Locomotion pattern generation and mechanisms of a new biped walking machine

BY HUN-OK LIM1,2,*, Y. OGURA2 AND ATSUO TAKANISHI2

1Department of Mechanical Engineering, Faculty of Engineering, Kanagawa University, 3-27-1 Rokkakubashi, Kanagawa, Yokohama 221-8686, Japan
2Humanoid Robotics Institute, Waseda University, 3-4-1 Ookubo, Shinjuku-ku, Tokyo 169-8555, Japan

This paper describes the mechanism of a 16 d.f. biped walking machine, Waseda biped humanoid robot-2 lower limb (WABIAN-2LL), which has two 7 d.f. legs and a 2 d.f. waist actuated by DC servo motors with reduction gears. WABIAN-2LL is designed with large movable angle ranges like those of a human. Its height and weight are 1200 mm and 40 kg, respectively. It is able to walk with its knees stretched using the redundancy of the legs and to move around an object using a hip-bending motion without touching the object. A knee-stretched locomotion pattern generation is also proposed in this paper, which separately creates joint angles in a supporting and a swinging phase. During knee-stretched walking, the joint rate of the knee will approach infinitely when the knee is stretched. This singularity problem is solved by using the motion of the waist, not the posture of the trunk. The effectiveness of the mechanisms and pattern generations of WABIAN-2LL is verified through dynamic walking experiments.

Keywords: biped walking machine; humanoid robot; knee-stretched motion; locomotion pattern; compensatory motion

1. Introduction

As many advanced countries enter the twenty-first century, a greying population is increasing steadily in number; as a result some serious problems occur. For example, the number of people who need some support in managing a rich daily life is increasing because they are healthy, but their body becomes weak like older people. In addition, a manpower shortage is forecasted in a wide range of industrial fields due to a decrease in the employment population. As one of the means to solve such problems, the importance of humanoid robots is pointed out, which can cooperate with a human and provide many services.

The mechanism and the control of biped humanoid robots have been studied by many researchers for about a quarter of a century. Also, some international conferences such as humanoid robots (humanoids) and climbing and walking robots (CLAWAR) have been held every year. In 1969, an artificial biped walking robot, Waseda leg-3

* Author and address for correspondence: Department of Mechanical Engineering, Faculty of Engineering, Kanagawa University, 3-27-1 Rokkakubashi, Kanagawa, Yokohama, 221-8686, Japan (holim@kanagawa-u.ac.jp).
WL-3), was developed by the biomechanics research group of Waseda University, which had electro-hydraulic servo-actuators. It performed a standing, swinging and sitting motion by using a master–slave control. In 1973, Waseda robot-1 (WABOT-1) was constructed, which consisted of a trunk and two arms and legs. It performed static walking on a horizontal plane for the first time in the world (Kato et al. 1973). The WL-series robots were constructed until 1997 to achieve dynamic complete walking on various terrains. Using the robots, dynamic walking was achieved on a flat or uneven terrain by using the program control and the sequence control (Takanishi et al. 1990a). In addition, they did not fall down and could tolerate unknown external forces applied to their waists (Takanishi et al. 1990b). In order to achieve a more reliable walking motion, a full-scaled humanoid robot Waseda biped humanoid (WABIAN) was constructed in 1996 (Setiawan et al. 1999). It has 35 mechanical d.f.: 3 d.f. in each leg; 7 d.f. in each arm; 3 d.f. in each hand; 2 d.f. in each eye; 2 d.f. in the neck; and 3 d.f. in the waist. Its height is approximately 1660 mm and its total weight is 107.4 kg. Using WABIAN series robots (from WABIAN to WABIAN-RVII), quasi-human biped walking, emotional and dancing motions were achieved (Lim et al. 2004a).

