Toe Joints that Enhance Bipedal and Fullbody Motion of Humanoid Robots

Koichi Nishiwaki† Satoshi Kagami‡ Yasuo Kuniyoshi† Masayuki Inaba‡ Hirochika Inoue‡

† Dept. of Mechano-Informatics, Univ. of Tokyo.
7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan. 
{nishi,kuniyoshi,ina}@sk.t.u-tokyo.ac.jp

‡ Digital Human Laboratory, AIST
2-41-6, Osumi, Kouto-ku, Tokyo, 135-0064, Japan.
s.kagami@ist.go.jp

Abstract

This paper addresses the extension of humanoid's action capability by attaching toe joints. Effectiveness of toe joints is discussed in three aspects. One is utilizing it to speed up the walking, another is using it to enable a humanoid to go up higher steps, and the other is using it to whole-body action in which knees are contacting to the ground. Feet with toe joints are developed for Humanoid ‘H6’. An experiment of the whole-body action in which knees are contacting to the ground is carried out to show the usefulness of toe joints for such actions. Then walking pattern generation system is extended to use toe joints. Using this extended system, maximum speed of knee joints can be reduced at the same walking speed and 80% faster walking speed is achieved on humanoid ‘H6’.

1 Introduction

Currently, research on humanoid type robot is active field in robotics society. Several researches of toe joint utilization in bipedal locomotion have been proposed such as, 1) passive toe joints in order to achieve stable foot lifting [1], 2) toe joints that are controllable both actively and passively for less energy consumption walking [2], and 3) active toe joints for step up stairs [3, 4]. However, most of all humanoid type robots have been developed with 6 DOFs legs without toe joints [5–7].

We also have been developing a humanoid robot H6 [8] & H7, in order to do research on both locomotion and high-level behavior by integrating tactile sensing/3D vision based perception and motion-planning. In this paper, development of toe joints for H6, and utilization of toe joints for walking and fullbody motion are described. There are three key issues, a) augment a walking speed, b) augment the height robot can step up, and c) whole-body action in which knees are contacting to the ground.

In this paper merits of toe joints for these these key issues are described. Then design requirements for toe joints and implementation to humanoid robot H6(Fig. 1) are described. Experiments on H6 utilizing toe joints show those merits.

2 Utilizing Toe Joints for Humanoid Motion

We designed toe joints to achieve following points.

- Knee down motion keeping the sole attaching to the ground,
- Walking speed augmentation,
- High step climbing.


2.1 Knee down motion

Knee down posture is regarded as one of the most important full body posture for humanoid type robot, since it has large stability margin against falling down and large number of DOFs remain controllable at the same time.

As shown in Fig.2, ankle pitch joint angle for forward direction $\theta$ must be larger than $90^\circ$ (when $a > b$), in order to kneel down keeping the sole attaching to the ground. However, considering the room and the stiffness, wide joint range design is difficult to realize. Instead of adopt such design, we attached toe joint to kneel down keeping the sole attaching to the ground.

2.2 Walking Speed Augmentation

It is mentioned that toe joints are not necessary for bipedal walking [5]. We also realized bipedal walking on H6 without toe joints. However, especially knee joint maximum speed limits step length and step cycle, and this determines the maximum walking speed.

When making step length wider, the knee joint of the next swinging leg becomes near straight, then the controllability of the foot especially for lifting up direction is reduced(Fig.3(a)).

By adding toe joints as shown in Fig.3(b), controllability to lift a leg is augmented. Therefore, faster walking motion (bigger stride or quicker cycle) can be achieved.

By extending leg links causes almost the same effect as shown in Fig.3(c). However knee joint load of the supporting leg will increase assuming feet and torso follow the same position trajectories.

2.3 Step Height Augmentation

When stepping up stairs, the knee joint of the leg that attaching to upper step is requdied to generate the highest torque while lifting up the body. This torque depends on bending angle of the knee joint, and the momentum of the whole body at the moment of detaching of the leg on lower step. Larger knee joint bending angle causes larger offset of the knee joint from the line that connects the foot and the center of mass, so that knee torque increases(Fig.4(a)).

