Abstract

The human foot has evolved over many years into a specialized mechanism for biped walking. It has a complicated mechanism with a number of bones and ligaments. In particular, the arch structure and the toe joints have important roles in walking. The arch structure acts as a shock absorber that enhances the adaptability of the foot with respect to the ground, and the toe joints move dynamically during walking. Although most humanoid robots have a simple foot
mechanism, a humanlike foot mechanism is key to the foot adaptability. This chapter reviews previous research on the humanlike foot mechanism, with special focus on the toe joint.

**Keywords**

Toe joint · Arch structure · Leg kinematics · Foot adaptability · Parallel four-bar linkage

## 1 Introduction

The human foot has evolved over many years into a specialized mechanism for biped walking [1]. It has a complicated mechanism with a number of bones and ligaments [2]. In particular, the arch structure and the toe joints have important roles in walking. The arch structure acts as a shock absorber that enhances the adaptability of the foot with respect to the ground, and the toe joints move dynamically during walking. Some biped gait analyses report that walking speed decreases and the upper body becomes unstable when the toe joints are mechanically constrained by shoes [3,4]. This supports the notation that the human foot mechanism, complex in nature, contributes to walking performance.

On the other hand, most humanoid robots have a simple foot mechanism: a flat sole, a rectangular shape, and no toe joints. Although an elastic material is usually used for the foot sole, complicated mechanisms such as toe joints are not often employed. Robotics researchers understand the importance of the human foot function but tend to prefer a simple foot mechanism when designing the total system of a humanoid. Controlling compliance or impedance is one solution to enhance the foot adaptability; however, it is difficult to achieve humanlike adaptability using only this control because of the inevitable delay associated with this control. To avoid this complication, a humanlike foot mechanism is key to humanoid robotics.

This chapter reviews previous research on the humanlike foot mechanism, with special focus on the toe joint. As mentioned, the human toe joint has important roles in biped walking, but its mechanism is complicated. How do we simplify the mechanism without compromising its function? First, there is a brief explanation of the human foot mechanism followed by a review of studies on humanoid toe joints, including the humanlike toe joint mechanism with four-bar linkage, and concluded with a summary of the findings.

## 2 Human Toe Joint Mechanism

The human foot is arguably the most complicated mechanism in human body. It consists of 28 bones (including 2 sesamoid bones) as shown in Fig. 1a, which are connected by muscles and ligaments. One important element in the human foot mechanism is the plantar arch. There are three main arches in the human foot: (1) the anterior transverse arch, (2) the lateral longitudinal arch, and (3) the medial
Humanlike Toe Joint Mechanism

Fig. 1  Human foot mechanism. Human foot consists of 28 bones including 2 sesamoid bones (a). There are three main arches in the foot (b), which function as a shock absorber-longitudinal arch (see Fig. 1b). These three arches connect the calcaneus, the first metatarsal, bone and fifth metatarsal bone, comprising three contact points with the ground. Each arch can be regarded as a leaf spring and functions as a sock absorber, mechanisms enabling foot adaptability with respect to the ground.

Another important element is the toe joint, which usually refers to the metatarsophalangeal (MP) joint of each toe. Figure 2 is a schematic illustration of the MP joint angle during the gait cycle (drawn based on [1, 5]), showing the foot contact...
Fig. 2  Schematic illustration of MP joint angle during gait cycle (Drawn based on [1, 5])

state and the ground reaction force vector at each gait phase: heel strike, foot flat, mid-stance, heel off, toe off, and mid-swing. The MP joint decreases 0° at the heel strike phase and maintains 0° before the heel off phase. It has a peak value of 50° at the toe off phase and begins to decrease again before the mid-swing phase.

One of the important functions of the MP joint is to maintain foot support during the time between the heel off and toe off phases. This helps with the kicking motion. As shown in Fig. 2, the ground reaction force becomes so large that it accelerates the body movement. This is the second peak of well-known two-peak profile of the ground reaction force. During this phase, the MP joint maintains the ground contact thereby stabilizing the kicking motion [5].