Other research groups have also studied biped walking robots to analyse the human walking motion (Raibert 1986; Hemami & Wyman 1992). Raibert and his co-workers developed one-, two- and four-legged hydraulically actuated robots, based on prismatic compliant legs, and developed the forward velocity, body attitude and hopping height control for locomotion. Asimo was developed by Honda Motor Corporation, which has 28 d.f.: 6 d.f. in each leg; 5 d.f. in each arm; 1 d.f. in each hand; and 2 d.f. in the head (Hirose et al. 2001). Its height and weight are 1200 mm and 52 kg, respectively. An intelligent real-time flexible walking technology is introduced to walk continuously while the robot changes direction. HRP-2P was developed by METI of Japan, which has the capability of walking on a plane and lying down on and getting up off the floor (Kaneko et al. 2002; Fujiwara et al. 2003). It consists of 30 mechanical d.f.: 6 d.f. in each leg; 6 d.f. in each arm; 1 d.f. in each hand; 2 d.f. in the neck; and 2 d.f. in the waist. Its height and weight are 1580 mm and 58 kg, respectively. Sony developed a small humanoid robot, SDR-4X (Ishida et al. 2002). It is controlled by a real-time integrated adaptive motion control, the height and weight of which are 580 mm and 7 kg, respectively. It consists of 38 d.f.: 6 d.f. in each leg; 5 d.f. in each arm; 5 d.f. in each hand; 4 d.f. in the head; and 2 d.f. in the waist. MK-5 was developed by the Aoyama Gakuin University (Furuta et al. 2000). It has 24 d.f.: 6 d.f. in each leg; 5 d.f. in each arm; and 2 d.f. in the head. Its height and weight are 356 mm and 1.9 kg, respectively. H7 was developed by the University of Tokyo (Kagami et al. 2001). Its height and weight are 1470 mm and 55 kg, respectively, and it has 30 d.f.: 6 d.f. in each leg; 6 d.f. in each arm; 1 d.f. in each hand; 1 d.f. in each foot; and 2 d.f. in the head. KAIST developed a 41 d.f. humanoid robot, KHR-2 (Kim et al. 2005) and the Technical University of Munich developed JOHNNIE (Loffler et al. 2003).

However, almost all biped walking robots described above have two 2 d.f. ankles, two 1 d.f. knees and two 3 d.f. hips in the legs. Such biped robots find it difficult to mimic human motion such as a knee-stretched locomotion and a hip-bending motion due to the mechanical structure. Hence, the mechanism of a 16 d.f. biped walking robot, Waseda biped humanoid-2 lower limb (WABIAN-2LL), which is capable of imitating various human motions is proposed in this paper. Each leg consists of a 3 d.f. ankle, a 1 d.f. knee and a 3 d.f. hip, and its waist has 2 d.f. Its height is approximately 1200 mm and weight 40 kg. All joints have larger movable angle ranges than those of a human except for the roll joint of the hip.

For the walking motion of biped robots, their joint angles are determined in advance. A simple offline and online pattern generation was proposed, which is able to deal with various terrains (Yamaguchi et al. 1999; Lim et al. 2002). The motion pattern of the foot according to terrain conditions is created by using a polynomial considering angle, angular velocity, angular acceleration and so on, and the other joints are determined by inverse kinematics. The whole walking pattern is generated on the basis of zero moment point (ZMP) and moment compensation. Another online pattern generation uses a linear inverted pendulum model to achieve real-time walking (Yamane & Nakamura 2000). Moreover, a fuzzy-logic pattern generator capable of reducing the swing motion of the trunk was studied (Park 2003).

In order to achieve dynamic stable walking, the biped robots should satisfy the function of the stability and be able to adjust the elasticity of the legs. The stability control, which is based on the motion of the trunk and the waist, was proposed to maintain good balance of the biped robot (Lim et al. 2004b). For the motion identification and control of biped robots, a foot rotation indicator and a centroidal moment pivot were proposed (Goswami 1999; Popovic & Goswami 2005). Also, the impedance control was studied by many researchers for the impedance adjustment of the legs (Park 2001; Lim et al. 2004b).

When a human walks on the ground, the knee is generally stretched out. If a biped robot walks with its knee stretched like a human, the joint rate of the knee will approach infinitely. It is difficult to obtain a locomotion pattern by the pattern generation methods described above. Hence, a knee-stretched motion pattern generation is described in this paper which is able to avoid singularity. While a pattern created by the pattern generator is executed, the moments produced by the motion of the legs should be compensated for stability. The motion of the waist will be used to minimize the moments (Takanishi et al. 1989). This paper is organized as follows. Section 2 describes a leg mechanism that is capable of achieving a human-like motion. Section 3 describes a pattern generation including compensatory motion. Section 4 describes three different walking simulations to confirm the walking pattern generation. Section 5 provides walking experiments to verify the mechanism of WABIAN-2LL. Finally, the conclusion and discussion are presented in §6.

