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Research Paper

The positions effect of biarticular muscles on the walking fatigue of bipedal robots

L'effet de la position des muscles biarticulaires sur la fatigue de la marche des robots bipèdes

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ABSTRACT

The objective of this paper is to model a bipedal robot with springs like biarticular muscles and to study the positions effect of biarticular muscles on the walking fatigue of bipedal robots through the analysis of the works of the ground reaction force (GRF) accumulated at joints and the analysis of the works done by biarticular muscles. We can define the walking fatigue in this paper by the fatigue of joints and muscles caused by the increment of the works accumulated at joints and the increment of the works done by biarticular muscles during the walk period of bipedal robots. It's found from this study that the position of the muscle biceps femoris (BF) has a strong impact on the fatigue of leg joints and the fatigue of the muscle itself during the walk period of bipedal robots.

RESUME

L'objectif de ce travail est de modéliser un robot bipède avec des ressorts comme des muscles biarticulaires et d'étudier l'effet des positions de ces muscles sur la fatigue pendant la marche des robots bipèdes par l'analyse des travaux de la force de réaction au sol (FRS) accumulés aux articulations et l'analyse des travaux réalisés par les muscles biarticulaires. Nous pouvons définir la fatigue de marche dans ce papier par la fatigue des articulations et des muscles causée par l'incrément des travaux accumulés aux articulations et l'augmentation des travaux effectués par les muscles biarticulaires pendant la période de marche des robots bipèdes. Il ressort de cette étude que la position du muscle biceps femoral (BF) a un fort impact sur la fatigue des articulations des jambes et la fatigue du muscle lui-même pendant la période de marche des robots bipèdes.

1 Introduction

In the fields of biomechanics and robotics, bipedal walking has been investigated for our further understanding of adaptive locomotion mechanisms of human and robots [1].Obtaining human-like robotic walking has been a long standing, if not always explicitly stated goal of robotic locomotion. Achieving this goal promises to result in robots able to navigate the myriad of terrains that humans can handle with ease; this would have, for example, important applications to space exploration [2,3] Moreover, going beyond purely robotic systems, if one can understand how to make robots walk like humans, this understanding can be used to build robotic assistive and prosthetic devices to aid people with walking impairments and lower extremity amputations walk more efficiently and naturally[3, 4-6] thus, the ability to obtain human-like robotic walking has important and far-reaching ramifications [3].. From the biomimetic point of view, it is valuable to look at the walking behaviors of humans in order to achieve a comfortable robotic walking [7, 8]. It's shown from the previous study [9] that biarticular muscles that correspond to rectus femoris (RF), biceps femoris (BF) and

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gastrocnemius (GAS) in human legs play significant roles in the stability and comfortable walking of human. Thus, using springs like biarticular muscles in the leg mechanism of bipedal robots are able to achieve the stability and comfortable walking of human-like leg walking compared with those that assume the bipedal robots like rigid body structures. The walking for a long time of bipedal robots with compliant legs causes the fatigue of leg joints and the fatigue of biarticular muscles. This fatigue is basically dependent on the increment of the works accumulated at joints and the increment of the works done by biarticular muscles. Practically, the increment of these works due to the repetitive shock of each compliant leg with the ground during the walk period of bipedal robots may inflict a serious damage of the leg mechanism. On the other hand, such an influence of shock might be mitigated if we choose carefully a good position of each muscle of biarticular muscles. In this sense, we need to check the works accumulated at joints of the ground reaction force (GRF) which is generated by the shock of each compliant leg with the ground and transferred from the foot space, and the works done by biarticular muscles according to the position's variation of each muscle of biarticular muscles during the walk period of bipedal robots. In addition, the works analysis at joints and the analysis of the works done by biarticular muscles are necessary to deal with the issue of comfortable walking for bipedal robotic applications. However, it actually requires significant effort to evaluate the comfortability of walking which is closely related to obtaining good performance of legged robots [8, 10-12].

The objective of this study is to analyze the walking fatigue of bipedal robots with springs like biarticular muscles through the works analysis at joints and the analysis of the works done by biarticular muscles. For this purpose our paper is organized as follows: in section 2, we model a bipedal robot with springs like biarticular muscles and establish the equations of the GRF, joint torques, joint works and the equations of the works done by muscles. The section 3 is devoted to the discussion of obtained simulation results to show the positions effect of biarticular muscles on the walking fatigue of bipedal robots, and the conclusion is drawn in the section 4.

