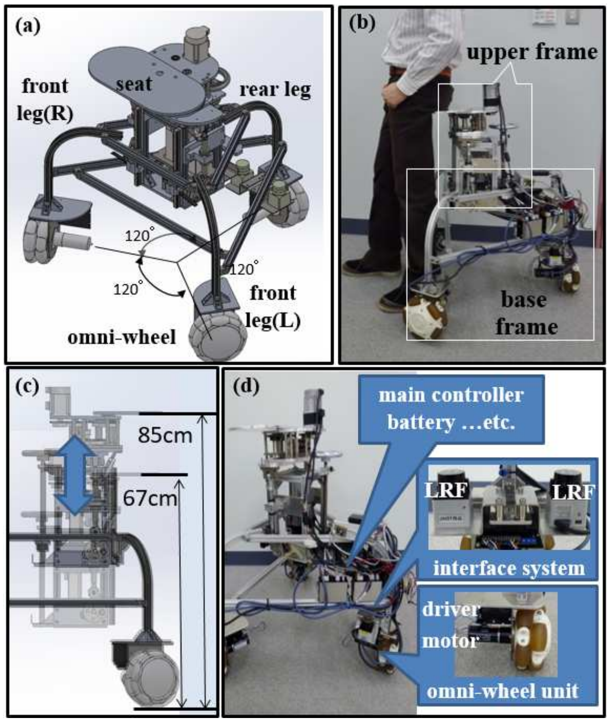


Fig. 3 JARoW-II's mechanical configuration: (a) mechanical structure of JARoW-II (b) upper frame and base frame (c) length modification according to the height of potential users, and (d) main controller, interface system, and wheel drive system

4.2 Wheel Drive System

The wheel drive system determines the speed and direction of the JARoW-II robotic walker in response to foot movements accompanying user walking. This system consists of an interface, main controller, and omni-wheel units. As shown in Fig. 3 (d), the interface incorporates two laser range finders (LRFs) from Hokuyo Automatic Co. Ltd. (model URG-04LX). Installed at a height of 210mm from the ground, these LRFs obtain coordinate data for the surface of the user's lower

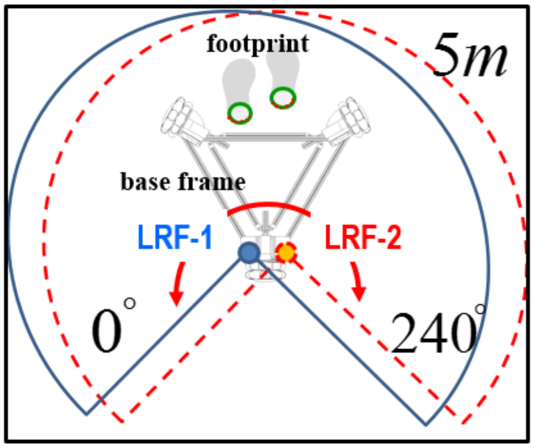


Fig. 4 Interface system detecting the relative locations of lower limbs modeled as cylinders