2. A new biped machine, WABIAN-2LL

(a) Ideal d.f. configuration

A human can perform various and complicated motions because the body consists of cartilage, bones, joints, ligaments, muscles and tendons. However, using conventional biped humanoid robots, it is difficult to simulate various human motions. Therefore, new mechanisms of the waist and hips of biped humanoid robots are required to mimic human motion properly. Consider the motion of a human hip and leg during steady walking. Some researchers have studied the gait analysis of humans. Figure 1 shows the motion of a human pelvis and knee during the right and left support phases (Wilson et al. 1963). As shown in figure 1, the supporting period of the right leg is from approximately 10 to 60% during steady walking. Also, we can see that the pelvis moves to the direction of the roll and yaw joint in the frontal and horizontal plane, respectively, while the pelvis seldom moves to the direction of the pitch in the sagittal plane. Hence, a biped humanoid robot is expected to perform the rolling and yawing motion of the waist independent of the posture of the trunk.

Figure 2 shows the structure of a human pelvis, which consists of the sacrum, coccyx and two hip bones. The hip bone is a large, flattened and irregularly shaped bone, which connects the trunk to the lower limb by extending from the sacrum to the femur. In steady walking, it is reported that both hip bones move with the pubic symphysis and are mutually shifting (i.e. slide by each other; Yoshida 1991). Hence, the motion of the hip might be similar to the motions of the crank mechanisms. Also, there might be circular motions at both hip joints. The roll and yaw axes of the waist of a biped humanoid robot should be orthogonal to the centre of both hips because the displacement of the trunk caused by the motion of the waist is smallest and the kinematics analysis can be greatly simplified.

The ankle of almost all conventional biped humanoid robots consists of 1 d.f. each in a pitch and roll axis, hence it is difficult to walk stably on a hilly and rugged terrain. If a biped humanoid robot has 3 d.f. ankles (a pitch, a roll and a yaw joint), it will enable the robot to select a stable position and reduce the impact and/or contact forces produced between the landing foot and the ground.

(b) Mechanism of WABIAN-2LL

We have developed a new biped machine, WABIAN-2LL, that has two 3 d.f. ankles, two 1 d.f. knees, two 3 d.f. hips and a 2 d.f. waist, as shown in figure 3a. The roll and yaw axes of its waist are perpendicular to one another in the centre of the pelvis for easy kinematics and a small pelvis structure. Various walking
motion patterns such as a knee-stretched and a hip-bended pattern can be easily generated by using the redundancy of its leg. Also, when the knees of WABIAN-2LL are bended, the direction of the knees will be changed independent of the position and orientation of the waist and feet. Therefore, it can walk in a narrow space, go up and down a ladder, ride on a horse and avoid an obstacle. Its height is approximately 1200 mm and weight 40 kg. The length of each segment was selected in view of appearance and cooperativeness on the basis of a Schmidt method that is used to measure and analyse the form of a human body. Table 1 shows the length distribution of each segment. It mainly employs duralumin as the structural material. Figure 3 shows a photograph of WABIAN-2LL. Table 2 shows the movable range of WABIAN-2LL in comparison with a human. Almost all the joints have larger movable angle ranges than those of a human.

For a compact body and light weight, a new drive system of WABIAN-2LL is developed. The actuator system of each axis consists of a motor, a timing belt and a harmonic drive gear, and two pulleys are employed as a high-performance speed reducer. This double-speed reduction mechanism allows WABIAN-2LL to have a high reduction ratio and sets the joint axis apart from the motor axis. The specification of its motors was selected on the basis of the software simulation that was conducted using the Newton–Euler method. In the simulation, the walking speed was 0.48 s per step and the step length was 0.3 m per step. The maximum torque of the waist roll is 70.4 N m while that of the waist yaw is 23.5 N m, as shown in Table 3.

(c) Electrical design of WABIAN-2LL

WABIAN-2LL is controlled by a PC/AT compatible CPU board with an Intel Pentium III 1.26 GHz processor. Its operating system is QNX, which enables the execution of real-time processes. The feature of QNX is essential for the identical
control of robot systems. A PCI backplane board with five slots (PCM-PCM05) is used to connect a CPU board and an I/O board. Similar to an I/O board, a Ritech interface board is employed, which has a 12-channel 12-bit A/D converter, a 16-channel 12-bit D/A converter, a 16-channel 24-bit counter and a 16-channel input/output PIO. Like servo drivers, Titech robot drivers (PC-0121-1) are used. The computer system is mounted on the waist and the servo driver modules are mounted on the waist and the link frames.