What would happen if there were no MP joints? Researchers investigated gait analysis with mechanically constrained shoes [3,4] and reported that walking speed and stability decreased when the MP joint was constrained by mechanical shoes. This mechanical constraint can be representative of humanoid walking. The reason for the decrease in speed and stability is as follows: The leg motion in the sagittal plane can be represented by a simple model with revolute joints in the hip, knee, ankle, and toe (see Fig. 3a). The total DOF is four which is considered redundant from a robotics aspect because a minimum of three DOF is required for sagittal plane motion: x, y, and rotation. When the MP joint is constrained, the leg DOF becomes three (nonredundant), as shown in Fig. 3b. Redundant DOF improve leg mobility, which implies the following kinematic improvement: smaller joint angular velocity and larger range of motion. It is easy to imagine that the motion range of Fig. 3b is less than that of Fig. 3a. As a result, the walking speed and stability are decreased. This implies that the DOF of the MP joint improves the leg mobility.

Another important function is to modulate the foot stiffness. Some research reported on the relationship between the plantar arch and the toe joint, which is
called the windlass mechanism \cite{6} (see Fig. 4) as being critical to foot stiffness. When the MP joints are flexed, the height of the arch is increased. At the same time, the plantar aponeurosis, which is connected to the thenar, is extended and becomes solid, thereby increasing the stiffness of the plantar arch. This mechanism allows the foot arches to change their stiffness during walking: elastic at the foot landing and stiff at the toe off. The former improves the adaptability to the ground, and the latter helps the kicking motion.

3 Humanoid Toe Joint Mechanism

Compared with such a complicated mechanism of the human foot, most humanoid robots such as ASIMO \cite{7} and HRP-2 \cite{8} employ a simple foot mechanism. The sole is flat and has a rectangular shape, and there is no movable toe joint.
While a simple mechanism makes the hardware design and control algorithm easier, it compromises the leg mobility and adaptability. One solution to improve the leg mobility is to utilize the toe edge contact as a virtual MP joint [9]. However, the control becomes more difficult because this creates a non-holonomic system.

In an effort to improve leg mobility and foot adaptability, the toe joint mechanism of humanoid robots has been studied. One of the oldest studies on designing a humanoid toe joint can be found in the 1970s [10]. Since the early 2000s, toe joint mechanisms have been implemented on actual humanoid robots. Table 1 briefly summarizes research on the humanoid toe joint mechanism. Below are descriptions of the toe joints of each of the listed humanoid robots.

### 3.1 MONROE, TOKAI ROBO-HABILIS 1, ROBIAN

In the early 2000s, three humanoid robots which had a one DOF toe joint were developed. Kumagai et al. [11] and Konno et al. [14] developed MONROE and ROBIAN, respectively. Both robots had a passive toe joint. Koganezawa et al. [13] proposed an interesting toe joint mechanism in the development of TOKAI ROBO-HABILIS 1 (TRH-1). It was a semi-active joint in which the toe joint moved simultaneously with the ankle joint.

### 3.2 H7

Nishiwaki et al. [12] developed H7, which had an active toe joint. Each leg had seven DOF including one redundant DOF of the toe joint. Utilizing the redundant DOF, they demonstrated several motions: a transition from standing to knee down posture, climbing stairs, and a walking motion, all using the toe joint (see Fig. 5a). They compared the angular velocity of the knee joint during walking motion of H7 with that of H6 [24], which was a previous version of their robots containing no toe joint. It was observed that the angular velocity of H7 decreased when compared with that of H6. The reduced angular velocity is an advantage for a robot because

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a joint actuator has a limit of the angular velocity. Such an improvement of the leg mobility is one of the advantages of utilizing a toe joint.

3.3 TOYOTA's One-Legged Robot

TOYOTA developed a one-legged robot capable of hopping motion [15]. The toe joint used was similar to that of H7: a simple one-DOF revolute joint with an actuator. A hopping motion requires a larger joint angular velocity and a wider range of motion of the leg as compared to a walking motion. Tajima et al. [15] verified that utilizing the toe joint drastically decreases the joint angular velocity, which proved to be one third of that of the robot without toe joint used in the simulation.
3.4 WABIAN-2

Ogura et al. [16] developed WABIAN-2 with a toe joint capable of a walking motion utilizing the toe joint. While the WABIAN-2 toe joint configuration is similar to that of H7 and TOYOTA’s one-legged robot, it was a passive joint, meaning that it had spring in place of an actuator. As a result, the total size of the foot mechanism was much smaller than those of H7 and TOYOTA’s robot. In the toe off phase of walking, the toe joint of WABIAN-2 generated a ground reaction force by using a spring to maintain the surface contact between the toe and the ground.