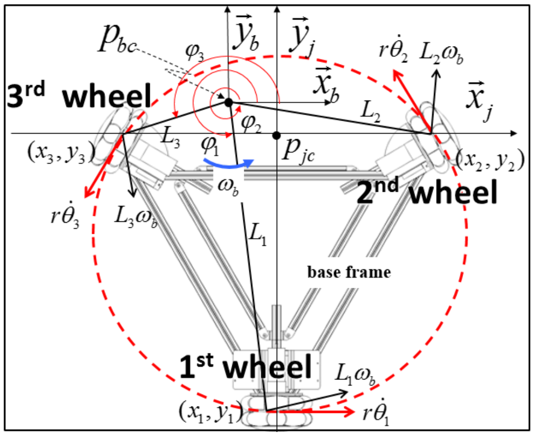


Fig. 5 Illustration of JARoW-II's kinematics

limbs, as shown in Fig. 4. Each LRF has a scanning range of 240° with a radius of $5m$. The system combines the range data obtained from these two LRFs to mutually supplement the foot position data of each. The interface also picks up environmental information such as obstacles that lie within 5 m of the direction of travel. This information is sent to the main controller for various types of computational processing. (Computational processing in the main controller is described in detail later.) The results of this processing are output as omni-wheel movement to move JARoW-II in a way that follows the user's movement. Each omni-wheel unit consists of an omni-wheel from Soai Co., Ltd. combined with a $120W$ brushless DC motor, 43:1 reducer, and motor driver from Maxon motor. A single motor controller integrates three omni-wheel units. This wheel drive system enables a maximum speed in the forward direction on level ground of 5.70 km/h, which is sufficient for accommodating the walking speed of elderly persons.

A simplified schematic of the base frame as seen from the underside is shown in Fig. 5. In the figure, the base frames virtual center position p_{jc} serves as the origin of local coordinate system $\vec{x_j}$, $\vec{y_j}$. In addition the users body center position $p_{bc} = (x_b, y_b)$ serves as the origin of local coordinate system $\vec{x_b}$, $\vec{y_b}$. Now, denoting $\vec{x_j}$, $\vec{y_j}$ coordinates of the ith wheel ($i = 1, 2, 3$) as (x_i, y_i), the angle of deviation φ_i is expressed as follows:

$$\varphi_i = \tan^{-1}\left(\frac{y_i - y_b}{x_i - x_b}\right). \tag{8}$$

Next, distance L_i between each wheel (x_i, y_i) and body center position p_{bc} is expressed as follows:

$$L_i = \sqrt{(y_i - y_b)^2 + (x_i - x_b)^2}. \tag{9}$$

From Eqs. (8) and (9), angular speed $\dot{\theta}_i$ of the ith wheel is expressed as follows given the users speed vector $[\dot{x}_b \ \dot{y}_b \ \omega_b]^T$

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} = \frac{1}{r} \begin{bmatrix} -1 & 0 & L_0 \cos(\frac{\pi}{2} - \varphi_1) \\ \cos\frac{\pi}{3} & -\sin\frac{\pi}{3} & L_1 \cos(\frac{7\pi}{6} - \varphi_2) \\ \cos\frac{\pi}{3} & \sin\frac{\pi}{3} & L_2 \cos(\frac{\pi}{6} + \varphi_3) \end{bmatrix} \begin{bmatrix} \dot{x}_b \\ \dot{y}_b \\ \omega_b \end{bmatrix}. \tag{10}$$

Here, r is the radius of the wheel and p_{bc} and p_{jc} lie on the same horizontal plane. These equations are used to drive JARoW-II so as to follow the walking speed of the user.

4.3 Seat Actuator System

A simplified schematic of the JARoW-II pelvis control unit built into the upper frame is shown in Fig. 6. The seat actuator system consists of the aforementioned interface and main controller and this pelvis control unit. This system, which is a distinctive feature of JARoW-II, calculates the user's current gait from the user's foot movements picked up by the interface and estimates pelvic movements applicable to those foot movements. Then, as output, the system controls the pelvis control unit to facilitate pelvic movements and assist the user in walking.

The pelvis control unit consists of three AC servomotors from Tamagawa Electronics Co., Ltd., associated drivers and reducers, and a motor controller integrating the three motors. It features a drive mechanism that independently facilitates rolling and yawing of the user's buttocks with respect to the direction of travel. To generate a yawing motion, the pelvis control unit transmits a force to the seat using a $60W$ AC servomotor and a 400:1 reducer. A rolling motion, meanwhile, can be produced by independently moving each end of the seat in the up-and-down direction. This is accomplished by using a $100W$ AC servomotor and a 175:1 reducer on each end of the seat to transmit a force via a