Two nickel metal hydride battery packs (NiMH; 24 V, 3.6 A h) for the motor drives and two NiMH packs (24 V, 4.0 A h) for the control computer are installed on the waist. Both battery packs are connected in series so that it is capable of walking for 30 min. A six-axis force/torque sensor is mounted between the foot and the ankle to measure the ground forces. The joint angles are sensed by incremental encoders and the data are fed into the computer through the counters. All the computations controlling WABIAN-2LL are carried out by the control computer and the control program is written in C language. The servo rate is 1 kHz.

3. Locomotion pattern generation

(a) Knee-stretched motion pattern

There are two kinds of walking phases: a support and a swing phase. During the swing phase, one foot is not constrained to the ground, while the other foot is on the ground. As soon as the heel of the swing foot reaches the ground, the swing phase is changed to the double support phase. A knee-stretched motion pattern is separately determined in a support and a swing phase because the joint rate of the knee will approach infinitely when the knee is stretched out during walking. In the pattern generation, the knee motion of the supporting leg is arbitrarily preset. On the other hand, the height of the waist is not preset because its position with respect to the foot frame of the supporting leg depends on the position of the knee of the supporting leg. In order to avoid a singular point, the rolling motion of the waist is used.
A world coordinate frame $O$ is fixed on the ground, and a moving coordinate frame $W$ is attached to the centre of the waist to determine a locomotion pattern. Also, the foot coordinate frame $F_s$ is attached to the centre of the supporting foot. Figure 4 shows coordinate frames and link parameters. A knee-stretched motion pattern is generated as follows: (i) setting parameters, (ii) calculating a

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**Table 1. Segment length of WABIAN-2LL.**

<table>
<thead>
<tr>
<th>parts</th>
<th>length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>height</td>
<td>1200</td>
</tr>
<tr>
<td>width</td>
<td>600</td>
</tr>
<tr>
<td>depth</td>
<td>320</td>
</tr>
<tr>
<td>foot</td>
<td>240×160</td>
</tr>
<tr>
<td>between foot and ankle</td>
<td>138</td>
</tr>
<tr>
<td>between ankle and knee</td>
<td>270</td>
</tr>
<tr>
<td>between knee and hip</td>
<td>300</td>
</tr>
<tr>
<td>between hip and waist</td>
<td>492</td>
</tr>
</tbody>
</table>

**Table 2. Movable range of each joint.**

<table>
<thead>
<tr>
<th>joint</th>
<th>movable angle (human/robot) ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ankle yaw</td>
<td>$-10$ to $+20$/$-90$ to $+90$</td>
</tr>
<tr>
<td>ankle roll</td>
<td>$-20$ to $+30$/$-25$ to $+40$</td>
</tr>
<tr>
<td>ankle pitch</td>
<td>$-45$ to $+25$/$-33$ to $+118$</td>
</tr>
<tr>
<td>knee pitch</td>
<td>$0$ to $+130$/$-50$ to $+160$</td>
</tr>
<tr>
<td>hip pitch</td>
<td>$-15$ to $+125$/$-98$ to $+100$</td>
</tr>
<tr>
<td>hip roll</td>
<td>$-20$ to $+45$/$-22$ to $+22$</td>
</tr>
<tr>
<td>hip yaw</td>
<td>$-45$ to $+45$/$-25$ to $+97$</td>
</tr>
<tr>
<td>waist roll</td>
<td>$-5$ to $+5$/$-18$ to $+18$</td>
</tr>
<tr>
<td>waist pitch</td>
<td>$-5$ to $+5$/$-45$ to $+45$</td>
</tr>
</tbody>
</table>