2 Modeling of a Bipedal Robot with Compliant legs

In order to have an effective analysis on the positions effect of biarticular muscles on the walking fatigue of bipedal robots, we consider a model of bipedal robot with springs like biarticular muscles as shown in Fig.1. The bipedal model shown in Fig.1 consists of four leg segments (H_1H_2, HK, AK_1 and BC), three joints (hip, knee and ankle joints) and four linear tension springs which are represented by the red dashed lines. The springs S1, S2, S4 correspond to biarticular muscles: rectus femoris (RF), biceps femoris (BF) and gastrocnemius (GAS) in human legs respectively. Additionally, the spring S3 that correspond to a monoarticular muscle: tibialis anterior (TA) in human legs is also used in this model. The reaction force generated in these tension springs $f = [f_1, f_2, f_3, f_4]$ is calculated in the case when the foot is in contact with the ground as shown in [9]. The parameters $k = [k_1, k_2, k_3, k_4]$ and $\vartheta = [\vartheta_1, \vartheta_2, \vartheta_3, \vartheta_4]$ shown in Fig.*1* characterize the spring constant and the angle between the reaction force f and (z) direction respectively. The point $P = [H_1, H_2, E, K_1, F, G, C, B]$ represent the spring attachment. The segment mass are defined at the center of each segment. The two segments H_1H_2 and BC are considered in our model to remain parallel with the contact surface of the foot mechanism with the ground during walking. In this case, the GRF coming from the ankle (A) is generated only in foot-flat and mid-stance phases, and for the sake of simplicity we consider that the GRF has only one component in (z) direction. At this moment, the GRF is nothing more than the algebraic summation of all body forces. Thus, the GRF at the ankle (A) can be classified by two types in our case: one reaction force is made by the bipedal weight (BW) and the other is determined by the reactions of muscles as shown in the following equation:

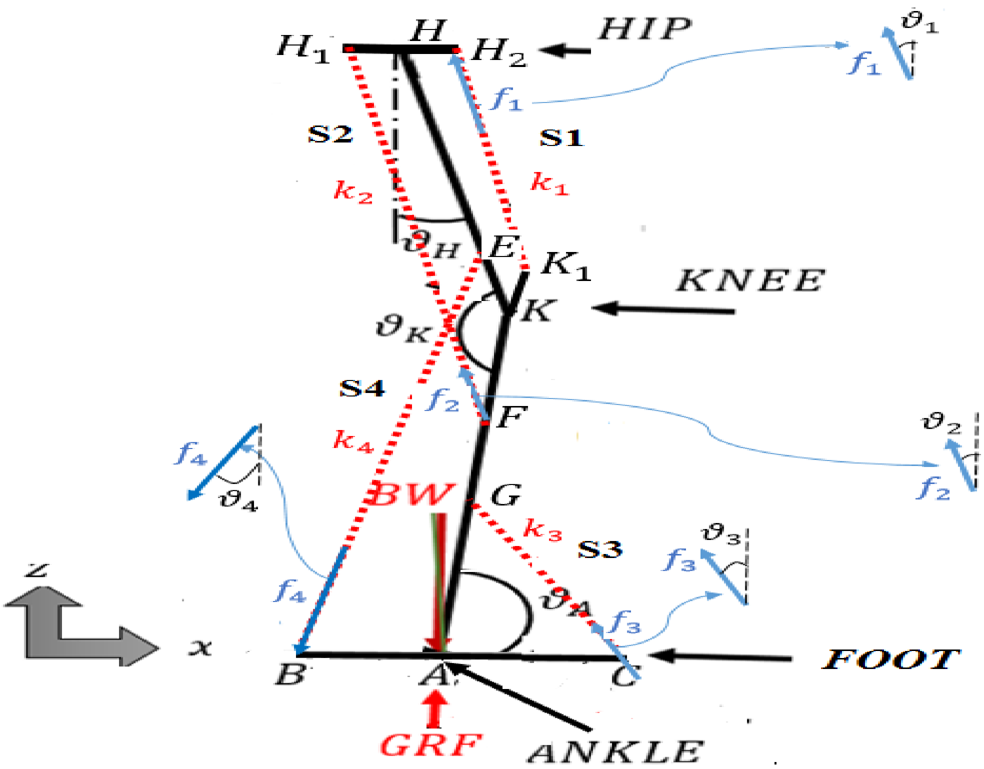

Fig.1-Bipedal locomotion model with compliant legs (only one of the two legs is shown in this figure)