By using toe joint as shown in Fig.4(b), torso is pushed up before the lifting of the foot on lower step and knee bending angle of the leg on upper step is reduced. Therefore it can climb up a higher step.

The same discussion can be made for extending leg links as mentioned in section 2.2.

Concludingly, toe joint causes the same effect as dynamic link length change in case of walking and climbing a step. This helps reducing the load of knee joints, where both very high torque and speed are required compared with other leg joints in order to achieve biped locomotion.

3 Design of Foot that has Toe Joint

3.1 Design of Toe Joint

DOF arrangement of toe and ankle joints, and the shape of contacting surface (sole) are shown in Fig.5. Toe joint axis is placed almost the center of the toe.
link in forward direction, instead of placing the rear end of toe link. Advantages of this design are the following, a) bi-directional torque can be generated by the toe joint, and b) ZMP [9] is usually designed near the center of supporting convex hull so that the torque required to the joint can be reduced. According to this advantages, small and light motor can be adopted. A defect of this design is breakage because the gear suffers bi-directional torque.

In order to estimate required motor power, static condition is considered to decide the maximum joint torque. Supporting the weight of the robot itself (about 50[kg]) at the front end of toe link (about 19.5[mm] from joint axis), 9.55[Nm] torque is required. As for joint speed, assuming that dual leg supporting phase is 0.2[sec], and 40[deg] is assumed as a maximum angle to lift the heel, then 200[deg/sec] is required. Therefore, we adopted Maxson 20W DC motor(RE25, 118754), and reduction gear ratio is set to 148:1 by planetary gear head (66:1) and spur gear (2:21). Specification of toe joint is shown in Table 1.

### 3.2 ZMP and Vertical Reaction Force Mesurement System

ZMP and vertical reaction force from the ground measurement system has been developed by using strain gauge. The system consists of several measurement units distributed in the foot, and each has a ground contacting cylinder and a beam with strain gauge that measures vertical component of the ground reaction force at each position (Fig.6). Assuming that no torque whose axis is parallel to the ground is transmitted at each contact point, torque around x, y axis and total force for z direction can be calculated by the output of distributed units, then ZMP can be obtained.

Beam is made of aluminimum and considering the elastic limit, it is designed to deform 2000[με] at 588[N](60[kgf]). There is a stopper above the cylinder to prevent permanent deformation (not shown in the figure).

Strain amplifier circuit is developed as small as possible by using single chip instrumentation amplifier (burr brown : INA 125). The board is attached inside the shank. Specification of the board is shown in Table 2. Since beams only measures single side strain, the circuit measures single side only.

Output of this strain amplifier is connected to AD converter input of I/O board (Fujitsu HF-01) that is connected to onboard PC by ISA bus. Fig.7 shows a relationship between force and AD reading, applying the force by digital force gauge (IMADA DPX-50T). Amplifier gain was about 800 in this experiment. Calibration is done by line fitting of this result using least square method for each unit. Since there is initial stress, load lower than about 5[N] can not be measured.

### Table 1: Specification of Toe Joints

<table>
<thead>
<tr>
<th>Angle Range</th>
<th>-60°(Up) ~ 15°(Down)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>DC 20W</td>
</tr>
<tr>
<td>Gear Ratio</td>
<td>148:1</td>
</tr>
<tr>
<td>Stopping Torque</td>
<td>23.9[Nm]</td>
</tr>
<tr>
<td>Angle Speed</td>
<td>264 deg/sec</td>
</tr>
</tbody>
</table>

1. After gear reduction.
2. After gear reduction with no load.

### Table 2: Strain Amplifier Specification

<table>
<thead>
<tr>
<th>Channel</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>90 × 5 × 13mm</td>
</tr>
<tr>
<td>Bridge Supply Voltage</td>
<td>2.5V</td>
</tr>
<tr>
<td>Output</td>
<td>0~10 V(Single Side)</td>
</tr>
<tr>
<td>Gain</td>
<td>000 ~ 2000</td>
</tr>
<tr>
<td>Bridge Balance</td>
<td>Manual</td>
</tr>
</tbody>
</table>