**Table 3. Motor specification for each joint.**

<table>
<thead>
<tr>
<th>joint</th>
<th>maximum torque (N m)</th>
<th>maximum angular velocity ($^\circ$ s$^{-1}$)</th>
<th>output (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ankle yaw</td>
<td>23.5</td>
<td>361</td>
<td>300</td>
</tr>
<tr>
<td>ankle roll</td>
<td>70.4</td>
<td>305</td>
<td>229</td>
</tr>
<tr>
<td>ankle pitch</td>
<td>55.8</td>
<td>386</td>
<td>181</td>
</tr>
<tr>
<td>knee pitch</td>
<td>150.9</td>
<td>314</td>
<td>365</td>
</tr>
<tr>
<td>hip pitch</td>
<td>55.8</td>
<td>386</td>
<td>181</td>
</tr>
<tr>
<td>hip roll</td>
<td>70.4</td>
<td>305</td>
<td>229</td>
</tr>
<tr>
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<td>23.5</td>
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<td>23.5</td>
<td>361</td>
<td>300</td>
</tr>
</tbody>
</table>
horizontal hip position of the supporting leg, (iii) determining the height of the waist with respect to the frame $\mathcal{F}_s$, and (iv) calculating the position of the hip of the swinging leg.

The initial positions and orientations of the foot and the waist and the angular velocity limit of the knee are given as leg motion parameters. However, the vertical position of the waist with respect to the frame $\mathcal{F}_s$ is not set. The position of the hip of the supporting leg, $\mathbf{P}_s \in \mathbb{R}^3$, can be calculated as follows:

$$
\mathbf{P}_s = \mathbf{P}_w + \mathbf{E}_w \mathbf{P}_{hw},
$$

where $\mathbf{P}_w \in \mathbb{R}^3$ is the position vector of the waist with respect to the frame $\mathcal{F}_s$; $\mathbf{E}_w \in \mathbb{R}^{3 \times 3}$ is the unit matrix of the waist; and $\mathbf{P}_{hw} \in \mathbb{R}^3$ is the position vector of the hip with respect to the moving frame.

The distance between the hip and the hip of the supporting leg, $L_{ah}$, is calculated as follows:

$$
L_{ah} = \sqrt{L_{r1}^2 + L_{r2}^2 - 2L_{r1}L_{r2}\cos\theta_{rk}},
$$

where $L_{r1}$ and $L_{r2}$ are the length of the calf and the thigh of the supporting leg, respectively; and $\theta_{rk}$ is the angle of the knee in the supporting leg.

Using equation (3.2), the vertical position of the hip of the supporting leg with respect to the $\mathcal{F}_s$, $\mathbf{P}_{rhz}$, is written as follows:

$$
\mathbf{P}_{rhz} = \sqrt{L_{rk}^2 - \left(P_{rhz}^2 + P_{rh}^2\right)},
$$

where $P_{rhx}$ and $P_{rhy}$ are the $x$ and $y$ position of the hip of the supporting leg, respectively.

The angles of the swinging leg can be determined on the basis of the position and orientation of the swinging foot and waist. However, it is difficult to obtain the angle of the knee if the leg does not reach the ground, or if the knee angle is over the angle limit. To solve this problem, the knee angle is set under the angle limit, and the waist rotates in a rolling direction around the
hip joint of the supporting leg. Then, the position of the hip of the swinging leg with respect to $F_s$, $P_{lh}$, can be determined by using the following simultaneous equations:

$$
\| P_{lh} - P_{la} \| = \sqrt{L_{l1}^2 + L_{l2}^2 - 2L_{11}L_{12} \cos \theta_{lk}}, \\
(3.4)
$$

$$
\| P_{lh} - P_{rh} \| = P_{lhw} + P_{rhw} \\
(3.5)
$$

and

$$
(P_{lh} - P_{rh}) \cdot \hat{O}_{wx} = 0, \\
(3.6)
$$

where $P_{la}$ is the position of the ankle of the swinging leg with respect to $F_s$; $L_{lhw}$ and $L_{rhw}$ are the pitch position of the left and right hip with respect to the frame $W$, respectively; and $\hat{O}_{wx}$ is a unit vector of the waist.
The position and orientation of the waist are calculated after the determination of the positions of both hips. Then, the joint angles of both legs are determined by inverse kinematics using the Newton–Raphson iteration method (Oh et al. 1984; Press et al. 1998). The waist can be moved in the roll and yaw direction regardless of the orientation of the trunk. Figure 5 shows the generation of the knee-stretched locomotion pattern.

(b) Moment compensation

When the biped walking robot walks according to the leg pattern created as described previously, moments are generated by the motion of the legs. For a stable walking motion, the moments should be minimized.