3.5 HRP2-LT

Kajita et al. [18] developed HRP2-LT also with a passive toe joint capable of a running motion. As demonstrated by TOYOTA’s robot, the active toe joint is valid for hopping. Similarly, HRP2-LT’s passive toe joint was capable of highly dynamic movements, specifically running. One of the disadvantages of a passive toe joint is the difficulty in choosing an appropriate spring constant. Kajita et al. [18] selected a spring constant value using the results of several simulations.

3.6 LOLA

Lohmeier et al. [19] developed LOLA, which had an active toe joint. Although no specific results using the toe joint were found, a toe joint mechanism similar to H7 and TOYOTA’s robot was employed.

4 HumanLike Toe Joint Mechanism

In the 2000s researchers focused largely on improving leg mobility through manipulation of the toe joint. Most toe joints of the 2000s (H7, TOYOTA robot, LOLA, WABIAN-2, HRP-2LT) had a simple mechanism. Since 2010, more humanlike toe joints have been developed.

4.1 Toe Joint with Parallel Four-Bar Linkage

A key aspect of the toe joint is joint configuration. Figure 6a shows the main joint configuration of the toe joint used in the 2000s. It is a simple mechanism. The foot is divided into tarsus and toe links, which are connected by a revolute joint. Only the toe link contacts the ground when a humanoid lifts heel up. A disadvantage of this configuration is that the total weight of the humanoid is supported only by the toe joint. The radial load on the toe joint axis becomes maximal, requiring a large-sized bearing and causing the total size of the toe joint to be as large as the other leg joint. This is the case with both H7 and TOYOTA’s one-legged robot. In
Fig. 6 Simple toe joint mechanism (a), the human toe mechanism (b), and proposed toe-thenar mechanism (c). The toe-thenar mechanism enables humanlike multiple-point contact with the toe and thenar.
contrast to humanoids with this joint configuration, when humans stand on tiptoe, the total weight is supported by not only toe but also the foot thenar as shown in Fig. 6b. In particular, the point of action of the ground reaction force is located close to the thenar during the heel off phase (see Fig. 2). By supporting a major part of the ground reaction force, the thenar mechanism decreases the radial load on the joint axis. Therefore, it can be expected that the joint size will not need to be as large when the toe is used in conjunction with a thenar mechanism as shown in Fig. 6c. Note that the thenar is called the ball of the foot [2]. Although thenar usually refers to the base of thumb in the hand, this term is used for the foot in this section.

Narioka et al. [21] employed the toe-thenar joint configuration shown in Fig. 6c in Pneumat-BB (see Fig. 12a). However, this mechanism caused unexpected shear forces at the toe and thenar (see Fig. 7). Human toe mechanism avoids this by bending multiple toe joints: not only the MP joint but also the proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints. Although Narioka et al. used elastic pads on the toe and thenar, causing elastic deformation and allowing the motion shown in Fig. 7, the motion range of the toe joint was limited to a maximum 10°.

To realize this complicated but humanlike motion of the human toe joints by a one-DOF mechanism, in 2007 Yamamoto et al. [17] proposed a toe-thenar mechanism with parallel four-bar linkage depicted in Fig. 8. Link A, the tarsus link, is equivalent to a toe pad with an arc-shaped cross section. Link C, the top toe link, is equivalent to a toe tip having a radius equal to that of link A. Links A and C are connected with links B and D, to form a parallelogram. The positions of joints 2 and 4 are set on the center of the circular arc of the toe pad and toe tip, respectively. When joint 1 is actuated, links A and C roll over the ground maintaining contact.
This toe joint mechanism was implemented on UT-μ2 [17] (see Fig. 9). The toe joint was actuated by a DC motor. The maximum angle of the toe joint was set to be 44° based on the motion range of human MP joint (see Fig. 2). A walking motion using the toe joint was also demonstrated (see Fig. 10). A similar four-bar link mechanism was employed in the toe joint of HRP4-C [20] in addition to a powered prosthetic leg [25] (see Fig. 11).
4.2 Windlass Mechanism by Toe Joint

