Human-carrying Biped Walking Vehicle

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***Abstract*—This paper describes the development of a prototype for a human-carrying biped walking vehicle named Waseda Leg – No. 16 Refined IV (WL-16RIV). This robot consists of two Stewart Platform type legs and waist with a passenger seat. This paper also describes a walking control method based on ZMP criteria. We introduced a passive dynamic model of a passenger in generating a walking pattern, and it enabled a more stable walking. The model consists of lower-limbs part assumed to be fixed to the robot, and the upper body assumed to be single particle with 2 DOF mounted on the seat via 2 springs and dampers. The parameters are identified through waist shaking experiments by using a force-torque sensor under the seat. The walking pattern generation method involves the proposed model built onto a strict model of the robot, and through iteration computation, a stable walking pattern is generated. We exhibited WL-16RIV at the Wired NextFest held in Los Angeles and held a test-riding event for the public for four days. In total, 172 people rode on this robot without accident. We confirmed the ruggedness and reliability of the developed mechanism and control method.**

I. INTRODUCTION

THE barrier-free concept has been disseminated in order to allow the elderly and disabled wheelchair users to be self-reliant and lead an active social life. However, realizing the barrier-free concept is very expensive and complex through infrastructure improvements alone. The final goal of this research is to build a biped walking wheelchair having locomotion and mobility equivalent to a human being. We believe that a biped walking wheelchair is a viable solution in barrier-free engineering that is much more effective and low-cost than infrastructure improvements.

There are some researches on locomotion modules that can carry human beings such as the “Walking Chair” [1], “My Agent” [2], “i-foot” developed by Toyota Motor Corporation [3], and “HUBO FX-1” developed by KAIST [4]. Through limited information about “i-foot”, the unladen weight is revealed at 200 kg, although the payload is 60 kg. As for “HUBO FX-1”, the robot’s weight is 150 kg, although the payload is 100 kg. They are too heavy for a human-living environment. An electric wheelchair “iBOT”, which negotiates stairs and slopes, is commercially available [5]. Although “iBOT” is set for completion as one suitable style of locomotion system for riders, the rider must grab a rigid stair rail while ascending and descending stairs. It is also impossible to move sideways. Moreover, its objective does not include operation within a narrow environment, full of non-traversable items, such as a Japanese traditional house.

Therefore, we have developed some biped locomotors, Waseda Leg - No. 15 (WL-15), WL-16, WL-16R, WL-16RII, WL-16RIII, and WL-16RIV which have 6-DOF parallel mechanism legs [6-10]. The newest prototype is WL-16RIV as shown in Fig. 1. This robot consists of two legs and a waist and is capable of walking independently with an unladen weight of about 80 kg. Using this robot, we studied the way to apply the biped walking robot to a mobile base. In November 2003, using WL-16, the world’s first of a dynamic biped walking while carrying a human was realized [7]. In addition, biped walking up and down stairs while carrying a human was realized in 2005 [8], and an outdoor walking was also realized in 2006 [9].

In this paper, our previous steps toward the realization of

Fig. 1. Waseda Leg – No.16 Refined IV (WL-16RIV).

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a human-carrying biped walking vehicle are described. Our steps include the development of hardware, control method and various experiments of the newest prototype WL-16RIV.

II. HARDWARE OF PROTOTYPE WASEDA LEG – NO. 16 REFINED IV

Considering the operation in a narrow environment such as a Japanese traditional house, a human-carrying biped walking vehicle should be small and lightweight. And of course, the robot must be able to carry a heavy load. To fulfill this requirement, the DOF configuration of the leg mechanism consists of a Stewart Platform as shown in Fig. 2. Most of biped robots adopt a serial linkage mechanism for their legs. However, it cannot be proved that a serial linkage mechanism is optimal to a biped walking. Table I compares general features of a parallel linkage mechanism and a serial linkage mechanism. A parallel linkage mechanism has some advantages compared with a serial one such as easily achieved inverse kinematics, an equalized position error, mechanism rigidity, a high output and so on.