$$\overrightarrow{GRF} = \overrightarrow{BW} + \vec{f_1} + \vec{f_2} + \vec{f_3} + \vec{f_4} \tag{1}$$

By projecting the Eqt1 in (z) direction, we obtain:

$$GRF = |BW| + k_1\Delta(k_1H_2)\cos(\vartheta_1) + k_2\Delta(H_1F)\cos(\vartheta_2) + k_3\Delta(CG)\cos(\vartheta_3) + |k_4\Delta(BE)|\cos(\vartheta_4) \tag{2}$$

The parameter Δ=[$\Delta(k_1H_2)$,$\Delta(H_1F)$, $\Delta(CG)$, $\Delta(BE)$] shown in Eqt2denotes the small linear displacement of muscles during the contact of the foot mechanism with the ground .

The GRF shown in Eqt 2 is helpful for us to manage the fatigue of leg joints. Thus, the corresponding torques at the hip and knee joints according to the GRF, (τ_H) and (τ_K) can be determined as follows:

$$\overrightarrow{\tau_H} = \frac{\overrightarrow{[HKcos(\vartheta_H)\cos(\pi - (\vartheta_H + \vartheta_K))}}{sin(\pi - (\vartheta_H + \vartheta_K))]\wedge \overrightarrow{GRF} + \overrightarrow{\tau_K}} \tag{3}$$

$$\overrightarrow{\tau_K} = \overrightarrow{[AKcos(\vartheta_A)]} \wedge \overrightarrow{GRF} \tag{4}$$

The corresponding works at the hip and knee joints according to their joint torques, $w_H(t)$and $w_K(t)$ can be expressed as the integral of the scalar product of the joint torques and relative angular velocities at joints [13]as shown in the following equations:

$$w_H(t) = \int_0^t \tau_H(t)\,\dot{\vartheta}_H(t)dt \tag{5}$$

$$w_K(t) = \int_0^t \tau_K(t)\,\dot{\vartheta}_K(t)dt \tag{6}$$

Finally, the works done by the muscles; rectus femoris (RF),biceps femoris (BF),tibialis anterior (TA) and the muscle gastrocnemius (GAS), w_{RF}, w_{BF}, $w_{TA}$and w_{GAS}can be defined as follows:

$$w_{RF} = \int_0^t k_1\Delta(k_1H_2)\,dt\ ,\ w_{BF} = \int_0^t k_2\Delta(H_1F)\,dt,\ w_{TA} = \int_0^t k_3\Delta(CG)\,dt,\ w_{GAS}\int_0^t k_4\Delta(BE)\,dt \tag{7}$$

Note that the work expressions shown in Eqts5, 6 and Eqt7 are useful for analysing the walking fatigue of bipedal robots.

3 Simulation and discussion

This section illustrates the simulation results of the GRF, joint torques , joint works and the simulation of the works done by muscles. For an effective simulation , the following conditions have been considered. The springs used in this simulation support the entire body weight, only the vertical motion of the hip is considered because we perform the simulation in a planar space for the sake of simplicity andthere is no slip between the surface contact of the foot mechanism with the ground.Since the motion style of two legs is the same as shown in Fig.5 and the two legs are identical, so we demonstrate only the simulation results of the right leg in this section.

In this paper , we focus on the variation of the position of the muscle biceps femoris (BF), while we consider that the positions of the muscles rectus femoris (RF),tibialis anterior (TA) and the muscle gastrocnemius (GAS) remain invariable, and we propose three cases: case (1) $KF = 92.43\ mm$, case (2) $KF = 150.62\ mm$ and for the case (3) $KF = 210.67\ mm$.