Another important function of the toe joint is the windlass mechanism. Narioka et al. [21] and Hashimoto et al. [22,23] developed toe joints mimicking the windlass mechanism. Narioka et al. [21] developed Pneumat-BB using McKibben pneumatic artificial muscles as the actuator. The main focus was to develop a humanlike musculoskeletal robot implementing variable stiffness with four pneumatic actuators, representative of the following human muscles and ligaments in the foot: extensor digitorum brevis, flexor hallucis brevis, long plantar ligament, and plantar aponeurosis (see Fig. 12a). It was demonstrated that a walking motion using this mechanism resulted in a change in the height of the arch similar to that of humans.

Hashimoto et al. [22,23] proposed another windlass mechanism using a wire. Figure 12b shows this mechanism, in which two elastic materials are switched as the toe joint angle changes. When the toe joint angle is 0°, the tarsus link which connects the toe and arch axes contacts one elastic material. When the toe joint angle becomes larger, the heel and tarsus links are pulled by the wire. As a result, the tarsus link contacts the other elastic material which has larger elastic modulus. By switching these elastic materials, it was possible to reproduce variable stiffness as seen in human.

Ogawa et al. [26] developed a foot mechanism which had a plantar arch and a one-DOF toe joint. They more focused on the viscoelastic characteristic of the human foot structure. They analyzed the viscoelastic parameter during walking and employed spring dampers for the plantar arch and the toe joint.
4.3 Multiple Toes

We have focused on the toe joint movement in the sagittal plane. As previously described, most humanoids have a one-DOF toe joint that is equivalent to the MP joint despite the fact that the human foot mechanism is more complicated. The number of bones is different in each toe: two bones, proximal and distal phalanxes, excluding sesamoid bones, in the first, and three bones proximal, middle, and distal phalanxes, in each toe from the second to the fifth. The directions of the joint axes also differ between each toe. The MP joint axis in the first toe is parallel to the lateral axis, whereas the MP joint axis in each toe from the second to the fifth toes is inclined from the lateral axis. Based on this physiology, Hashimoto et al. [22] developed the foot mechanism with two distinct toes as shown in Fig. 13a. One is the first toe and the other is equivalent to the second through fifth toes. The windlass mechanism is associated with the first toe. A shoe-wearing foot mechanism was also demonstrated as shown in Fig. 13b [23].
5 Analysis of Toe Joint Mechanisms

The author introduced a mechanism with the parallel four-bar linkage as a human-like toe joint. This section provides a detailed comparison between the following three mechanisms: (1) simple toe joint mechanism shown in Fig. 6a, (2) the toe-thenar mechanism shown in Fig. 6c, and (3) the toe joint mechanism with parallel four-bar linkage shown in Fig. 8. In particular, we analyze the force and torque acting on the toe joint during a given motion. In the following discussion, it is sufficient to consider the motion to occur in the sagittal plane.

First, the simple toe joint mechanism is modeled as shown in Fig. 14. Let $m$ be the robot mass and $p_G = [x_G\ y_G]^T$, $p_T = [x_T\ y_T]^T$, and $p_Z = [x_Z\ y_Z]^T$ be the positions of the center of gravity (COG), the toe joint, and the zero moment point (ZMP) [27], respectively. Here, it is assumed that the mass of the toe link is so small that its effect is negligible compared with the total mass of the robot and that its moment of inertia is ignored. The model 1 in Fig. 14 can be divided into two parts: one is a model above the toe joint, the other is model of the toe tip link. The equations of motion for the upper part (Fig. 14a) are written as follows:
Fig. 14 Model 1: simple toe joint mechanism which was employed in humanoid robots such as H7 [12], TOYOTA’s robot [15], WABIAN-2 [16], HRP2-LT [18], and LOLA [19]

\[
m \ddot{x}_G = f_{Tx} \tag{1}
\]

