



of human subjects. As one of the applications as the human motion simulator, we carried out walking experiments with a walk-assist machine<sup>4</sup> (see Fig. 3). Generally, an armrest of a walk-assist machine is set to equal height of a user's elbow. It is also known that the severer his/her disability is, the lower we should set the armrest. Measuring the current value of the actuators at

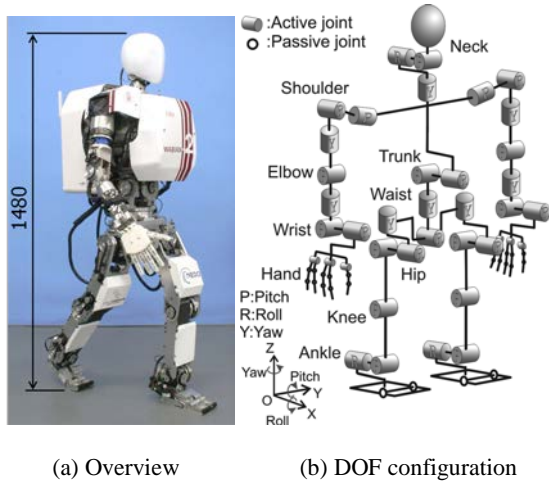


Fig. 1. Biped humanoid robot, WABIAN-2.

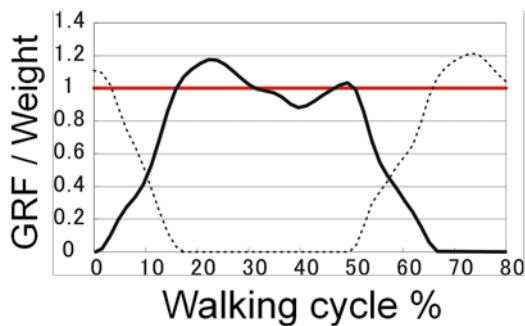


Fig. 2. Ground reaction force during the knee-stretched walking. Two peaks appear like the human ones.

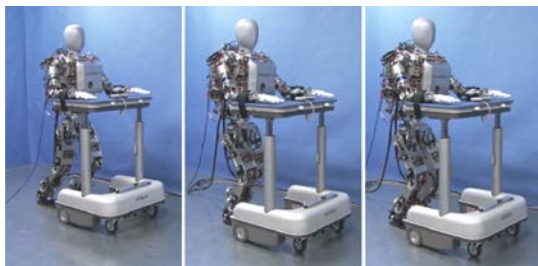


Fig. 3. Quantitative evaluation of walk-assist machine.

the knee joints and the forces and torques applied to the arms and legs, we can calculate the energy consumption at knee joints and the load to arms. Then we found the fact with quantitative data that the lower we set the height of the armrest, the less the load of knees is. This is a good example that human motion simulator can evaluate empirical facts quantitatively. From the results of these experiments, we confirmed that we can evaluate welfare and rehabilitation instruments quantitatively with a human motion simulator.

We also use WABIAN-2 to clarify the function of the foot arch structure.<sup>5</sup> We developed a human-like foot mechanism that mimics the changes of the elasticity of the medial longitudinal arch with the change of the arch height during walking. As experimental results using the biped humanoid robot, WABIAN-2 mounted on the human-like foot mechanism, we confirmed that the arch elasticity could absorb a foot-landing force at the plantar contact phase. Furthermore, the windlass mechanism which caused change of the arch height contributed to a strong thrust at the push-off phase.

### 3. Biped Running Robot

We are now developing a new biped humanoid robot that can mimic various characteristics of human running for investigating human running mechanisms and human motion control. If a robot could perform motions that would improve sports performance, it would be possible to identify more effective human motions and create a novel sports coaching program.

Human running can be modeled by a spring-loaded inverted pendulum (SLIP) model, which is composed of a body mass and spring leg inspired by the linear relationship between the ground reaction force and the vertical body displacement during running.<sup>6</sup> This model describes human running in a simple, straightforward way and is used on the studies of biped running robots. Moreover, the knee and ankle joints in a standing leg act like torsion springs which emerge the leg stiffness.<sup>7</sup> Furthermore, an important characteristic that has not yet been reported is that a pelvic movement in the frontal plane can help to increase jumping forces.

On the basis of the analysis of human running motion, we propose a new model named SLIP<sup>2</sup> (Spring-Loaded Inverted Pendulum using Pelvis). This model is

composed of a body mass, a pelvis, and leg springs. In this model, the knee and ankle joints in a standing leg act like torsion springs and the pelvic sine movement causes the resonance for hopping.

We have developed a biped running robot with a pelvis and a joint stiffness adjustment mechanism that uses two leaf springs mimicking the joint stiffness of a human leg during running (see Fig. 4). The robot has realized hopping motions by utilizing the pelvic movement and leg elasticity.

