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Gait analysis for the development of the biped robot foot structure

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Abstract: The flexibility and deformations of the human plantar arch are among the most important issues when walking. Especially, the efficiency and mechanisms of the plantar arch should be demonstrated because there are few beings that have such a complex structure, in particular bipeds. On the other hand, nowadays biped robots have a too simple foot structure and they cannot walk like human in particular on the irregular grounds. If biped robots had flexible feet, its walk could be improved by increasing the area of contact with the ground in spite of the irregular ground.
In order to apply the human plantar arch to biped robots, we analyzed the human gait against the asperity. Our approach is mechanical. We measured the human gait when wearing a mechanical foot made to imitate the human plantar arch. We compared the dynamics calculation data with different conditions of the mechanical foot. The results made obvious that a flexible foot helps in decreasing the torque at the ankle, knee and hip, however it is necessary to change the elasticity during the gait cycle in order to mimic the characteristics of the human plantar arch. We could indicate the efficiency of the elastic change against the irregular grounds quantitatively throughout the experiment.

Keywords: Human-centered design, Biped robot, Gait analysis, Plantar arch, Foot structure

1. INTRODUCTION

During walking, the flexibility of the foot plantar arch is an important component, however it is usually dealt with as a rigid link in the field of the human gait analysis. Actually, the human foot can be divided into the three parts that have each degrees of freedom with respect to each other due to the bones structure (Neumann (2010)). In addition to mobility, their viscoelastic characteristics act as a shock absorbers and promoting springs. The size of the human foot is larger than any other four-legged walking animals' one considering the size of their whole body, and it is a human specificity to touch the ground by not only fingers but also the whole plantar and heel. Our previous study (Ogawa et al. (2013)), as shown that the high flexibility of the plantar allows to adapt to the irregular ground by changing its shape mechanically.

The ankle joint needs larger torque than the hip and knee joint during walking. Similarly, it is considered that the plantar arch is loaded with as large torque as the ankle (Takashima (2003)). It is difficult and idealistic to consider the foot as a rigid body, because it is composed of 28 bones connected by over 50 ligaments and tendons. The foot deformation is an important component when considering the gait mechanism so that many prosthetic foot imitates the plantar arch elasticity using carbon fiber plates (Takashima (2003)), in particular during the toe-off to insure propulsion. The human characteristic structure consists of the plantar aponeurosis that is one of the largest tendon covering the whole plantar arch. However, there are very few works dealing with the adaptability of the foot stepping on the irregular ground. The plantar arch moves intricately during walking with the viscoelasticity which the ligaments and tendons have. This structure can be assumed as a joint that has some degrees of freedom (DoFs) and some viscoelastic properties. Yet, it is difficult to define the irregular ground and estimate its effect on human gait, because human's ability to walk stably is so high and it derives from sensing and acting that can not be distinguished by the stability derived purely from mechanical flexibility.

Our purpose in this paper is to find out the plantar arch behavior during stepping on the irregular ground from the view of Robotics, and to test our Robotics feet on asperities. We analyzed the viscoelastic properties of the plantar arch quantitatively using identified body dynamics parameters, (Ayuasawa et al. (2009)), (Venture et al. (2009)) in our previous works. Here, we present the robot foot with a plantar arch that we have developed that can absorb asperities of the ground. The model of the foot that has an arch joint (2 DoF) and a toe joint (1 DoF) is shown in Fig. 5. The joints of this model are dealt with passive joints that have viscoelastic properties (springs and dampers). Motion capture and ground reaction force (GRF) data was used to calculate the body inertial parameters and viscoelastic parameters of the human foot. We then analyzed the gait data when wearing the robotic feet. The joint torque and power during walking calculated from these data were compared to the one with the constrain condition of the plantar arch and stepping on the asperity. These dynamic values are considered as the estimated value of balancing control of walking like the research of (MacLellan et al. (2006)).