\[
m(\ddot{z}_G + g) = f_{Ty} \tag{2}
\]

\[
(y_G - y_T) m \ddot{x}_G - (x_G - x_T)m(\ddot{z}_G + g) = -\tau \tag{3}
\]

where \( f_T = [f_{Tx} \ f_{Ty}]^T \) is the constraint force of the joint and \( \tau \) is the joint torque. On the other hand, equations for the lower part (Fig. 14b) are written as follows:

\[
f_{Ex} - f_{Tx} = 0 \tag{4}
\]

\[
f_{Ey} - f_{Ty} = 0 \tag{5}
\]

\[
(y_T - y_Z)f_{Ex} + (x_T - x_Z)f_{Ey} = \tau \tag{6}
\]

where \( f_E = [f_{Ex} \ f_{Ey}]^T \) is the ground reaction force. Note that \( y_Z \) is the ground level and it is known. Therefore, when the motion of the COG is given, the joint force and the external force, namely, \( f_{Tx}, f_{Ty}, \tau, f_{Ex}, f_{Ey}, x_Z \), are uniquely determined from Eqs. (1), (2), (3), (4), (5), and (6).

Next, the toe-thenar mechanism is modeled as shown in Fig. 15. Let \( f_{E1} = [f_{E1x} \ f_{E1y}]^T \) and \( f_{E2} = [f_{E2x} \ f_{E2y}]^T \) be the external forces acting on the thenar and the toe tip, respectively. Equations of motion for the upper part (Fig. 15a) are written as follows:

\[
m \ddot{x}_G = f_{E1x} + f_{Tx} \tag{7}
\]

\[
m(\ddot{z}_G + g) = f_{E1y} + f_{Ty} \tag{8}
\]

\[
(y_G - y_T)m \ddot{x}_G - (x_G - x_T)m(\ddot{z}_G + g) = l_1 f_{E1y} - hf_{E1x} - \tau \tag{9}
\]
Model 2: the toe-thenar mechanism with one-DOF serial link mechanism, which was employed in Pneumat-BB [21]

where $h \equiv y_T - y_1 = y_T - y_2$ and $l_1 \equiv x_T - x_1$. Equations for the lower part (Fig. 15b) are written as follows:

\[ f_{Tx} + f_{E2x} = 0 \]
\[ f_{E2y} - f_{Ty} = 0 \]
\[ hf_{E2x} + l_2f_{E2y} = \tau \]

where $l_2 \equiv x_2 - x_T$. Comparing Eqs. (1), (2), (3), (4), (5), and (6) and Eqs. (7), (8), (9), (10), (11), and (12), qualitatively, the constraint force of the joint in Fig. 15 is smaller than in Fig. 14 because the external forces $f_{E1}$ and $f_{E2}$ act on the points of multiple links. However, from Eqs. (7), (8), (9), (10), (11), and (12), the joint forces and the external forces, namely, $f_{Tx}$, $f_{Ty}$, $f_{E1x}$, $f_{E1y}$, $f_{E2x}$, and $f_{E2y}$, are not determined uniquely. We can obtain these forces by the following linear programming formulation:

\[ \tau \longrightarrow \text{min} \quad \text{subject to equations (7), (8), (9), (10), (11), and (12)} \]

Finally, the toe joint mechanism with the parallel four-bar linkage is modeled as shown in Fig. 16 and can be divided into four parts shown on the right side. In Fig. 16, $f_1$, $f_2$, and $f_3$ are constraint forces of the passive joints. Although we can obtain a total of twelve equations of motion, the unknown values, namely, the constraint forces, the torque of the joint, and the external forces, are not determined uniquely because there are thirteen unknown values. Therefore, we determine the joint forces and the external forces by linear programming that minimizes the joint torque, in a similar way to model 2.
The author simulated the joint forces and the external forces, while a robot stood on tiptoe and the COG moved. The robot mass $m$ was set to 7.5 kg assuming the mass of a miniature humanoid. The configuration of the toe link was set as follows: $l_1 = 12.5$ mm, $l_2 = 22.5$ mm, and $h = 42$ mm. The COG moved from $x_G(0) = -5$ mm to $x_G(T) = 0$ during $0 \leq t \leq T$, while the height of the COG was constant ($y_G(t) =$ constant). The referential trajectory was generated through interpolation from $x_G(0)$ to $x_G(T)$ using spline interpolation. The results of the simulation are shown in Fig. 17. Considering the constant $y$-axis of the constraint force, the robot’s entire weight always acts on the joint in the case of model 1. On the other hand, in the case of model 2 or 3, the weight acting on the joint becomes smaller because the robot can additionally contact the floor at the toe pad thereby assuming a portion of its weight.