Considering that a humanoid robot is a set of particle models, the balancing moment around a contact point \( p \) in a supporting polygon can be expressed with respect to the world coordinate frame \( W \) as

\[
\sum_{i=1}^{n} m_i (r_i - r_p) \times (\ddot{r}_i + G) + T - \sum_{j=1}^{n} (r_j - r_p) \times (F_j + M_j) = 0, \tag{3.7}
\]

where \( r_p \) is the position vector of the point \( p \) from the origin of the frame \( W \); \( m_i \) is the mass of the particle \( i \) of the biped humanoid robot; \( r_i \) and \( \ddot{r}_i \) denote the position and acceleration vectors of the particle \( i \) with respect to \( W \), respectively; \( G \) is the gravitational acceleration vector; \( T \) is the moment vector acting on the contact point \( p \); \( r_j \) denotes the position vector of the particle \( j \) with respect to \( W \); and \( F_j \) and \( M_j \) denote the force and the moment vectors acting on the particle \( j \) relative to the frame \( W \), respectively.

It is difficult to derive analytically the compensatory motion of the waist from equation (3.7). In order to get the approximate solution analytically, we assume that (i) the upper body is modelled as a four-mass model, (ii) the moving frame does not rotate and (iii) the waist does not move vertically. The moments are known values, which are derived from the motion of the legs and a time trajectory of the ZMP. Also, the moments are periodic functions because each particle of the legs and the time trajectory of the ZMP move periodically with respect to the moving frame. Therefore, the linearized equation can be represented as a Fourier series. By comparing the Fourier transform coefficients, the approximate periodic solutions of the waist can be easily obtained.

The strict solutions of the waist motion can be calculated using a recursive method. First, the approximate periodic solutions are computed by the linearized equation. Second, the periodic solutions are substituted into the moment equation (3.7), and the errors of moments generated by the leg motions are calculated according to the planned ZMP. These errors are accumulated to the linearized equation and the approximate solutions are computed again. Finally, these computations are repeated until the errors fall below a certain tolerance level (Lim et al. 2004b).

4. Walking simulation

In order to confirm the knee-stretched pattern generation method, software simulations were conducted. In these simulations, a full-scaled biped humanoid robot was considered, the height of which is 1500 mm, upper body’s length
The mass distribution of its upper body is approximated as shown in Table 4. The maximum angular velocity of the knee was set as 170° s⁻¹.

In the simulations, three different locomotion patterns with five steps forward were created by the locomotion pattern generator. (i) Simulation I is knee-bended walking with a constant height of the waist. The heel and toes land on and lift from the ground at the same time. (ii) Simulation II is knee-stretched walking with a variable height of the waist. The heel and toes land on and lift from the ground at the same time. (iii) Simulation III is knee-stretched walking with a variable height of the waist. It is heel-contact and toe-lift walking.

The knee pattern of the supporting leg in a stretched-walking pattern was determined by consideration of the knee pattern of a human (Figure 1). Hence, the knee angle of the supporting leg, \( \theta_k(t) \), is approximated as follows:

\[
\theta_k(t) = -10 \left( 1 + \sin \left( \frac{2\pi}{T} t \right) \right),
\]

where \( t \) is the sampling time and \( T \) is the supporting period that is set as 0.96 s in the simulations.

In these simulations, a step cycle is 0.96 s per step, a step height is 0.04 m and a step length is 0.30 m. The angle of the foot is set as 15° when the heel lands, while its angle is set as 5° when the toes lift. In the knee-bended pattern, the height of the waist is set as 0.52 m.

Figure 6a–c shows five-step stick diagrams of simulations I–III, respectively. In these simulation results, we can see that the knee-stretched walking is similar to human walking, rather than the knee-bended walking. The heel-contact and toe-lift walking is more likely to be that of human walking, as shown in Figure 6c. Figures 7 and 8 show the pitch angle of the knee and the roll angle of the waist in simulations I–III, respectively. For a comparison between the human and the robot walking pattern during steady walking, the joint angles are plotted only for two steps from 10 to 60%. The supporting period of the right leg is from 7.5 s (10%) to 8.84 s (60%). We can see that the angle pattern of the knee in simulation I is generated between −100° and −60° while in simulations II and III between −50° and 0°. The reason is that the height of the waist is properly changed during the walking. The angle pattern of the knee is similar to that of

Table 4. Mass description of a biped walking robot model.