2. EQUATION OF MOTION OF BIPEDAL SYSTEMS

2.1 Estimating joint torque

In order to evaluate the efficiency of the arch joint, we compare the changes in the joint torque and the power of the leg joints during walking. However, it is difficult to measure the joint torque directly for all the degrees of freedom of the human leg. Thus the calculation of the torque is chosen. The calculation of the joint torques requires the mass and the inertia of the human body for each segment and that are subject specific. To overcome this problem we identified them using motion capture and GRF data. The human body is modeled as a rigid body systems (Ayuasawa et al. (2009); Venture et al. (2009)). The equation of motion for a bipedal systems to obtain the minimal identification model can be expressed by Eq. (1).

$$\begin{bmatrix} \boldsymbol{Y}_{\mathrm{B}1} \\ \boldsymbol{Y}_{\mathrm{B}2} \end{bmatrix} \boldsymbol{\phi}_{\mathrm{B}} = \begin{bmatrix} 0 \\ \boldsymbol{\tau} \end{bmatrix} + \sum_{\mathrm{k}=1}^{\mathrm{N_c}} \begin{bmatrix} \boldsymbol{K}_{k1} \\ \boldsymbol{K}_{k2} \end{bmatrix} \boldsymbol{F}_k \tag{1}$$

where:

- $Y = \begin{bmatrix} \boldsymbol{Y}_{\mathrm{B}1} \\ \boldsymbol{Y}_{\mathrm{B}2} \end{bmatrix}$ is the regressor, which is the function of the system, joint angles of the whole body θ, and vector of generalized coordinates, $\boldsymbol{q}_0$ which represents the 6 DoF of the base-link, and their first and second derivatives,
- $\boldsymbol{\phi}_{\mathrm{B}}$ is the vector of inertial parameters,
- $\boldsymbol{\tau}$ is the vector of joint torques,
- $\mathrm{N_c}$ is the number of contact point with the environment,

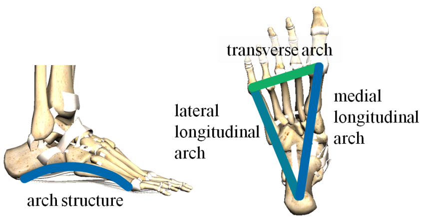

Fig. 1. Human Plantar arch

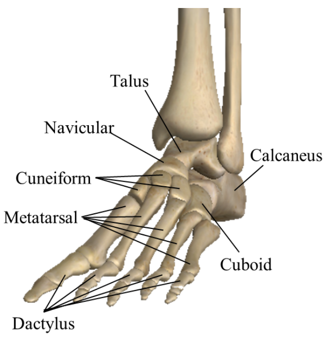

Fig. 2. Human Foot bone

- $\boldsymbol{F}_k$ is the k^{th} vector of external forces,
- $\boldsymbol{K}_{k1}$ and $\boldsymbol{K}_{k2}$are matrices multiply by $\boldsymbol{F}_k$ to the generalized force vector.

Using the least squares method from the external forces and positions of each segment it is possible to identify the base parameters $\boldsymbol{\phi}_{\mathrm{B}}$. The base parameters can be calculated using solely the upper part of Eq. (1) that does not need the joint torque, (Ayuasawa et al. (2009); Venture et al. (2009)). The external forces acting on the human body are measured using the ground reaction forces and the base parameters can be identified regardless of the number of contact points between the foot and the force plate. The lower part of Eq. (1) is transformed in Eq. (2) and we can obtain the joint torque $\boldsymbol{\tau}$.

$$\boldsymbol{\tau} = \boldsymbol{Y}_{\mathrm{B}2}\boldsymbol{\phi}_{\mathrm{B}} - \sum_{\mathrm{k}=1}^{\mathrm{N_c}} \mathrm{K}_{\mathrm{k}2}\boldsymbol{F}_{\mathrm{k}} \tag{2}$$

3. EXPERIMENT

3.1 Motion capture

The movements of each segment of the whole body were measured using a six cameras optical motion capture device. The cameras are Hawks (Motion Analysis) and the GRF were measured using 6 force plates FP4060 (Kistler). The sample rate of these sensors are 200 Hz and 1000 Hz, which are re-synchronized at 200 Hz for post-processing. The subjects walked over the force plate, and performed one single step. Two types of the marker sets were used. One marker set is for the bare foot experiment and consists of 49 markers. 27 markers are placed on prominent positions of the human whole body and other 22 markers are placed the feet. Another marker set is for walking with the mechanical feet. The details of the mechanical feet is explained in the following section. This marker set consists of 27 markers for the body and 24 markers for the mechanical foot.