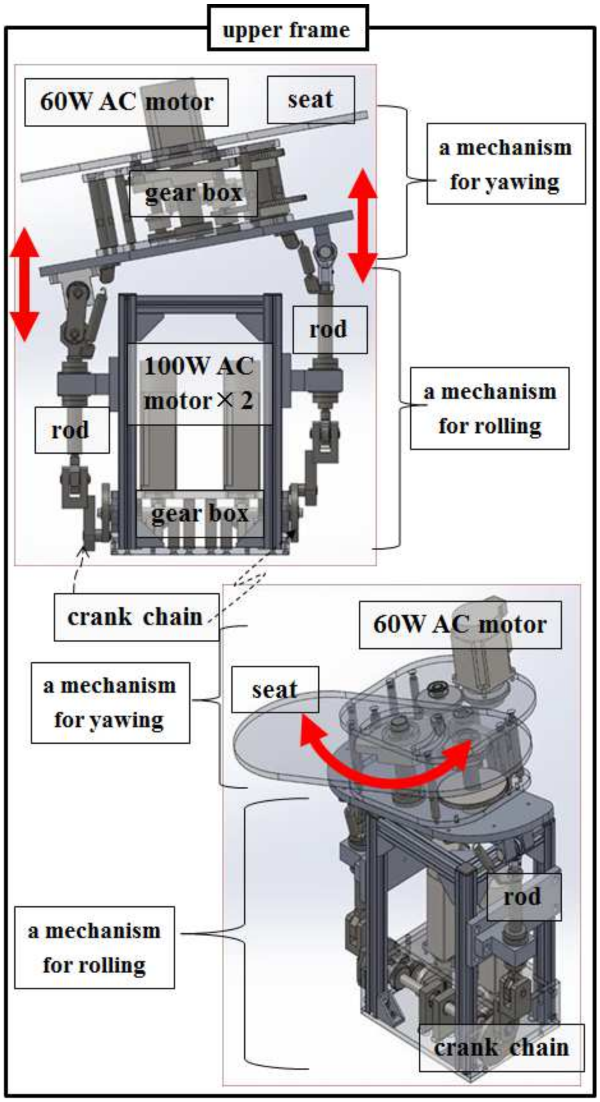


Fig. 6 Details of pelvis control unit in upper frame of JARoW-II

crank mechanism and a connecting rod. The pelvis control unit can generate a maximum yaw angle of 15° as a rotation and a maximum roll angle of 20° as a tilt about the seat's center. These maximum angle settings provide for a sufficient range of motion in everyday walking behavior.

4.4 Main Controller

The control flowchart of the JARoW-II robotic walker is shown in Fig. 7. The main controller inputs the coordinate data for the surface of the user's lower limbs obtained by the interface and calculates the movement of the JARoW-II omni-wheels and seat as output at intervals of approximately 100ms. The main controller incorporates two key modules: the observation module that observes and estimates the current movements of the user and the motion control module that generates JARoW-II movements based on the observed and estimated user movements. The observation module, in turn, consists of a measurement function and a walking behavior state determination (WBSD) function. The motion control module, meanwhile, consists of a walker motion generation function and human motion generation function.

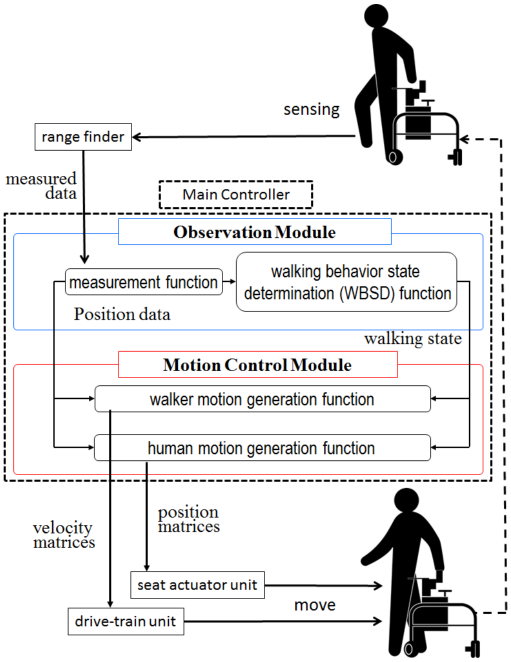


Fig. 7 Control flow in the main controller of JARoW-II

First, the measurement function uses the coordinate data for the surface of the user's lower limbs to observe and estimate the current movement of each foot's center position and the user's body center position. Then, based on the results obtained, the function calculates the relative distance between both feet and continuously calculates the mean value and standard deviation of that value from multiple samplings over a fixed period. It simultaneously calculates stride length and walking speed as well.