<table>
<thead>
<tr>
<th>part</th>
<th>weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>arm</td>
<td>8.500×2=17.000</td>
</tr>
<tr>
<td>trunk</td>
<td>10.300</td>
</tr>
<tr>
<td>waist</td>
<td>3.801</td>
</tr>
<tr>
<td>hip</td>
<td>4.816×2=9.632</td>
</tr>
<tr>
<td>knee</td>
<td>2.124×2=4.248</td>
</tr>
<tr>
<td>ankle</td>
<td>1.838×2=3.676</td>
</tr>
<tr>
<td>foot</td>
<td>0.644×2=1.288</td>
</tr>
</tbody>
</table>

792 mm and lower limb’s length 708 mm (Table 1). The mass distribution of its upper body is approximated as shown in Table 4. The maximum angular velocity of the knee was set as 170° s⁻¹.
human, as shown in figure 7c. However, the waist roll pattern is different to that of a human, as shown in figure 8a–c. Figure 8d shows the required torque of the knee in simulations I–III. We can see that the torque in knee-stretched walking is smaller to that in knee-bended walking. The larger the step length is, the more
the knee is stretched in the swinging period. Thus, we should consider a heel-contact and toe-lift locomotion pattern for a biped humanoid robot.

5. Walking experiments

Various walking experiments were conducted to verify the mechanisms and the walking pattern generation of WABIAN-2LL. Using the pattern generator, two kinds of 10-step walking patterns were generated: knee-bended and knee-stretched walking. In both walking patterns, the heel and toe contacted and lifted at the same time, with a step cycle of 0.96 s per step, a step height of 0.04 m and a step length of 0.20 m. In the knee-bended walking, the height of the waist was set as 0.52 m, but in the knee-stretched walking the height of the waist was changed. The knee angle of the supporting legs in the knee-stretched walking pattern was set by equation (4.1). Then, the supporting period $T$ was 0.96 s. Also, the compensatory motion was determined by the pattern generator that was based on the ZMP and the motion of the legs (see §3).

Figure 9a shows the Y-ZMP trajectories in the knee-bended and knee-stretched walking. We can see that the ZMP error between the measured and the reference ZMPs in stretched walking is smaller to that in the knee-bended walking, as shown in figure 9a. Also, the result shows that the measured ZMP is inside a supporting polygon (foot size 240×160 mm). The measured ZMP deviates a little from the reference ZMP, but it seldom affects the stability of the robot’s body. Figure 9b,c shows the angles of the right and left knees, respectively, and figure 9d shows the angles of the roll of the waist. In these results, we can see that the errors between the measured and reference angles are very small.
In order to compare the energy consumption in the knee-stretched and knee-bended walking, the currents of the knee joint are plotted, as shown in figure 10. The energy consumption of the knee-stretched walking was 697 J while that of the knee-bended walking was 1295 J. We can see that the knee-stretched walking consumes less energy than the knee-bended walking.

6. Conclusion and discussion

A new biped machine (WABIAN-2LL) that can deal with various walking was developed. It is different to conventional biped humanoid robots in the d.f. configuration. Owing to its redundancy, it can do deep knee-bended and knee-stretched walking. Also, a knee-stretched walking pattern generation was
generated using numerical inverse kinematics. The walking pattern simulation showed that the walking pattern is similar to a human walking pattern. However, the knee pattern in the stretched walking pattern was not smooth because the velocity might be changed radically when the support phase was changed to the swing phase at 8.84 s. If the knee pattern is arbitrarily set during both the support and the swing phases, then the problem will be solved. Through the walking experiments, the effectiveness of the knee-stretched walking pattern and the mechanisms of WABIAN-2LL was confirmed.

In order to achieve more human-like motions such as knee-bended and knee-stretched motions, several problems should be solved. A human selects a trajectory of the legs, considering a natural posture of the waist and the height of the foot, depending on the terrain condition. Hence, the pattern generator that creates the motion of the foot in advance should be revised. In addition, a human suitably uses the yaw motion of his waist during the whole walking cycle. If a biped humanoid robot uses the yaw motion of the waist, the step length should be increased and the torque should be decreased. The pattern of the knee joint is approximated to the pattern of a human knee joint. However, it is not enough to mimic human walking motion. Hence, the pattern of the knee joint in a supporting phase should be determined by an optimization or learning method. In the near future, we will develop an upper body that will be mounted on WABIAN-2LL.

**References**