3.2 Mechanical foot

Our mechanical foot is an orthotic foot that mimic the human plantar arch, developed to confirm the function of the plantar arch during walking on the irregular ground. Each orthotic foot has 3 degrees of freedom. The arch joint has 2 DoFs, corresponding to the dorsal/plantar flexion and the eversion/inversion. We call these degrees of freedom pitch and roll over the direction of the body standing normally. The remaining DoF is the toe joint that can be rotated in the pitch direction. Details of this orthotic foot are shown in the table 1. Each joint has a viscoelastic characteristic that was identified in previous work, (Ogawa et al. (2013)). The cylinders with the compressional coil springs are arranged over the joints in order to reproduce elasticity of the human arch joint. These springs can be exchanged easily and adjusted with subject specific parameters or with the participant's preference. In this experiment, we use 3 types of the arch joint springs as shown in table 2.

In addition, the arch joint has a viscosity produced by the 2 rotary dampers. The 2 big gears placed at the both side of the mechanical foot translate the joint rotation to the

Fig. 3. Marker set

Fig. 4. Mechanical foot

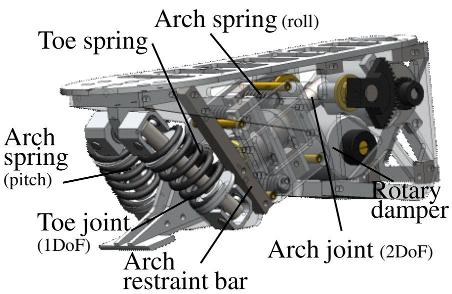

Fig. 5. Mechanical foot model

Table 1. Specification of the mechanical foot (one side)

Length [mm]	Width [mm]	Height [mm]	Weight [kg]	Maximum Load [kg]
290	108	135	3.030	70

dampers. If needed the arch joint can be constrained by using the steel bars.

The frame of this orthotic foot is made by aluminum alloy. The shoes and ankle supporter for sports is fixed on the top plate, and this plate restrains the movement of the human plantar arch. The structure of the mechanical foot works instead of the human plantar during the walking experiment.

3.3 Gait conditions

The subjects conducted a total of 10 types of experiments to verify the effect of the plantar arch against the irregular ground, each with different walking conditions repeated 10 times. These conditions can be divided generally into 2 types: the plantar arch condition and the ground surface condition. The 5 types of plantar conditions are experimented varying the arch joint elasticity of the mechanical foot. Those are 1. bare foot (bare), 2. wearing the mechanical foot using the weak springs (weak), 3. using the middle strong springs (mid), 4. using the strong springs (strg), and 5. with the mechanical foot restrained the arch joint (stat). The strong spring approximately equals the identified elasticity of human plantar arch.

Table 2. Specification of the springs

Type	Strength	Spring constant [N/mm]	Num
Arch pitch	Weak	15.16	2
Arch pitch	Middle	19.60	2
Arch pitch	Strong	41.39	2
Arch roll	-	205.1	4
Toe roll	-	588.9	1

The surface conditions describe the irregular ground. We used a 18mm thick wooden plate as an asperity. Gait experiments are conducted with/without the asperity in each plantar conditions.