The weight of WL-16RIV is 74 kg including 11 kg battery weight. We adopt a lithium-ion battery of Micro Vehicle Lab., Ltd. Lithium-ion battery has no memory effect, and it is rechargeable without refreshing. Each leg mechanism has 6 linear actuators and passive joints at the both sides of each linear actuator. For upper passive joints, we adopted commercial universal joints using needle bearings which are small, lightweight and have little backlash. For lower passive joints, new lightweight 3-DOF combination passive joints were developed in cooperation with HEPHIST Seiko Co., Ltd. (Fig. 3 (b)). In the previous prototype WL-16RIII, the housing bushing was made of resin (Fig. 3 (a)). If a large impact force acts on a robot's feet, the housing bushing has distortions, causing a backlash. Therefore, we changed the material of the housing bushing from resin to steel balls. The maximum movable angle of this joint is ± 35 deg.

Each linear actuator consists of a 150 W DC servo motor and a ball screw, and has a negative operation electro

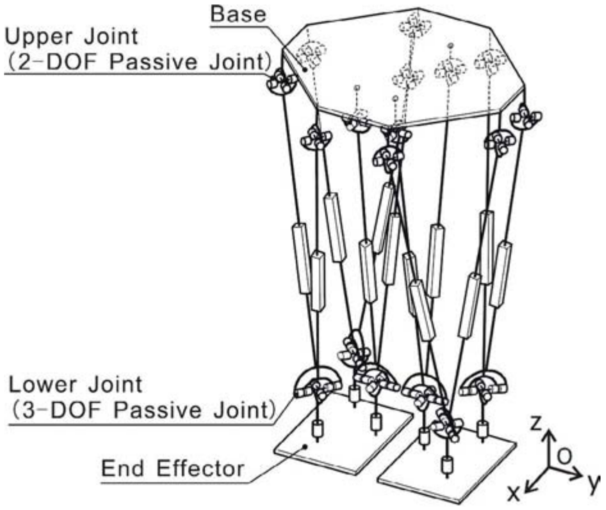
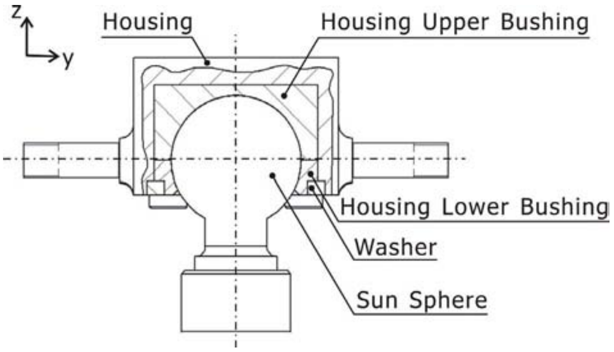


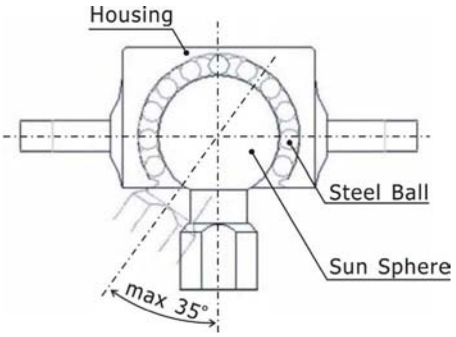
Fig. 2. DOF configuration of WL-16RIV.

TABLE I
FEATURES OF SERIAL / PARALLEL LINK

Features	Serial	Parallel
Position error	Accumulated	Mean
Stiffness	Low	High
Output power	Low	High
Working area	Wide	Narrow
Inverse kinematics	Difficult	Simple
Forward kinematics	Simple	Difficult



(a) 3-DOF passive joint of the previous prototype WL-16RIII.



(b) 3-DOF passive joint of the newest prototype WL-16RIV.

Fig. 3. 3-DOF passive joint developed by HEPHIST Seiko Co., Ltd.

Fig. 4. Passenger seat of WL-16RIV.