6 Planning of Walking Motion Using Toe Joint

Utilization of the toe joint motion and the toe contact phase can improve the leg mobility. Here, we review how to generate a walking motion utilizing the toe joint.

A popular approach for the biped gait planning is to use a simple model focusing on the dynamics between the COG and the ZMP. Figure 18 shows the gait planning procedure for a normal walking without toe joint motion. The procedure to generate a one-step motion in a walking is as follows: First, a trajectory of the ZMP is designed so that the ZMP moves from the kicking foot to the supporting foot,
which are specified in advance. Then, the COG trajectory is computed based on the COG-ZMP dynamics. Here, parameters of the COG and ZMP trajectories are simultaneously computed so that the motion continuity and the constraint on the ZMP are satisfied. Finally, the COG trajectory is resolved into the whole-body joint trajectory by the inverse kinematics computation.

In the gait planning by utilizing the toe joint motion, there are two keys. One is the ZMP movement with the support polygon change. When a walking motion includes the toe contact phase, the change of the support polygon is more complicated than that of a normal walking, as shown in Fig. 19. Yamamoto et al. [28] proposed a gait planning method which considered the two-phase ZMP movement:

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**Fig. 17** Simulated results of the joint constraint forces, the joint torque, and the external forces while the COG moves
Fig. 18 Gait planning of a normal walking without toe joint motion

Fig. 19 Gait planning of a normal walking with toe contact phase

one is from the kicking foot to the center of the supporting foot, and the other is from the center to the toe tip of the support foot. This is based on the COP trajectory in a human gait analysis [29]. It is observed that the COP stays near the thenar in the
last half of the gait cycle. The two-phase ZMP movement can imitate such a COP trajectory. Figure 10 shows a walking motion generated by this method.

The other key is the inverse kinematics. In particular, the toe joint makes it easier to generate a knee-stretched motion. For example, Ogura et al. [16] proposed an inverse kinematics method for a knee-stretched walking. They firstly set the knee joint trajectory and then solved the inverse kinematics excluding the knee joint DOF. Because of the toe joint DOF, the leg DOF remained six excluding the knee joint, and the inverse kinematics was solvable. Hernandez-Santos et al. [30] presented a closed-form solution of the inverse kinematics for the lower limb including the toe joint. Tanaka and Sugihara [31] proposed a general computation method of the inverse kinematics. They generated a knee-stretched walking motion by using a robust inverse kinematics solver and switching the prioritized contact points with the ground depending on the ZMP movement.

7 Summary

This chapter reviewed previous research on the toe joint mechanism of humanoid robots. While the toe joints in the 2000s consisted of a simple one-DOF mechanism, more humanlike toe mechanisms have been developed recently: the toe joint mechanism with the parallel four-bar linkage, the windlass mechanism, and the multiple-toe mechanism. This section also described the mechanical analysis on the toe joint mechanism with the parallel four-bar and verified its mechanical advantage compared with the simple one DOF mechanism.

As mentioned, it is difficult to perfectly reconstruct the human toe structure. The important thing for designing a humanoid toe joint is to select key aspects from the human toe structure and to simplify the mechanism without compromising them. One of key aspects would be the layout of the MP joints, which is ignored in the existing toe mechanisms. Although the foot mechanisms developed by Hashimoto et al. [22, 23] have two toes comprising the toe joint, their joint axes fall within the same direction (see Fig. 13), differing from human MP joints. The human MP joints are positioned along the arc of the ball of the foot [2]. This layout is important because the COP moves along this arc [29]. Therefore, a more humanlike configuration of toe joint axes and walking motion synthesis utilizing it would be future work.

References