4. RESULTS

4.1 Normalized joint torque and power curves

Fig. 6 shows the joint torque computed by the inverse dynamics approach for each leg joint at the rotation about the sagittal plane and Fig. 7 shows the joint power. The torque are normalized by the gait speed because the joint torque of legs depend on the gait speed: faster gait generates larger joint torques. The joint torque is normalized by dividing by the joint peak moments computed by relational expression derived from the works of Lelas et al. (2003). The curves presented the mean of the 10 trials of each condition. The colors of lines shows the plantar conditions (blue: bare foot, green: wearing the mechanical foot using weak springs, red: using middle strong springs, purple: using strong springs, cyan: static arch joint), and the type of line means the surface conditions (solid line: no asperity, broken line: with asperity).

The joint power is also calculated by the normalized joint torque being multiplied by the mean of joint angle velocity of 10 trials. The number of subject is 1. The horizontal axis is the time normalized by the stance phase of one stride: 0% is the time of the heel contact, and 100% is the time of the toe off.

Hip joint In Fig. 6, the normalized joint torque at the hip of the condition of bare foot is different from the all other conditions, the condition of bare foot is smaller than the condition of wearing the mechanical foot during the stance phase. Similarly, in Fig. 7, the normalized joint power of the condition of bare foot is smaller than any other conditions. This difference is occurred by increasing the weight and length of the foot regardless of the condition with/without the asperity.

Knee joint It is the most remarkable that normalized joint torque of condition using the middle springs indicates the biggest peak from heel contact (5%) to mid stance (40%) in Fig. 6. Comparing with the normalized joint power in Fig. 7, walking with the condition of using the middle strong springs is the most inefficient in the all conditions for the knee joint as a shock absorber because walking with this condition needs the largest joint torque and power. Walking with the condition of static arch joint and using strong springs with asperity follow the one of using middle springs. Otherwise, the most efficient condition is suitably walking with the condition of bare foot because the least joint torque generates the forth biggest power at this phase. Walking with other conditions generate less joint power than walking with the condition of bare foot in spite of the necessary for the larger joint torque. Comparing between the condition of no asperity and with asperity in this phase, the condition that absorbs the asperity like the condition of the bare foot is using the weak and middle strong springs. The larger joint torque generates the larger power walking with condition of the strong springs and static arch joint with asperity than the condition of no asperity. Therefore, there are slim and none difference between the surface conditions with the condition of using the weak springs and middle strong springs. It is better to use soft stiffness spring in order to absorb the asperity in the knee joint.

Ankle joint Looking at both normalized joint torque (Fig. 6) and normalized power (Fig. 7), in the phase of the mid stance (20-55%), the ankle joint can not absorb the mid stance shock with the static plantar, the condition of using the strong spring and static arch joint. The joint torque and power with the condition of using the weak springs and middle strong springs approximate the condition of bare foot. The most effective joint in the leg is the ankle joint during toe off. In the phase of toe off (55-100%), minimum torque generates the power as strong as the strongest condition, using the strong spring and static arch joint. On the other hand, the power of the condition of these static plantar conditions needs high torque. In the condition of the soft plantar, the high torque is necessary as strong as the condition of the static plantar but it generates the lower power than the one of with the static plantar. It is the more effective to use the more static plantar during the toe off phase.

Looking about the asperity in this toe off phase, in the condition of using weak and middle strong springs, the power of with the condition of the asperity is larger than