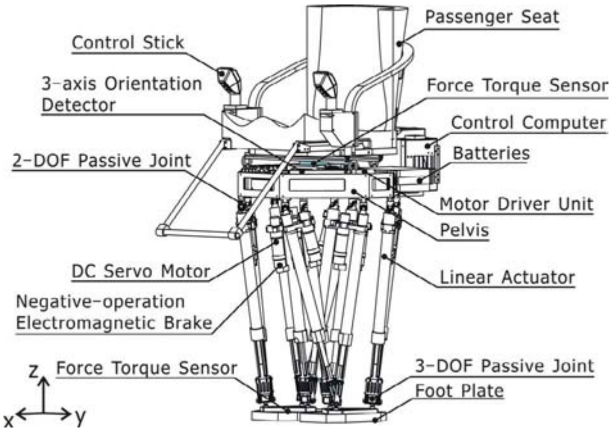


Fig. 5. Isometric view of WL-16RIV.

magnetic brake, so this robot can hold its posture without power supply. The control computer is arranged at the rear of the pelvis, and the batteries, DC servo drivers and a body angle detector are arranged inside the pelvis. A passenger seat is on the pelvis. And a control stick is mounted on the passenger seat (Fig. 4). So, a passenger can change the direction of the robot freely. The weight of the passenger seat is 5 kg.

Fig. 5 shows the isometric view of this robot, and Fig. 6 shows the exploded view of the linear actuator.

III. WALKING PATTERN GENERATION

The walking control method of WL-16RIV is based on Zero Moment Point (ZMP [11]) criteria. In our previous research, a stable human-carrying biped walking has been realized by generating a walking pattern, based on the assumption that the passenger is fixed on the seat. So a passenger cannot move on the robot and cannot relax.

For the practical application of a biped walking wheelchair, the biped walking vehicle must compensate for external disturbances caused by a passenger's motion. A dynamic passenger model is very important to realize our final goal.

A. Passive Dynamic Passenger Model

The passenger seat of WL-16RIV is mounted on the waist through a force-torque sensor, and moves on a plane during walking motion.

Therefore within the passenger's body, the lower limbs are assumed to be fixed on the robot, and the upper body is assumed to be a single particle with 2 DOF mounted on the seat, through 2 springs and dampers (Fig. 7). The weight of this particle can be computed from the passenger's body weight, based on data stating that the human body's weight ratio of the upper body, including the head and upper limbs, is 65.7 % for a male and 63.9 % for a female respectively [12].

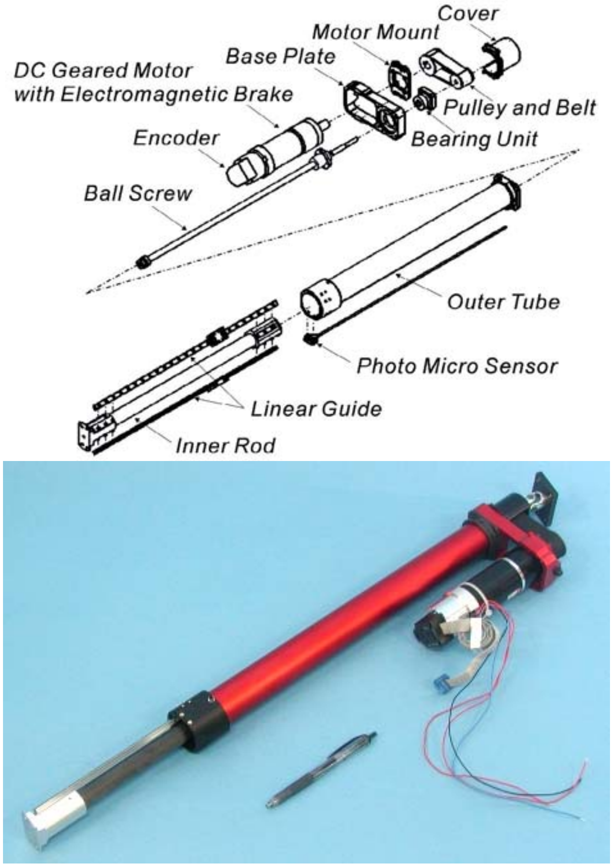


Fig. 6. Exploded view of the linear actuator.

The equation of motion is as follows:

$$\begin{aligned} & m_h \ddot{\mathbf{r}}_h(t) + \mathbf{C}(t)\left(\dot{\mathbf{r}}_h(t) - \dot{\mathbf{r}}_w(t)\right) \\ & \quad + \mathbf{K}(t)\left(\mathbf{r}_h(t) - \mathbf{r}_w(t)\right) = \mathbf{0} \end{aligned} \tag{1}$$

where m_h is the weight of the upper body particle, $\mathbf{r}_h(t)$ is the position of the upper body particle and $\mathbf{r}_w(t)$ is the position of the robot's waist. $\mathbf{K}(t) = diag\left(K_x(t), K_y(t), 0\right)$ is the stiffness variable matrix and $\mathbf{C}(t) = diag\left(C_x(t), C_y(t), 0\right)$ is the damping variable matrix respectively.