Next, the WBSD function determines the user's walking behavior based on each foot's center position and the user's body center position obtained by the measurement function and on displacement values from past data. User walking behavior is divided into six states: forward and backward motion, left/right linear motion, and left/right turning motion. The movements of JARoW-II are determined every 100ms as movement modes corresponding to those six states of walking. These modes are combined to produce JARoW-II movement in any direction.

Continuing on, the walker motion generation function calculates JARoW-II movement speed in accordance with user walking speed. Specifically, this function serves to move JARoW-II so that the user's body center position $p_{bc} = (x_b, y_b)$ estimated by the measurement function and the JARoW-II virtual center position $p_{jc} = (x_j, y_j)$ always match up in the local coordinate system on the same horizontal plane. The walker motion generation function determines JARoW-II speed by an estimating equation that takes into account walking speed based on proportional-integral-derivative (PID) control. Now, denoting the difference between p_{bc} and p_{jc} as $e = (e_x, e_y) = (x_j - x_b, y_j - y_b)$, we can express speeds $\dot{x}_b$, $\dot{y}_b$ in the $\overrightarrow{x}_b$, $\overrightarrow{y}_b$ directions as follows:

$$\begin{array}{rcl} \dot{x}_b &=& K_{p,x}\ e_x + K_{i,x}\ \int e_x dt + K_{d,x}\ \dot{e}_x \\ \dot{y}_b &=& v_{bve} + K_{p,y}\ e_y + K_{i,y}\ \int e_y dt + K_{d,y}\ \dot{e}_y \end{array} . \quad (11)$$

Here, v_{bve} is the estimated user walking speed, which can be set as follows in terms of stride length d_{sl} and stride time t_{sl}:

$$v_{bve} = \frac{d_{sl}}{2t_{sl}}. \quad (12)$$

For details on the measurement function, WBSD function, and walker motion generation function, you can see the following [14].

Next, the human motion generation function estimates gait from the current location of the user's feet and calculates the angle of rotation and angle of tilt of the user's buttocks. In addition, it simultaneously controls the pelvis control unit based on these calculated movements. This function takes the following data as given: center position of the left foot $p_l = (p_{l,x}, p_{l,y})$ and center position of the right foot $p_r = (p_{r,x}, p_{r,y})$ calculated by the measurement function, absolute distance $d_y(t) = |p_{ly} - p_{ry}|$ between both feet in the $\overrightarrow{y}_j$ direction (direction of travel) at time t, and new stride length $d_{sl}(t)$ at time t. Using this data, buttocks yaw angle ω_{yaw} and roll angle ω_{roll} at time t are set as follows:

$$\omega_{yaw} = k_{yaw} \sin(\alpha(t) + \varphi_1) \quad (13)$$

$$\omega_{roll} = \{ \begin{array}{ll} k_{roll1} \cos(\alpha(t) + \varphi_2) & \text{if}(v_{ly} > 0) \\ k_{roll2} \cos(\alpha(t) + \varphi_2) & \text{if}(v_{ry} > 0) \end{array} \quad (14)$$

where $\alpha(t)$ is given

$$\alpha(t) = \frac{\pi}{2} \cdot \frac{d_y(t)}{d_{sl}(t)}. \quad (15)$$

In these models, k_{yaw}, k_{roll1}, and k_{roll2} are coefficients related to buttocks movements corresponding to the yaw angle and roll angle. These coefficients are set according to the physical characteristics and gait characteristics of each user. In addition, φ_1 and φ_2 denote phase differences related to yaw angle and roll angle that consider the time difference between buttocks movement and pelvic movement and system-type differences related to measured foot positions and actual pelvic movements. Maximum amplitudes of the yaw angle and roll angle are taken to be 5° and 4-7°, respectively [20], and parameters are set to achieve those values. Finally, v_{ly} and v_{ry} are relative speeds of the left foot and right foot, respectively, in the $\overrightarrow{y}_j$ direction as seen from JARoW-II.