The Fig.5 shows the simulation of the walking bipedal robot by using SolidWorks 2015 according to the motions of the hip knee and ankle joints shown in Figs. 2, 3 and Fig.4 respectively and to the kinematic parameters of the leg mechanism shown in Tab.1. We can notice from this figure that the BW can be applied periodically on the right ankle (A) in ($-z$) direction during the walk period of bipedal robots as shown in Fig.6. In practice, the vertical force pattern applied on the ankle (A) depends on the mass of the robot body and the acceleration of the leg motion during walking [8]. But for an effective analysis on the walking fatigue of bipedal robots, we prescribed such a maximum force pattern during the walk period which equals to the scalar product of the bipedal mass and the gravitational acceleration.

The Figs from 7~9 show the GRF and the joint torque patterns when the stiffness coefficients of muscles have been assigned as: $k_1 = k_2 = k_3 = k_4 = 8000N/m$. We can say from these figures that the position's variation of the muscle biceps femoris (BF) plays an important role on the increase and decrease of the GRF and the torques at joints. To be specific, if the muscle biceps femoris (BF) using in the walking of bipedal robots is short, the GRF and the torque at joints are increase with the time. When the muscle biceps femoris (BF) using in the walking of bipedal robots is long,however, the GRF and the torques at joints can be reduced relatively.

The resultant works accumulated at the hip and knee joints and the works done by monoarticular and biarticular muscles of the right leg have been illustrated from Fig.16~19.We can notice from these figures that during the walk period of bipedal robots, the works at joints and the works done by muscles increase gradually. Actually, the increment of those works cause the fatigue of leg joints and the fatigue of muscles as well as the entire robot system and our robots become tired gradually. This means that , the diminution of the works accumulated at joints and the works done by biarticular muscles conducts to mitigate the fatigue and ensure the comfortable walking for bipedal robots.

