Abstract—The paper describes a biomimetic design of humanoid curved foot able to absorb an impact thanks to the deflection of curved foot. The curved foot is designed in such a way to imitate the shape of human longitudinal arch. Also, comparative study with the conventional flat foot is suggested through simulation results.

I. INTRODUCTION

There have been several references related to stable walking of humanoid robots. Since the impact is one of major issues to implement stable walking, we are to focus on the humanoid foot design based on biomimetics. First, two dampers and rubber bush have been attached to ankle in order to absorb an impact [1]. Second, bonding the rubber plate to the foot was devised for absorbing the impact [2]. Third, walking stability could be improved by designing the foot pad as like the shoe sole [3].

In order to reduce the impact on robotic foot during walking, we are trying to imitate the human foot. As shown in Fig. 1, human foot has two major arches such as transverse arch and longitudinal arch. It is known that the transverse arch provides the stability in the horizontal direction and the longitudinal arch offers a function of shock absorbing. When the foot contacts to the ground, the human weight is transmitted to the ankle and finally it affects the longitudinal arch in such a way to decrease the arch height. In detail, when the arch is lowered, the load is transmitted to the front end and the back end of the foot with a ratio of about 1:2, respectively. This paper proposes a humanoid foot design using a curved beam that imitates a longitudinal arch on the human foot, ultimately, to reduce the impact on foot and ankle of humanoid.

II. CURVED FOOT DESIGN

Let us design humanoid foot imitating human longitudinal arch. In Fig. 2, $W_g$ is humanoid weight, $\delta$ is deflection of the curved foot, $W$ is load applied to toe, $x$ is length variable from foot center to toe, $R$ is radius of the curved foot, and $\theta$ is an angle between front end of foot and center line. The moment $M$ at the front end is expressed as following form:

$$M = WR\sin\theta.$$  

(1)

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Fig. 1. Human foot arches, where the transverse arch is formed on the inside and outside of the foot, and the longitudinal arch is formed from heel to toe [4]

Fig. 2. Beam deflection when impact is applied to toe, where variable $x$ is a function of radius $R$ and angle $\theta$

According to Euler Bernoulli’s beam theory, a deflection $\delta$ in the Fig. 2 can be obtained by solving the following equation:

$$\frac{d^2\delta}{dx^2} = \frac{M}{EI} = \frac{WR\sin\theta}{EI},$$  

(2)

where $EI$ is flexural rigidity. Using $x = R\sin\theta$, we have

$$\delta = \frac{R^4W}{8EI} \left(\sin\theta - \frac{1}{3}\sin 3\theta\right).$$  

(3)

The relationship between the load to toe and the deflection can be understood from Eq. (3). Also, a contact time during
the deflection is increased and it makes the impact to be reduced. In order words, an amount of the foot deflection is deeply related to the contact time. On the other hand, we have another concern because the foot may be broken according as the deflection of beam is large. Shock absorption capability is also related to the allowable stress of the material in an elastic limit.

III. SIMULATION RESULTS

Simulations are conducted to confirm the advantage of the proposed curved foot through the comparative study with a conventional flat foot. Assume that material of the foot is pure AL7075-T6 without any additional materials. The force/torque sensor (Robotous, RFT80-6A01) is mounted on the foot. The foot weighs 1.2[kg] including force/torque sensor. If we remove the force/torque sensor, it weighs about 1[kg]. When we assume that total weight of humanoid is 600[N], the load on toe W is 209[N], the radius R is 1041[mm], and the angle \( \theta \) is 8.28\(^{\circ} \). On the other hand, the load on heel is 391[N], the radius is 300[mm], and the angle is 15.47\(^{\circ} \).

Figs. 4 and 5 show free fall simulation environment of DAFUL dynamic simulator and its results, respectively. As we can see in the Fig. 5, the curved foot reduces the impact force and bouncing effect compared with the conventional flat foot. The maximum stress applied to the foot was 452.1[MPa]. Fortunately, it means that the proposed curved foot could endure the applied stress because it remains within the maximal allowable stress 505[MPa]. The reaction force of the flat foot arrived at about 135,000[N], while the proposed curved foot was about 95,000[N]. The reaction force of the proposed foot was much less than that of the flat foot.

IV. FUTURE WORKS

The paper suggests a humanoid curved foot designed in such a way to mimic the human longitudinal arch. The deflection was estimated by using Euler Bernoulli’s beam theory. Our future work will be checking the performance of shock absorbing function through experiments.

REFERENCES