5 Experiments Using Actual Equipment and Subjects

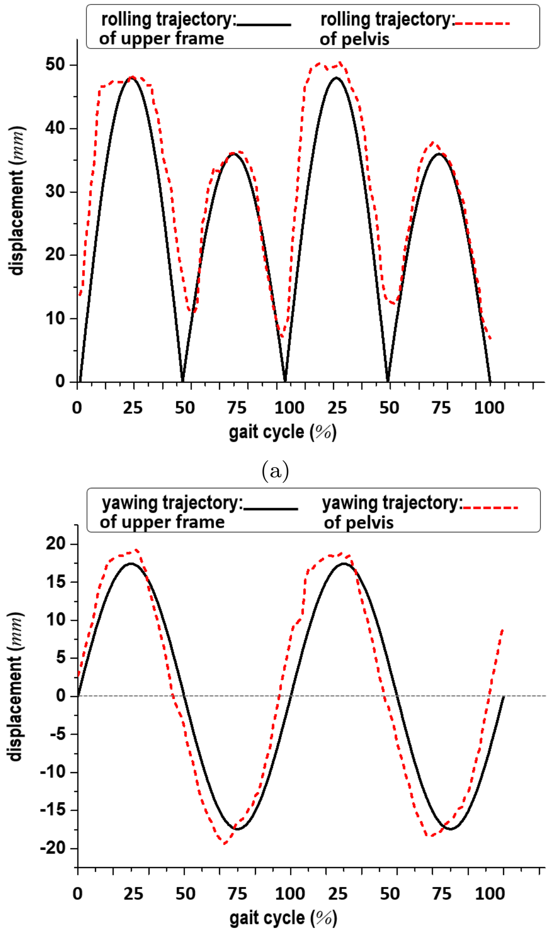
5.1 Experiment on Movement of Pelvis Control Unit

We conducted an experiment to see if the prototype pelvis control unit could reproduce the pelvic movements described in Section 3. First, we set the height of the seat installed on the JARoW-II robotic walker to the user's leg length. In the experiment, the user sets his or her buttocks on the seat (without completely sitting down) and proceeds to walk. The seat includes no belt or harness to restrain the user. Instead, the seat is "tucked in" the buttocks from the left side to the right side of the pelvis by a plate while nudging the user's center to the center of the seat. This plate has the role of prompting the user to move toward the center at all times without applying a constraining forcethe user is allowed to slide to the left or right. In this experiment, we examined the difference between the movements of the seat as the user walked and the actual movements of the user's pelvis endpoints (defined in Section 3.1). Here, seat endpoints are defined as the intersection of the seat surface and the line dropped vertically from the pelvis endpoints in a stopped state.

Experimental results are shown in Fig. 8. These results show displacement $[cm]$ of a subject's right pelvis endpoint (broken line) and of the seat's right endpoint (solid line) versus gait cycle [%]. In agreement with the gait cycle shown in Fig. 2, 0% in the gait cycle of these results corresponds to the instant in which the user's right heel touches the ground. Here, Fig. 8-(a) shows rolling trajectories with the point at which the seat end point is lowest set to 0, while Fig. 8-(b) shows yawing trajectories with the amount of displacement at the time of no revolution set to 0 and displacement in the direction of travel taken to be positive. It can be seen from these results that the seat trajectories track the pelvis trajectories well. It has therefore been shown on

Table 1 Breakdown of subjects' ages and physical conditions

subject	gender	age	height (cm)	walking status	notes
A	female	79	156	cane	knee condition
B	male	80	173	free	hip condition
C	male	78	165	free	unstable walking after stroke
D	female	75	153	free	back condition
E	male	84	160	free	



(a)

(b)

Fig. 8 Experimental results of comparing (a) rolling trajectories of the seat in the upper frame and rolling trajectories of a subject' pelvis and (b)yawing trajectories of the seat in the upper frame and yawing trajectories of a subject' pelvis