4 Fullbody Motion using Toe Joints

As mentioned before, it is possible to kneel down keeping the sole attaching to the ground using toe joints.
Fig. 7: Load vs. Output of Strain Amplifier

Table 3: Pitch Angles at Knee Down Motion [deg]

<table>
<thead>
<tr>
<th></th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip</td>
<td>-35.0</td>
<td>-65.0</td>
<td>-65.0</td>
<td>-132.0</td>
</tr>
<tr>
<td>Knee</td>
<td>148.0</td>
<td>148.0</td>
<td>148.0</td>
<td>148.0</td>
</tr>
<tr>
<td>Ankle</td>
<td>-60.0</td>
<td>-60.0</td>
<td>-60.0</td>
<td>-60.0</td>
</tr>
<tr>
<td>Tor</td>
<td>-52.0</td>
<td>-52.0</td>
<td>-52.0</td>
<td>-52.0</td>
</tr>
<tr>
<td>Should</td>
<td>0.0</td>
<td>0.0</td>
<td>-30.0</td>
<td>-10.0</td>
</tr>
<tr>
<td>Elbow</td>
<td>-20.0</td>
<td>-20.0</td>
<td>0.0</td>
<td>-37.0</td>
</tr>
<tr>
<td>Wrist</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>-35.0</td>
</tr>
</tbody>
</table>

Fig. 8 shows an experiment on H6, (a) Torso vertical and knee contacting the ground, (b) Torso bending almost stability limit, (c) Arm contacting the ground, and (d) Torso horizontal. Table 3 shows pitch angles of this procedure.

5 Walking Motion with Toe Joints

5.1 Walking Trajectory Generation from Given ZMP Trajectory

In general, ZMP trajectory can be analytically led from the robot motion trajectory, however leading robot trajectory that satisfies given ZMP trajectory analytically is difficult, since it has to solve non-linear, interfered 2nd order differencial equation with link constraints. In this section, a fast generation method of walking trajectory that follows given ZMP trajectory by modifying horizontal torso trajectory from given initial walking trajectory.

5.1.1 Linearize and Non-Interferencize the Dynamics Equation about ZMP

Let $i^{th}$ robot link position, mass, inertia tensor, angular velocity vector be $r_i = (x_i, y_i, z_i)^T$, $m_i$, $I_i$, $\omega_i$, and gravity be $g$. Set coordinates as $x$-$y$ plane be the ground and as $z$-axis be negative gravity direction. Let ZMP position be $P = (x_p, y_p)^T$.

Then equation to lead ZMP from robot motion is described as follows (the same for $y_p$):

$$x_p = \frac{\sum m_i z_i x_i - \sum \left\{ m_i (\ddot{z}_i + g) x_i + (0,1,0)^T I_i \dot{\omega}_i \right\}}{-\sum m_i (\ddot{z}_i + g)}$$

(1)

Let robot trajectory be described as follows;

$$A(t) = (x_1(t), y_1(t), z_1(t), \theta_1(t), \phi_1(t), \psi_1(t), \cdots, x_n(t), y_n(t), z_n(t), \theta_n(t), \phi_n(t), \psi_n(t))$$

(2)

ZMP trajectory $P_n(t) = (x_{p1}, y_{p1}, 0)^T$ can be solved by Eq. (1). Now consider to generate trajectory that follows desired ZMP $P_n(t)$ by only modifying $x_i(t), y_i(t)$ in $A(t)$ to $x_i'(t), y_i'(t)$.

$$x_p' = \frac{\sum m_i z_i x_i' - \sum \left\{ m_i (\ddot{z}_i + g) x_i' + (0,1,0)^T I_i \dot{\omega}_i \right\}}{-\sum m_i (\ddot{z}_i + g)}$$

(3)

This problem is solving $x_i'$ that satisfies Eq. (3) (the same for $y_i'$). Eq. (1) – Eq. (3) gives a following equation;

$$x_p = \frac{\sum m_i z_i x_i' - \sum m_i (\ddot{z}_i + g) x_i'}{-\sum m_i (\ddot{z}_i + g)}$$

(4)

Here, $x_p' = x_p - x_{p1}, x_i' = x_i - x_i$.
Since there is redundancy, consider $x_i^e = x^e$, that is, modifying the horizontal position of all the link in same distance. In reality, feet position can not be changed relative to the ground, however upperbody can satisfy this modification. When modifying upper body position in horizontal plain, the position changes of leg links, which are led by inverse-kinematics, are approximately proportional to the upper body in horizontal plane and little for rotational and vertical component.