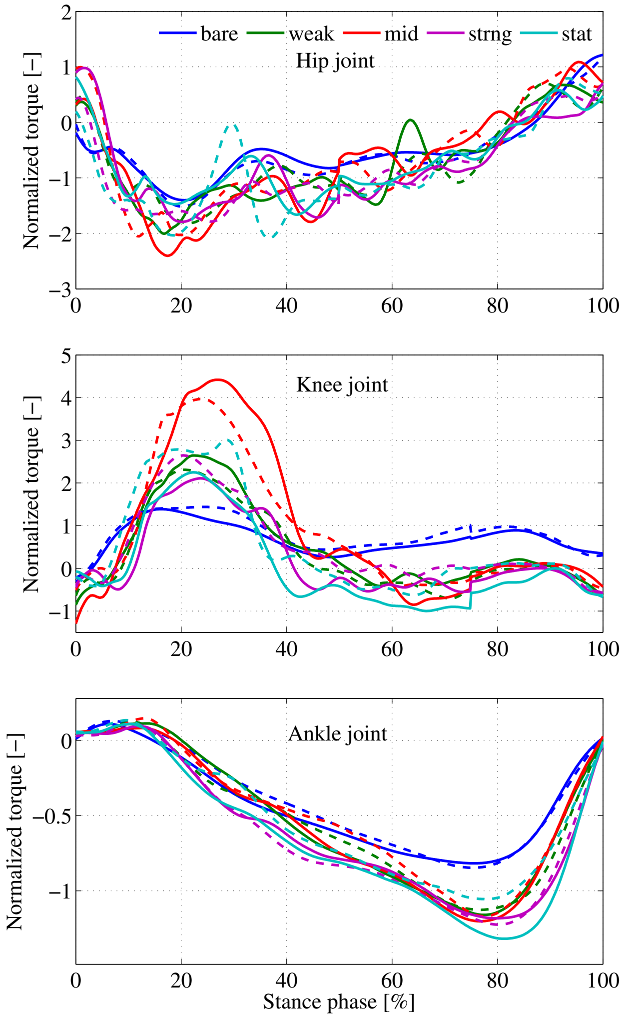

Fig. 6. Right leg joint torque in the pitch: sagittal plane (solid line: no asperity, broken line: with asperity)

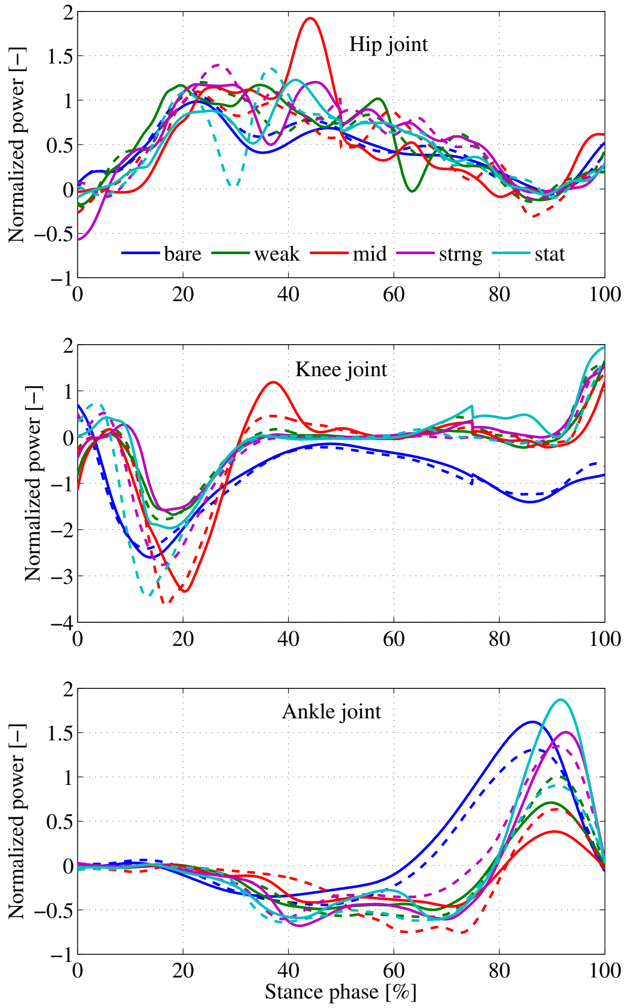

Fig. 7. Right leg joint power in the pitch: sagittal plane (solid line: no asperity, broken line: with asperity)