Equation (1) can denote the motion of the upper body particle with $\mathbf{K}(t), \mathbf{C}(t)$ and its initial position. These parameters can be identified with a force-torque sensor placed under the seat.

The stiffness and damping variable matrices are computed from the weight, the initial particle position and the moment when the robot moves.

When a passenger sits naturally, the robot outputs a waist shaking pattern while standing on both feet, and a seat reaction moment $\mathbf{M}_{w\_ex}$ is measured.

Meanwhile, by using (1), $\mathbf{r}_h(t)$ can be computed with a temporary value of $\mathbf{K}(t), \mathbf{C}(t)$, and the theoretical value of the seat reaction moment $\mathbf{M}_{w\_th}$ can be computed with the

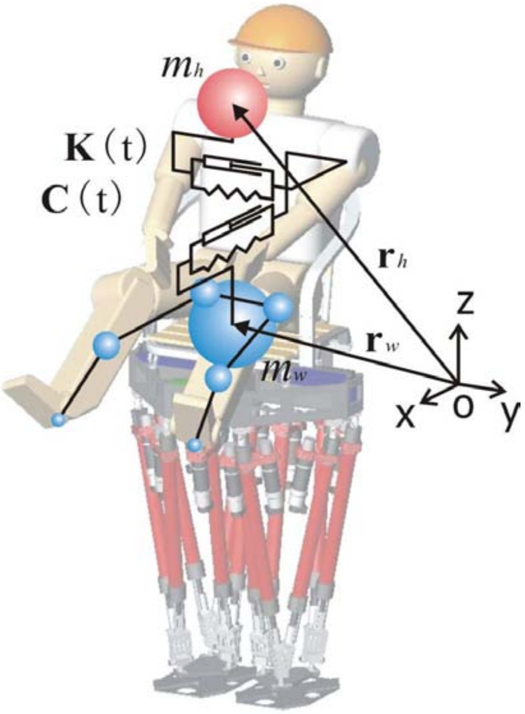


Fig. 7. Passive dynamic passenger model.

following equation:

$$\mathbf{M}_{w\_th} = m_h\left(\mathbf{r}_h(t) - \mathbf{r}_w(t)\right) \times \left(\mathbf{G} - \ddot{\mathbf{r}}_h(t)\right) \tag{2}$$

By comparing $\mathbf{M}_{w\_ex}$ and $\mathbf{M}_{w\_th}$, suitable $\mathbf{K}(t)$ and $\mathbf{C}(t)$ are collected. Examples of $\mathbf{M}_{w\_ex}$ and $\mathbf{M}_{w\_th}$ are shown in Fig. 8, and those of $\mathbf{K}(t), \mathbf{C}(t)$ are shown in Fig. 9.

B. Walking Pattern Generation Using Passive Dynamic Passenger Model

Since WL-16RIV is also a biped robot that has 6 DOF legs, the walking control problem is basically the same as that of existing biped robots, including humanoid robots. As the control method of this robot, we use a model based walking control method based on ZMP criteria [6].

This algorithm consists of the following main parts:

1. Modelling of the robot
2. Derivation of the ZMP equations
3. Computation of approximate waist motion
4. Computation of strict waist motion by iteratively computing the approximate waist motion

Let the walking system be assumed as follows:

(1) The robot is a system of particles.

(2) The floor for walking is solid and does not be moved by any force or moment.

(3) A Cartesian coordinate system is determined as shown in Fig. 10. The x and y axes form a plane identical to that of the floor.

(4) The contact region between the foot and the floor is a set of contact points.

(5) The friction coefficient for rotation about the x, y and z axes is zero at the contact point.