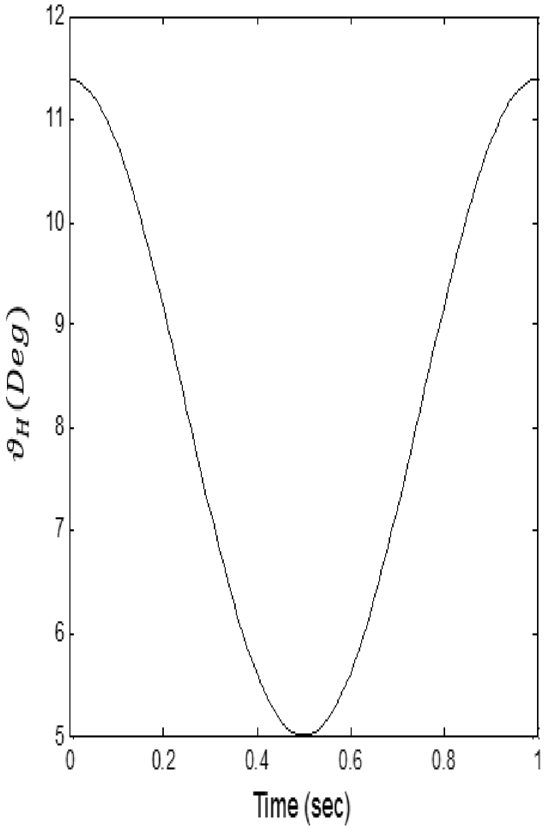

Fig. 2 -Motion pattern of the hip joint

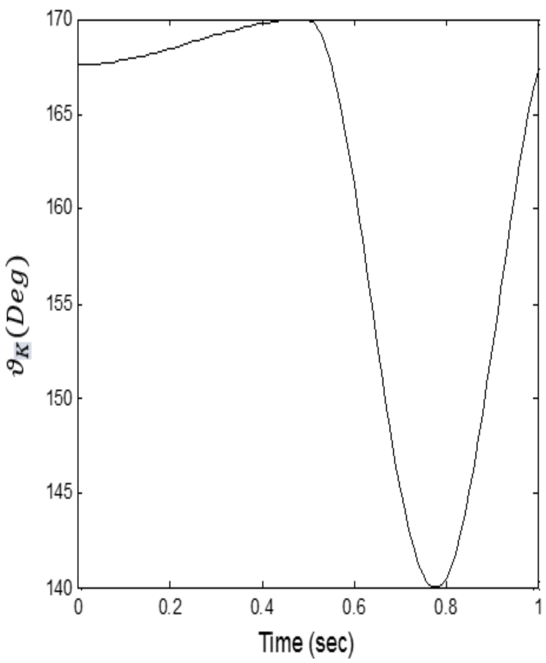

Fig. 3 - Motion pattern of the knee joint

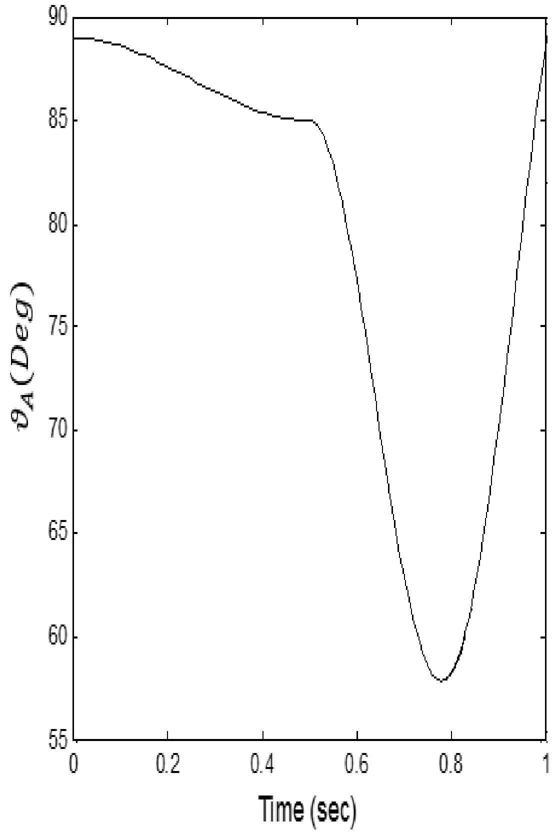

Fig. 4 -Motion pattern of the ankle joint

Table 1 - Kinematic parameters and mass distribution of the leg mechanism of bipedal robot

HK	$418mm$ / $5.2Kg$
KA	$445mm$
AB	$28.56mm$
AC	$83.38mm$
HH_1	$100mm$
HH_2	$30mm$
KK_1	$100mm$
HE	$339.30mm$
KG	$259.72mm$
$HH_1/AK_1/BC$	1Kg/2.79Kg/1.01Kg