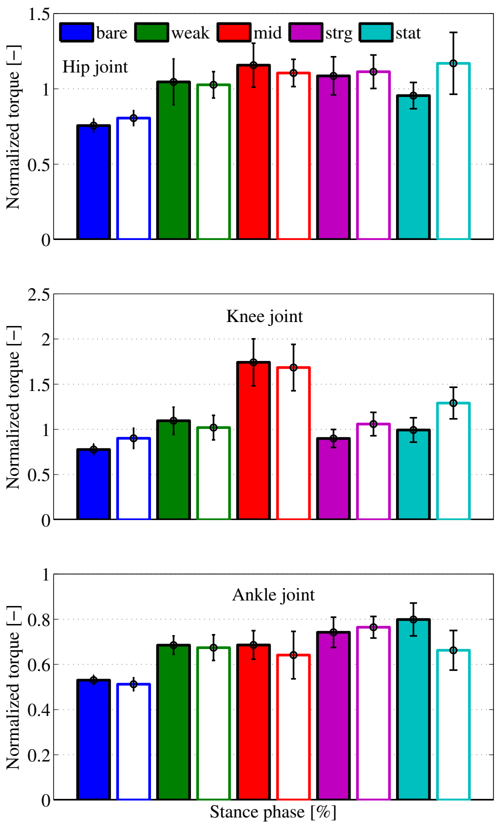

Fig. 8. RMS of right leg joint torque in the pitch: sagittal plane (with face color: no asperity, white face: with asperity), error bar: standard deviation of each trial

the one of no asperity. Otherwise, in the condition of the bare foot, using the strong springs and in particular, static arch joint, the power of with the condition of the asperity is smaller than the one of no asperity. This indicates that the stiffness more than the condition of the strong springs is effective against the asperity.

4.2 RMS of the normalized joint torque and power

Fig. 8, 9 shows the RMS of the normalized joint toque and the normalized joint power. The each colors indicate the condition of the plantar (blue: bare foot, green: wearing the mechanical foot using weak springs, red: using middle strong springs, purple: using strong springs, cyan: static arch joint). The bar with the face color means the condition of walking on the no asperity, and the bar with no face color means the condition with asperity.

Hip joint In Fig. 8, joint torque with every condition of with asperity is larger than with the condition of no asperity, especially the condition of the static arch joint. It is found that the asperity increases the joint torque and the amount of the increase of the condition of static arch joint that does not have the plantar arch structure is the greatest. Excepted for the condition of the static arch joint, the plantar arch structure both bare foot and the mechanical foot works well against the asperity. In Fig. 9, looking at the surface condition, the normalized power of the condition of the with the asperity is equal or larger than the condition of no asperity expect for the condition of using strong spring. It is considered that walking on the asperity needs more power in order to step up on the asperity or to absorb the shock of ground contact.

Knee joint In Fig. 8, similarly as the hip joint torque, the knee joint torque with the condition of with asperity is larger than the condition of no asperity excepted for the condition of using the weak springs and middle strong springs. Especially, with the condition of using the middle springs, the difference of the normalized torque between no asperity and with asperity is larger than any other condition and this difference can be seen the best work of the plantar arch against the asperity. However, the absolute value of the normalized joint torque is the largest. The condition of using the middle spring has the most effective against the asperity, but it is not suitable for walking comparing the normalized joint torque with the other conditions. In Fig. 9, the power absorption of the condition of bare foot is different from the rest condition. Following this characteristics, the condition of using the middle spring and condition of static arch joint is the second and third largest power absorption. In addition, looking the each plantar condition about the surface condition, normalized joint power with the asperity is larger than the condition of no asperity, expect for the condition of using the middle spring. The more power can be absorbed stepping on the asperity. There seems to be no relation between the plantar conditions. The condition needs largest normalized joint torque at the knee joint is using the middle spring (from Fig. 8), but this condition