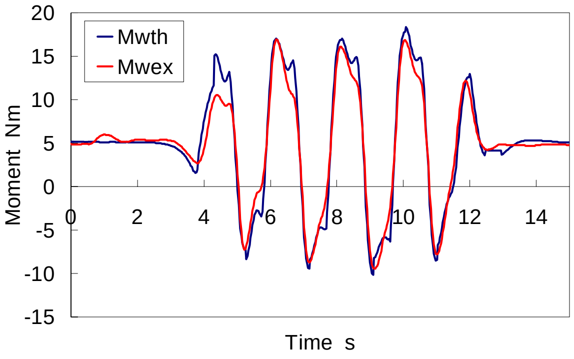


Fig. 8. Experimental and theoretical seat reaction moment about the roll axis to collect the stiffness and damping variable matrix.

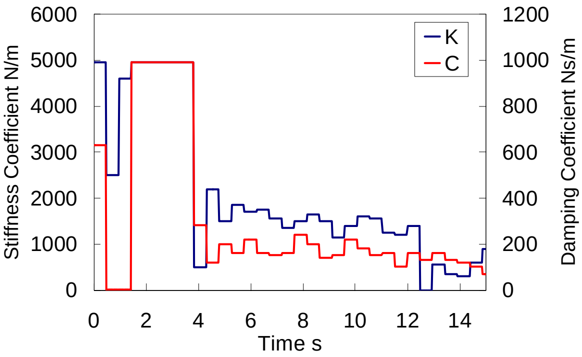


Fig. 9. Stiffness and damping variable matrix of the y axis.

First, we define an approximation model of the waist and the position vectors like Fig. 7. The moment balance around the point P on the floor can be expressed as below:

$$\sum_{i}^{all\_particles} m_i(\mathbf{r}_i - \mathbf{r}_p) \times (\ddot{\mathbf{r}}_i + \mathbf{G}) + \mathbf{T} = \mathbf{0} \tag{3}$$

If the point P is defined as ZMP, $\mathbf{T} = \left[0, 0, T_z\right]^T$. We denote the position vector of P as $\mathbf{P}_{zmp}(x_{zmp}, y_{zmp}, 0)$. To consider the relative motion of each part, a moving coordinate Σ_m is established on the waist of the robot parallel to the fixed coordinate Σ_O.

$\mathbf{Q}(x_q, y_q, z_q)$ is the position vector of the origin of $\sum_m$ from the origin of Σ_O. Using the moving coordinate frame, equation (3) can be modified as follows:

$$\begin{aligned}&\sum_{i}^{all\_particles} m_i({}^m\mathbf{r}_i - {}^m\mathbf{r}_{zmp}) \times \{{}^m\ddot{\mathbf{r}}_i + {}^m\ddot{\mathbf{Q}} - {}^m\mathbf{G} \\ &+ {}^m\dot{\boldsymbol{\omega}} \times {}^m\mathbf{r}_i + 2\,{}^m\boldsymbol{\omega} \times {}^m\dot{\mathbf{r}}_i + {}^m\boldsymbol{\omega} \times ({}^m\boldsymbol{\omega} \times {}^m\mathbf{r}_i)\} = \mathbf{0}\end{aligned} \tag{4}$$

where ${}^m\mathbf{r}_{zmp}$ is the position vector of ZMP with respect to $\sum_m$. ${}^m\boldsymbol{\omega}$ is the angular velocity vector of the origin of Σ_m.

Assuming that a moving coordinate does not rotate, this equation is expanded into (5) and (6) by putting the terms representing the moment generated by the lower limb particles on the right-hand side as known parameters, named M_x and M_y respectively:

$$\begin{aligned}&m_w({}^m z_w - {}^m z_{zmp})({}^m\ddot{x}_w + {}^m\ddot{x}_q - g_x) \\ &- m_w({}^m x_w - {}^m x_{zmp})({}^m\ddot{z}_w + {}^m\ddot{z}_q - g_z) = -M_y\end{aligned} \tag{5}$$

$$\begin{aligned}&m_w({}^m y_w - {}^m y_{zmp})({}^m\ddot{z}_w + {}^m\ddot{z}_q - g_z) \\ &- m_w({}^m z_w - {}^m z_{zmp})({}^m\ddot{y}_w + {}^m\ddot{y}_q - g_y) = -M_x\end{aligned} \tag{6}$$