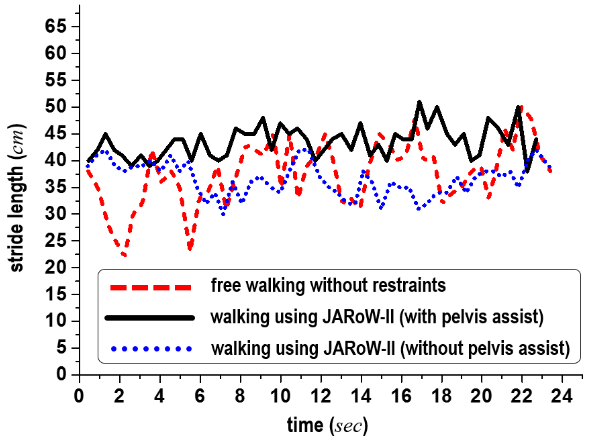
the basis of this experiment that movements of the prototype pelvis control unit can be correlated with pelvic movements.

5.2 Evaluation Experiment: Purpose and Method

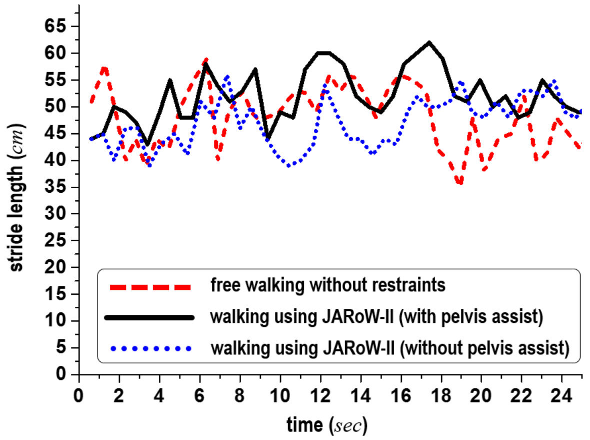
We developed JARoW-II with the aim of approaching ideal walking by the proposed walking-assist system. Here, we define ideal walking as walking with a fewer number of steps over a fixed travelling distance even at the same walking speed. In this evaluation experiment, our purpose was to see whether JARoW-II could function for subjects with any step length. We focused, in particular, on changes in stride length and accompanying changes in speed between ordinary walking and walking using JARoW-II.

Fig. 9 Outdoor experiment scene using JARoW-II with pelvis assist

We received the cooperation of five subjects for this evaluation experiment. These subjects consisted of three males and two females having different stride lengths and walking rates and all capable of walking on their own. Basic information on these subjects is listed in Table 1. As shown in Fig. 9, the experimental envi-



(a) results by a subject-1



(b) results by a subject-2

Fig. 10 Experimental results for the variations of stride lengths according to three walking conditions: free walking without any restraints (red dashed line), walking using JARoW-II with pelvis assist (black solid line), and walking using JARoW-II without pelvis assist (blue dotted line)