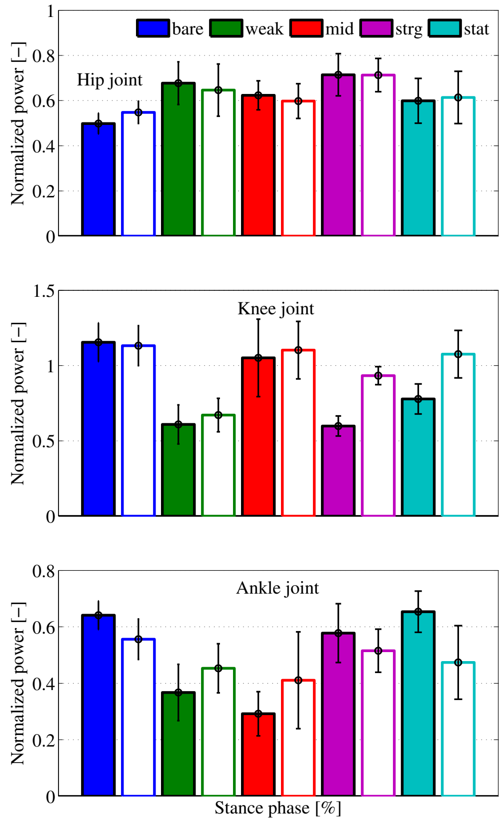

Fig. 9. RMS of right leg joint power in the pitch: sagittal plane (with face color: no asperity, white face: with asperity), error bar: standard deviation of each trial

is also the largest power absorption. Thus it is considered that the large load needs large power absorbing because the condition of using the middle spring is not suitable for the walking.

Ankle joint The total normalized torque with the conditions of with the asperity cannot store the energy except for the the condition of using weak and middle strong springs. From the view of the value of the power during the toe off phase comparing the surface conditions, it is better to use the strong stiffness plantar condition, but from the view of the power restoring, the condition of using the middle strong springs is better than the condition of using strong springs. This power restoring and releasing is found in Fig. 9. Looking at each plantar condition, the biggest joint power generates from the condition of static arch joint, following the condition of bare foot and the condition of using the strong springs. Accepting the hypothesis that the stiffness of plantar arch become as strong as rigid body as stance phase progress, it is indicated that toe off with condition of stronger stiffness generates larger power release. On the other hand, the power generated by the plantar with weak stiffness, weak and middle strong springs conditions is smaller than the other conditions, nevertheless the plantar with weak stiffness need as big torque as the plantar with strong stiffness, seen in Fig 8. However, with this weak stiffness condition, the power releasing with the condition of with the asperity is larger than the condition of no asperity. It is advantageous for the toe off power release to step on the asperity with the weak stiffness plantar. This results is nothing else but the evidence that indicates the the plantar arch ability absorbing the asperity.

5. DISCUSSION

The final purpose of this study is to improve the biped robot gait on the irregular ground. Therefore we made the human like mechanical foot to confirm the human plantar effect against the irregular ground before testing the robot. We need to experiment with human subject because the characteristic of the human foot is not well-known system. The experiment and dynamic analysis make sure the effect.

In this experiment, we used the mechanical foot with 3 types of the various elasticities and the static condition and we gained some knowledge about the elasticity of human plantar arch. First, the elasticity of human plantar arch can be changed during walking and the phase can be divided generally into 2 phases. Changing the elasticity of the human plantar arch have been obvious in the works of Takashima (2003). We can confirm the changes of the plantar arch quantitatively using the mechanical approach.

Considering to minimize the each leg joint torque generated or loaded like human, in the first half phase, it is better to use the softer stiffness (like the condition of using weak springs). This elasticity has the enough softness to move the joint of the plantar arch and this movement absorbs the shock of the heel contact in the joint of knee and ankle.

In the last half of the phase, the stronger stiffness (like the condition of the using strong springs and static condition) is needed for the toe off movement. We found that the stronger stiffness generates the greater propulsion. It is possible to design the suitable joint load robot, e.g., the knee kind robot adjusting the plantar elasticity.

The change from the weak stiffness to the strong stiffness during walking is necessary to completely mimic the characteristic the human plantar arch. This change is desired to go passively considering not only the walking but also the recovery from falling. This is the our next subject to apply the this structure to the biped robot.

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