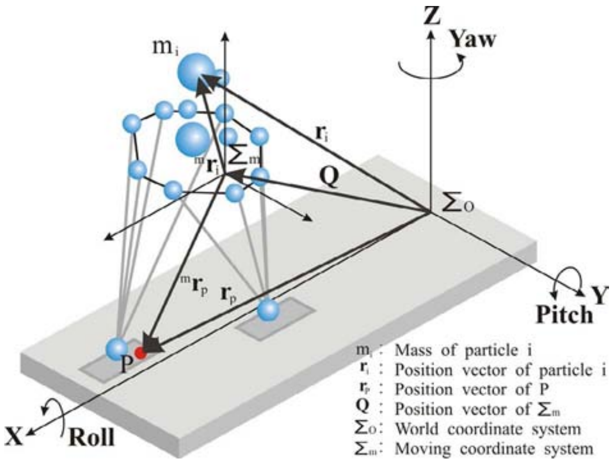


Fig. 10. Definition of coordinate systems and vectors.

These equations are interferential and non-linear. Thus, by assuming that the waist particles do not move vertically, the equations can be decoupled and linearized with the right side, including the replacement of the known clause of the left side with M^*_x and M^*_y, as follows:

$$m_w({}^m z_w - {}^m z_{zmp}){}^m\ddot{x}_w - m_w(-{}^m g_z){}^m x_w = -M^*_y \tag{7}$$

$$-m_w({}^m z_w - {}^m z_{zmp}){}^m\ddot{y}_w + m_w(-{}^m g_z){}^m y_w = -M^*_x \tag{8}$$

In these equations, M^*_x and M^*_y are known because they are derived from the motion of the lower limb's motion and the time trajectory of ZMP. In the case of steady walking, M^*_x and M^*_y are periodic functions because each particle of the lower limbs and the time trajectory of ZMP move periodically for the moving coordinate. Thus, each equation can be represented as a Fourier series. By comparing the Fourier transform coefficients from both sides of each equation, we can easily acquire the approximate periodic solution for the trunk motion.

In order to obtain strict solutions of the body, the approximate solutions are subtracted into (3) and ZMP is computed. In this step, the motion of a passenger's upper body particle is computed solving (1) by using the Runge-Kutta method. Subsequently, the strict motion of the body is obtained using an iteration method.

The flowchart of this method is shown in Fig. 11.

C. *Walking Stability Control*

Our biped robots are controlled by a model-based control algorithm as mentioned above. However, since a walking pattern is previously generated offline, it makes the robot somewhat unstable when the feet land on terrain or when external force acts on it. So, we have already developed a walking technology adaptable to uneven terrain [9] and a stabilization control under unknown external disturbance caused by passenger's active dynamic motion [10].

We omit the details these stability controls due to limitations of space, so please refer to the references for further information.

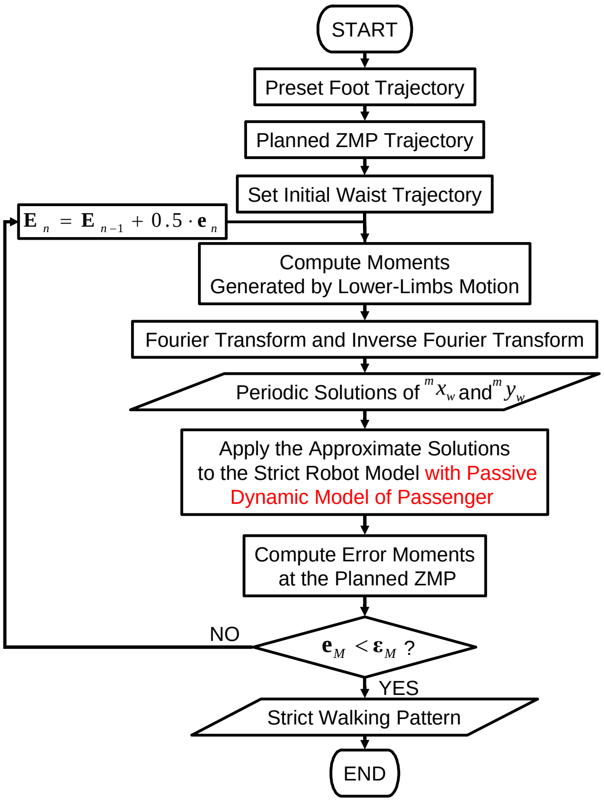


Fig. 11. Flowchart of walking pattern generation method with passive dynamic model of a passenger.