Table 2 Data analysis for experiments conducted with individual subjects

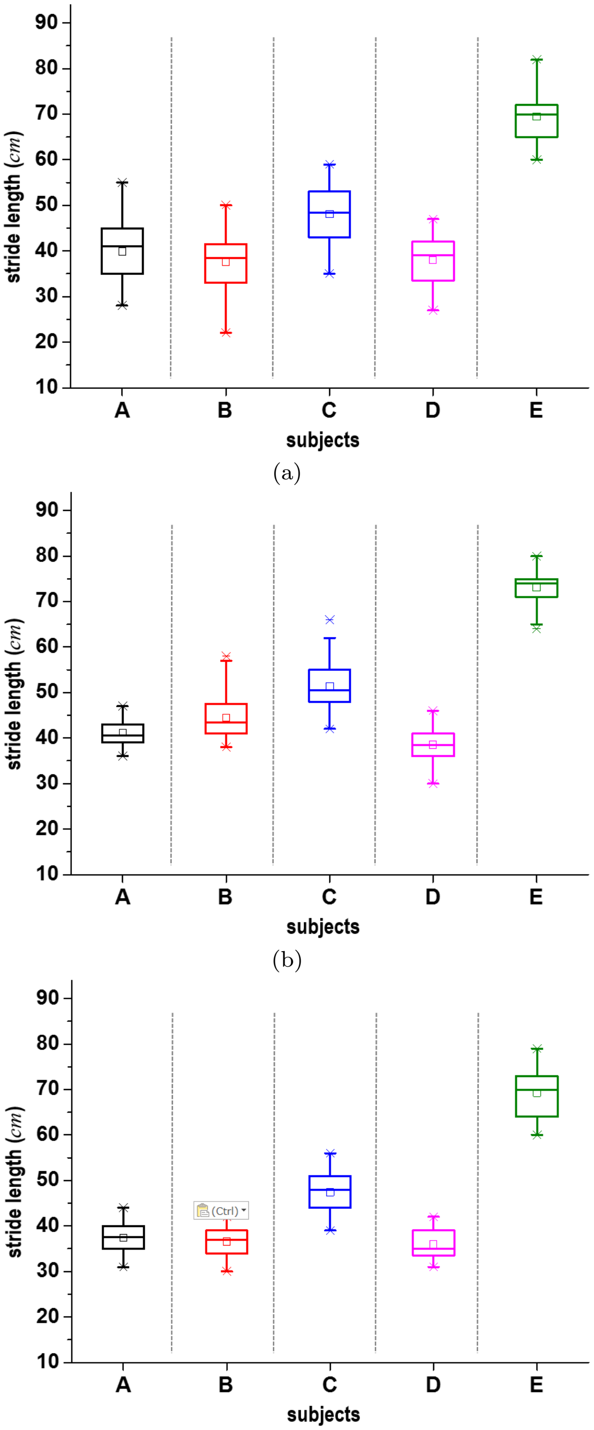
	subject	(a)	(b)	(c)
ave. walking speed[m/min]	A	34.2	34.6	32.6
	B	50.1	61.1	48.5
	C	48.4	51.0	48.2
	D	39.8	40.4	37.6
	E	60.0	64.2	61.7
ave. stride length [cm]	A	39.9	41.2	37.4
	B	37.6	44.5	36.6
	C	48.1	51.4	47.4
	D	38.0	38.5	35.9
	E	69.5	73.1	69.3
walking rate [$step/min$]	A	85.7	84.0	87.2
	B	133.2	137.4	132.5
	C	100.5	99.2	101.6
	D	104.6	104.9	104.6
	E	86.3	87.8	89.0

ronment consisted of a flat, stone-paved surface approximately 15m long. We first performed measurements to obtain walking data while each subject walked freely at a comfortable speed. We then obtained walking data while each subject used JARoW-II from five to eight times (number of times differed between subjects). We also performed a walking experiment using JARoW-II with the seat in a non-moving state (no pelvis assist) to clarify the effects of the pelvis control unit on walking. These walking measurements consisted of stopwatch measurements taken at traveling interval, stride length measurements, and measurements taken with an acceleration sensor attached to the subject. Images obtained by a fixed-point camera were also used in judging results. Each subject in Table 1 is walking while resting his or her buttocks on the JARoW-II seat without being completely seated, so backward tilting of the pelvis can hardly be seen in the postures shown here.

5.3 Evaluation Experiment: Results and Discussion

In this subsection, these experimental data was tabulated over approximately 10m of the walking experiments 15m to exclude acceleration/deceleration intervals. To begin with, Figs. 10 (a) and (b) show the comparison results performed by two anonymous subjects. These graphs plot the variations of the subject's stride lengths according to walking conditions. The red dashed lines, the black solid lines, and the blue dotted line indicate free walking without any restraints, walking using JARoW-II with pelvis assist, and walking using JARoW-II without pelvis assist, respectively. Although there were individual differences, compared to the red dashed lines, the the black solid lines enabled JARoW-II to generate pelvic motions with a smaller sum of variations (and larger stride lengths), resulting in smoother forward movements. From the results, we confirmed that a walking-support technique improved walking behavior by facilitating pelvic movements while walking.