5.1.2 Numerical Solution of Differential Equation

Set $x_i^e = x^e$ to Eq. (4), then following equation is obtained;

$$\frac{\sum m_i \ddot{z}_i}{\sum m_i (\ddot{z}_i + g)} \ddot{x}^e + x^e = x_i^p. \quad (5)$$

In order to solve numerically time is descritized to $0, \cdots, t_m$ with time step $\Delta t$. Acceleration at each time $\ddot{x}^e(t_i)$ can be represented as follows;

$$\ddot{x}^e(t_i) = \frac{x^e(t_{i+1}) - 2x^e(t_i) + x^e(t_{i-1})}{\Delta t^2}. \quad (6)$$

Then Eq. (4) can be expressed as trinomical equations. Setting boundary conditions as $x^e(0), x^e(t_m) = 0$, $x^e(i)(i = 1 \text{ to } t_m - 1)$ are obtained.

Therefore, robot trajectory can be calculated that satisfies given ZMP trajectory $P^*_A(T)$.

5.1.3 Design of Walking Trajectory Generation System

Walking trajectory generation is carried out in following steps: 1) Initial posture, initial velocity, final posture, final velocity, arm trajectory, foot posture at each discrete step, time for single & dual leg support phase, torso posture at the middle of dual leg support, etc. are given, 2) Initial motion trajectory, and desired ZMP are generated, and 3) The motion trajectory that satisfies desired ZMP is solved as mentioned above. Dynamics calculation is carried out using "Z-DYNAFORM" library [10].

5.2 Toe Joint Utilization for Walking

On H6, in case of without using toe joint, knee joint maximum velocity limits the walking speed (cycle and step length). Maximum knee joint speed at $24[V]$ is $190[\text{deg/sec}]$ in specification (without load). Fig.9 shows knee joint angle and angle velocity in $160[\text{mm}], 1[\text{sec}]$ per a step walking. Maximum angle velocity was about $140[\text{deg/sec}]$.

![Figure 9: Left Knee Angle and Angle Velocity (160[mm], 1[sec] per a step) ](image)

Then, toe joint utilization is introduced. The toe joint of the next swinging leg bends during the dual leg support phase in order to reduces the maximum knee joint angle velocity. In Fig.9, toe joint bending angle was 15.0[deg] at the time of lifting the swinging leg, then maximum knee joint angle velocity was reduced to about $80[\text{deg/sec}]$ in the same walking condition.

By using this method, we achieved $270[\text{mm}], 1[\text{sec}]$ per a step walking (Fig.11). Fig.10 shows a left knee angle and angle velocity. Toe angle at lift was 20.0[deg] and maximum knee angle velocity was 128[deg/sec].

Fig.12 shows a 100[mm] stair climbing experiment. Lifting a heel during the dual leg support phase make torso heiger when lifting the leg on the lower surface.

6 Conclusion

In this paper, toe joint utilization for fullbody humanoid robots is discussed and three key issues are described: 1) walking speed augmentation, 2) step up height augmentation, and 3) knee down motion. Then we developed feet with toe joint and attached to our humanoid robot H6 and H7 to examine.

Robot trajectory generation system was enhanced to use toe joint. By using this system, walking speed augmented by 80%. On H7, we achieved $400[\text{mm}], 1[\text{sec}]$ per a step walking and $25[\text{cm}]$ height of step climbing. Next research will be 1) optimal toe joint trajectory generation, and 2) toe joint utilization during the sin-
ingle leg support phase.

References