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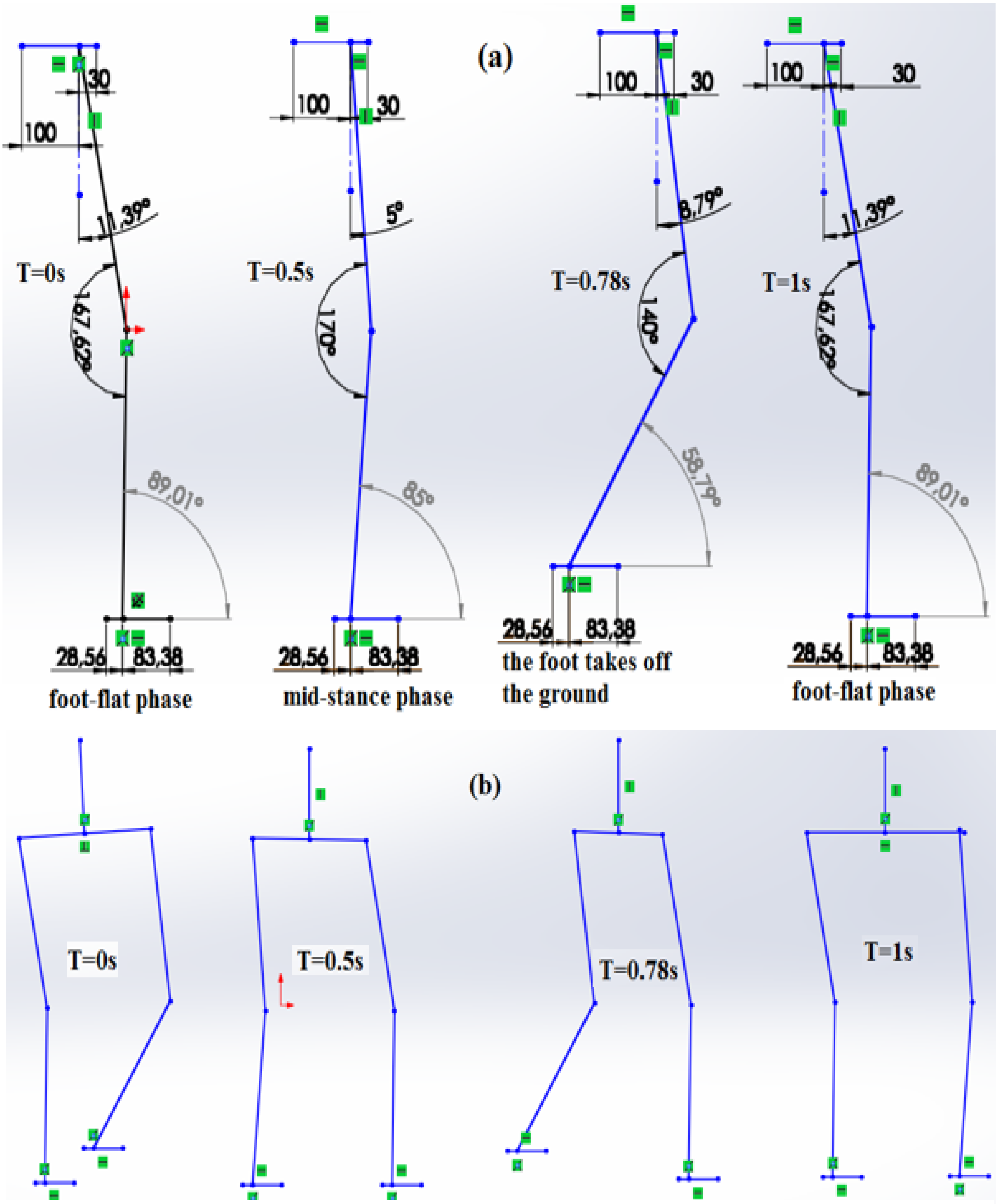

Fig. 5-Simulation of one gait cycle of bipedal robot by using SolidWorks2015 (a) theright leg, (b) the two legs

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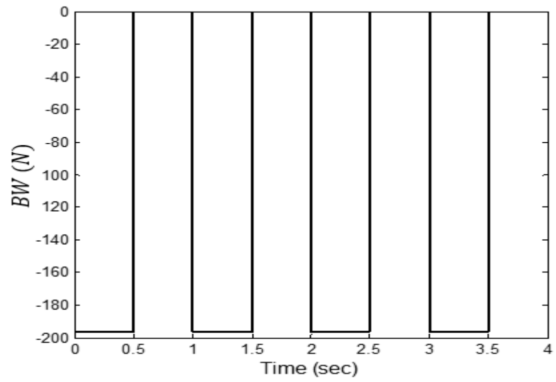