Next, the experimental results for each subject are listed in Table 2. The tabulated values for the stride lengths of each subject are shown in Fig. 11 for (a) free walking without any restraints, (b) walking using JARoW-II with pelvis assist, and (c) walking using JARoW-II with no pelvis assist. Comparing results for situations (a) and (b), it can be seen that stride lengths increased for all subjects. In addition, walking rate changed only slightly if we exclude subject B, and walking speed rose with increase in stride length for all subjects. We attribute this small change in walking rate to the fact that walking with the robotic walker can be performed in the same way as free walking. Compared to the other subjects, subject B is tall with a long



(a)

(b)

(c)

Fig. 11 Comparison results for individual subjects with different stride lengths: (a) free walking without any restraints, (b) walking using JARoW-II (with pelvis assist), and (c) walking using JARoW-II (without pelvis assist), (Here, the error bars represent 95% confidence intervals and the boxes indicate distributions of measured data in the range of 25-75%)

leg length, so we consider that the assistance effect of rotational movement in putting the foot forward was large in his case. Conversely, the two female subjects of short stature exhibited a certain increase in stride length, but the effect here was minimal compared with the relatively tall male subjects. In addition, these results show that variation in step length was kept low for all subjects. This holds true even on comparing the results for situations (a) and (c), which leads us to infer that applying a little body weight to JARoW-II in situation (c) results in steady stepping by the user. Finally, on comparing the results for situations (b) and (c), it can be seen that stride length tends to shorten for situation (c) in which no pelvis assist is provided. This is because pelvic movements while walking are limited with no pelvis assist. Additionally, it can be said that a subject having no change in walking speed makes up for a drop in walking speed due to a decrease in stride length by increasing walking rate.

On the basis of this experiment targeting the elderly, it can be said that the newly developed pelvis control unit exhibits a certain effect. This can be seen by comparing "unconscious free walking of elderly persons = walking with a short stride length typical of the aged" with "walking with JARoW-II = walking with a long stride length and higher walking speed" for subjects having different step lengths. According to comments made by the subjects during and after the experiment, all five subjects had a favorable opinion of JARoW-II. In particular, it was found that they liked the sensation of being pushed along at their hips and of having a rhythm induced in their walking. Objectively speaking, these results cannot be said to be effective in preventing the need for nursing care. Nevertheless, it can be said that they had some kind of effect on how each elderly subject view everyday walking when performed by "unconscious walking typical of the aged" or "conscious walking using JARoW-II".

6 Conclusions

This paper proposed a walking-support technique that improves walking behavior by facilitating pelvic movements while walking. To evaluate the effectiveness of this technique, we constructed a prototype robotic walker (JARoW-II) having a mechanism for assisting pelvic movements. JARoW-II features a system that needs to input only user foot location data to output robotic-walker movements. In this way, the system becomes aware of the user's walking intent, which enables the robotic walker to be operated without the use of any maneuvering equipment. It was shown by experiments that the mechanism incorporating the proposed walking-support technique facilitated pelvic movements according to the gait of the user.

As our future studies, we will perform walking experiments with many elderly persons having a variety of walking characteristics to further assess the effectiveness of the developed system. In this paper, we described evaluation experiments with five subjects differing in stride length and walking rate as an initial stage of testing. It was found that the system could increase stride length, reduce variation in walking characteristics, and increase walking speed compared with free walking. Next, the physical energy issue of two phases of stance and swing during on gait cycle is extremely important. Toward the practical use of JARoW-II, from the viewpoint of the physical energy consumption, what may happen when individual users employ JARoW-II must be clearly examined.

In each of the experiments described in this paper, we adjusted various types of gain based on common walking data and made settings for individual subjects to approximate ideal pelvic movements while walking. As a next step, we will need to update the system to make individual settings unnecessary by referencing the results of past evaluation experiments and estimating and predicting pelvic movements from foot location data obtained by range finders. Moreover, we are planing to pursue long-term testing to determine whether further improvements in walking can be achieved with JARoW-II to prevent nursing care.

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