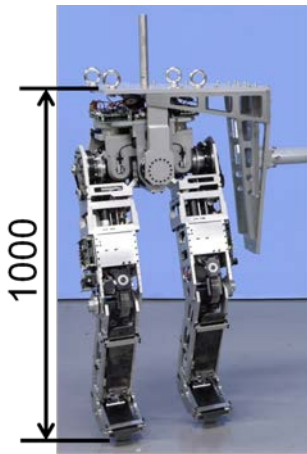
#### 4. Biped Vehicle, WL-16

We consider that a biped vehicle is a viable solution in barrier-free engineering that is much more effective and

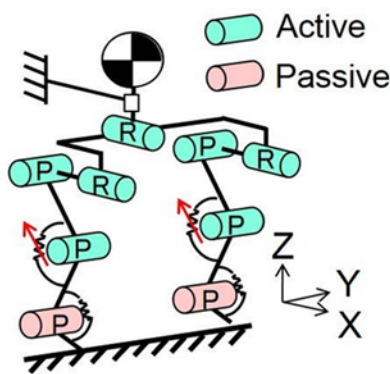
low-cost than infrastructure improvements. Therefore, we have developed a human-carrying biped vehicle named WL-16 as shown in Fig. 5.

The weight of WL-16 is 74 kg including 11 kg battery weight. Each leg mechanism has six linear actuators and passive joints at the both sides of each linear actuator. The upper passive joints are commercial universal joints which use needle bearings with little backlash. The lower passive joints are lightweight 3-DOF spherical rolling joints, which were newly developed in cooperation with HEPHIST Seiko Co., Ltd.

Each linear actuator consists of a 150W DC servo motor and a ball screw. The control computer is

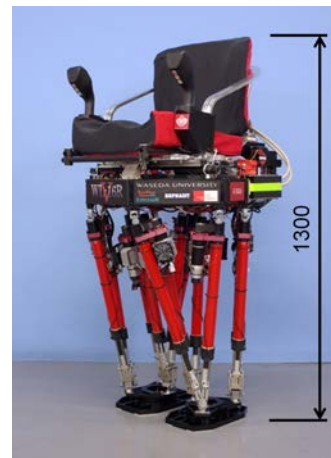


(a) Overview

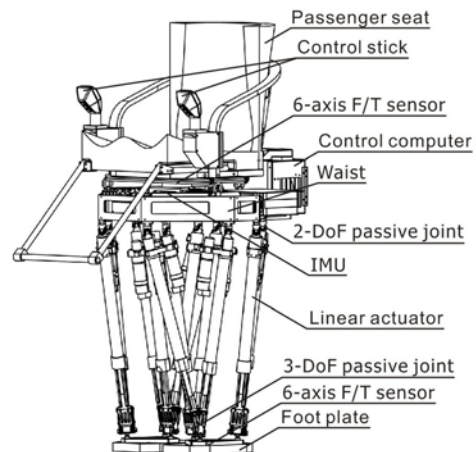


(b) DOF configuration

Fig. 4. Biped running robot.



(a) Overview



(b) Mechanism and sensors

Fig. 5. Biped vehicle, WL-16.

arranged at the rear of the waist. The batteries, DC servo drives and an IMU sensor are arranged inside the waist part. A passenger seat is on the waist, and a control stick is mounted on the passenger seat. A passenger can change the direction of the robot freely by using the control stick.

## 5. Conclusions

We introduced our latest biped robots developed at Waseda University. WABIAN-2 is the biped humanoid robot which can walk with the knees stretched, heel-contact and toe-off motion by utilizing a foot mechanism having a passive toe joint and a waist mimicking a human's pelvic motion. WABIAN-2 can quantitatively evaluate welfare and rehabilitation instruments by analyzing the data from a lot of sensors throughout the body. WABIAN-2 also can evaluate ride quality of WL-16 (see Fig. 6). WL-16 is the biped vehicle consisting of two Stewart Platform type legs and waist with a passenger seat. It can be used as a substitute for a wheel chair.

The new biped running robot is designed based on the analysis of human running motion, and it can jump by utilizing the pelvic movement and leg elasticity. We

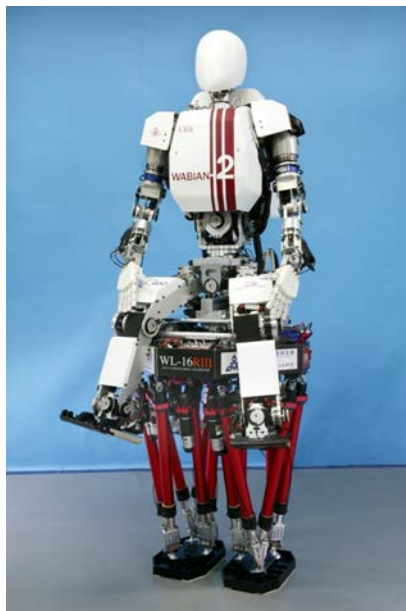


Fig. 6. Cooperative relation between WABIAN-2 and WL-16.

will identify more effective human motions by using the running robot and try to create a novel sports coaching program.

## Acknowledgements

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