IV. EXPERIMENTAL TESTS AND CONSIDERATION

In the past papers, we have already confirmed the basic effectiveness of WL-16RIV's mechanism and control method [9], [10]. So, we exhibited WL-16RIV at the Wired NextFest held in Los Angeles from September 13th to the 16th in 2007. We demonstrated WL-16RIV four or five times a day and held a test-riding event for the public after the demonstration everyday.

In the demonstration, a student of our group rode on the robot, the robot went up and down stairs, and the passenger navigated the robot on a flat plane by using the control stick (Fig. 12). For the public, we limited a rider's weight to 60 kg and conducted forward walking demonstrations. Two students stood along the robot to support a passenger for the safety, and one student was ready to operate the electro magnetic brakes attached to all motors to hold the robot's

(a) The robot goes up and down stairs with the rise of 150 mm and the pedal tread of 300 mm continuously.

(b) The passenger navigates the robot by using the control stick mounted on the passenger seat.

Fig. 12. Walking demonstration at the Wired NextFest held in Los Angeles in 2007.

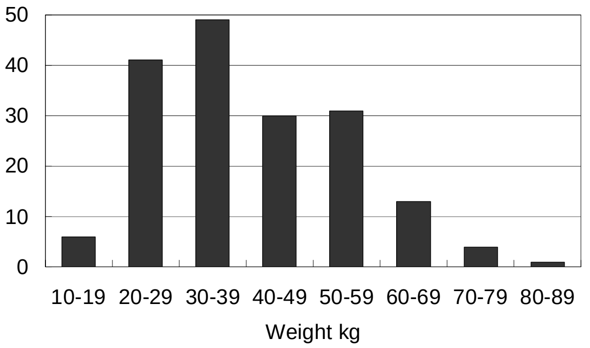


Fig. 13. Data of passengers' weight. 172 people rode on this robot, and the average weight of them was 41 kg.

Fig. 14. The mayor of Los Angeles takes a test ride on the human-carrying biped walking vehicle at the Wired NextFest held in Los Angeles in 2007.

posture just in case. Although we took all possible measures to ensure the safety, we requested the public to sign a liability waiver.

As a result, 172 people rode on this robot without accident during four days, and the average weight of them was 41 kg. Fig. 13 shows the data of passengers' weight. Because we adopted the Li-ion battery, we could charge the battery between intermissions of every demonstration without refreshing.

From children to the elderly enjoyed riding on the robot, and the oldest rider was a 92-year-old woman. The mayor of Los Angeles also rode on the human-carrying biped walking vehicle (Fig. 14). Through this demonstration, we confirmed the ruggedness and reliability of the developed mechanism and control method.

In this test-riding event, although we should apply the passive dynamic passenger model as mentioned above, we prepared four walking patterns every 10 kg from 30 kg to 60 kg beforehand, depending on a passenger's body weight. Because it takes ten minutes or more to identify the passenger's parameters through waist shaking experiments.

It is our future work to identify the passenger's stiffness and damping coefficient matrices as soon as a human ride on the robot.

V. CONCLUSIONS AND FUTURE WORK

We developed a prototype biped walking wheelchair, WL-16RIV that consists of two Stewart Platform type legs and waist with a passenger seat was developed.

We also developed a passive dynamic model of a passenger, and it enabled a more stable walking even if a passenger sits naturally. The model consists of a section of lower limbs, which is assumed to be fixed onto the robot, and the upper body, assumed to be a single particle with 2 DOF mounted on the seat through 2 springs and dampers. The initial position of the upper body particle and the stiffness and damping coefficient matrices were identified through twice-repeated waist shaking experiments using a force-torque sensor under the seat. In the walking pattern generation method, the proposed passive dynamic passenger model is built onto a strict model of the robot, and through iteration computation, a stable walking pattern is generated. Through the demonstration at Wired NextFest held in Los Angeles, we confirmed the ruggedness and reliability of the developed mechanism and control method.

Our future work is to identify the passenger's stiffness and damping coefficient matrices as soon as a human ride on the robot. And we must develop a method for biped robots to avoid falling and stop safely when a biped robot loses balance.

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