Fig. 6-The (BW) applied at the right ankle in $(-z)$ direction during walking

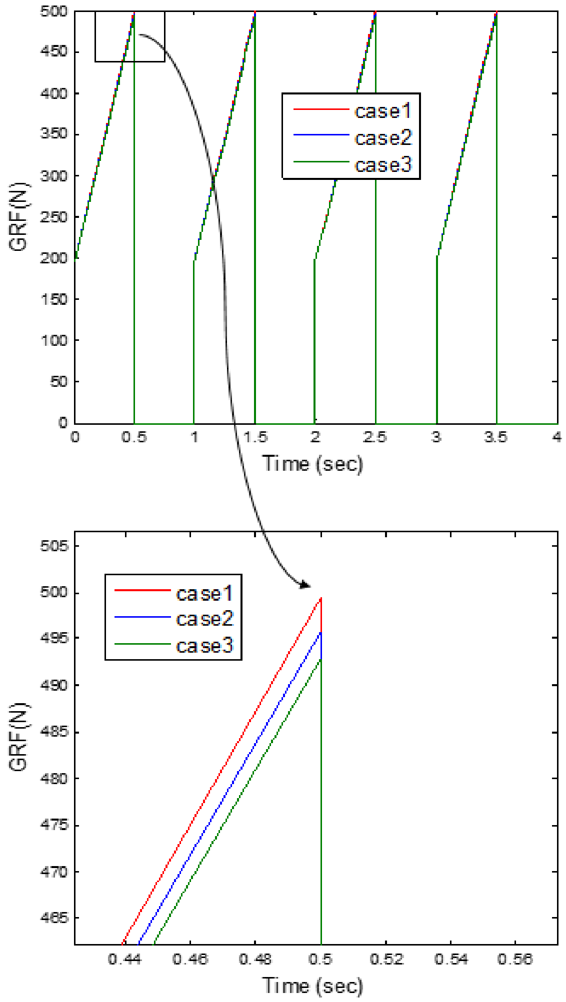

Fig. 7-The (GRF) patterns at the right ankle

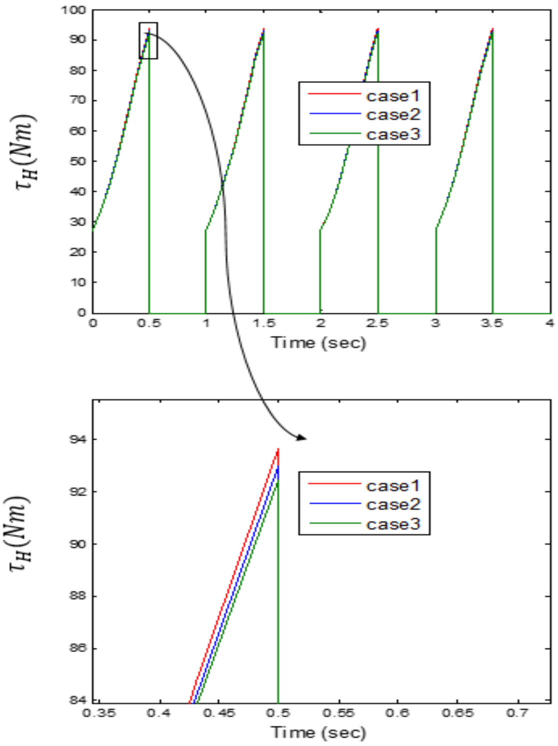

Fig. 8-The torque patterns at the hip joint

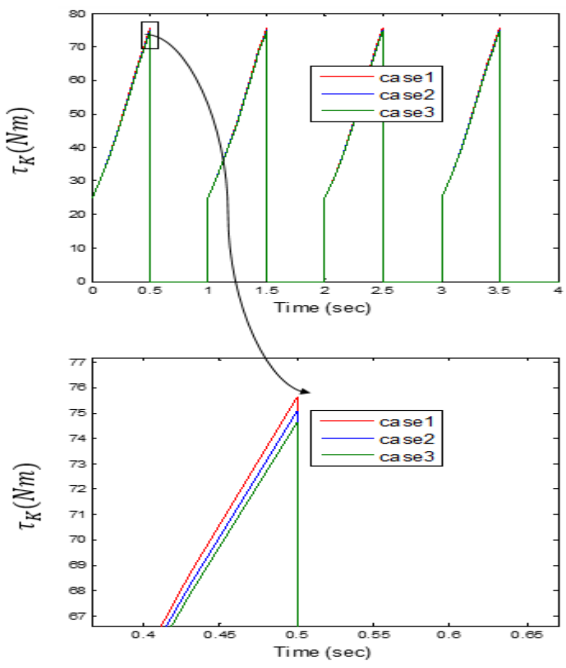

Fig. 9-The torque patterns at the knee joint

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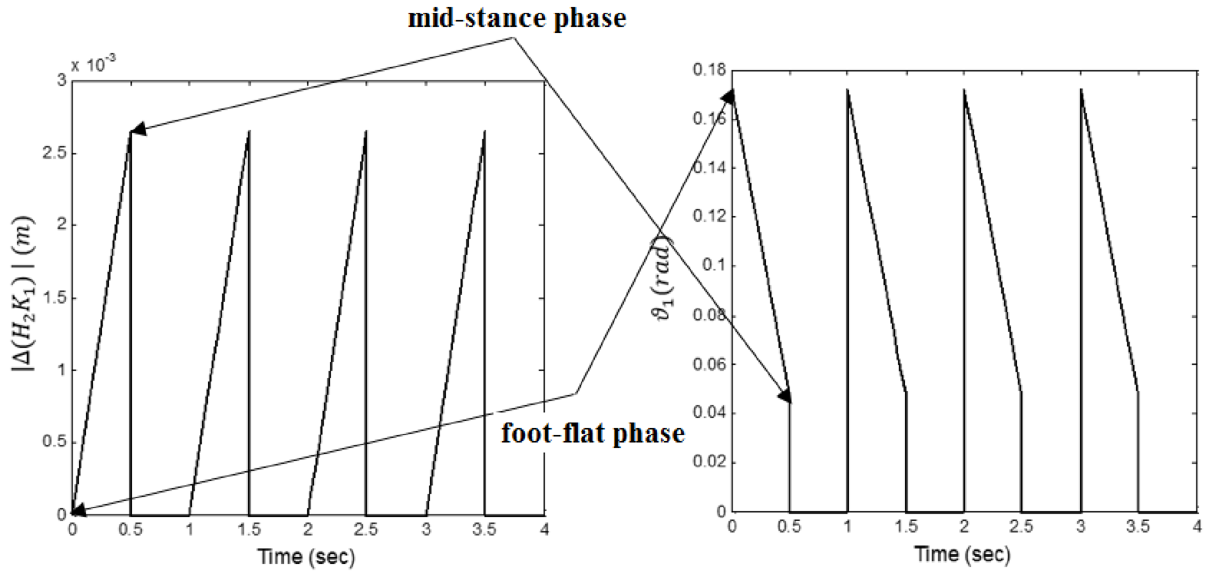

Fig. 10-The reaction force parameters generated in the muscle rectrusfemoris (RF)

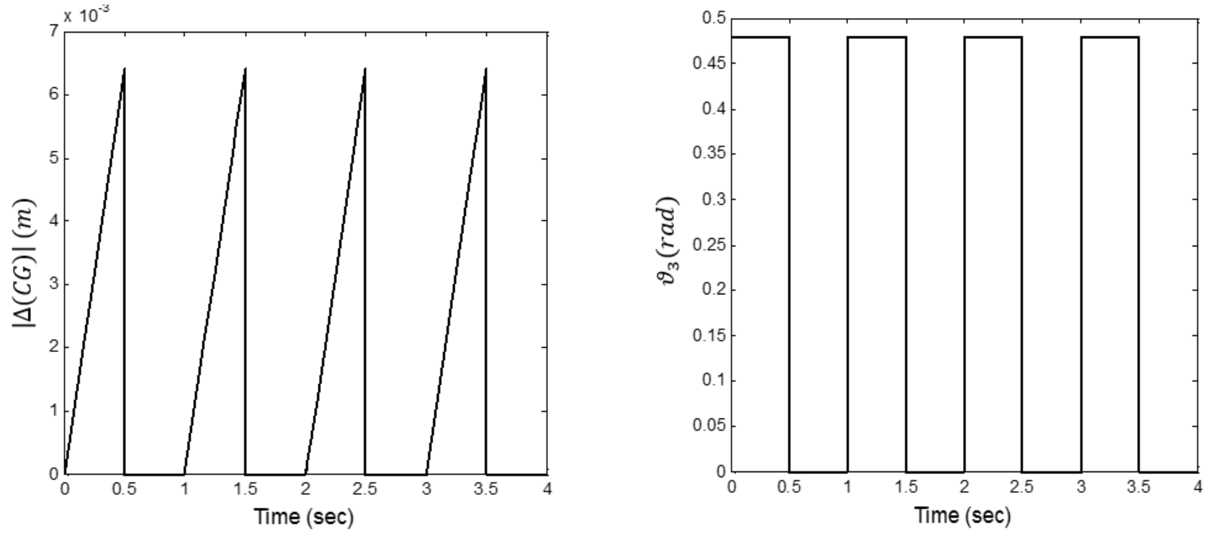

Fig. 11-The reaction force parameters generated in the muscle tibialis anterior (TA)

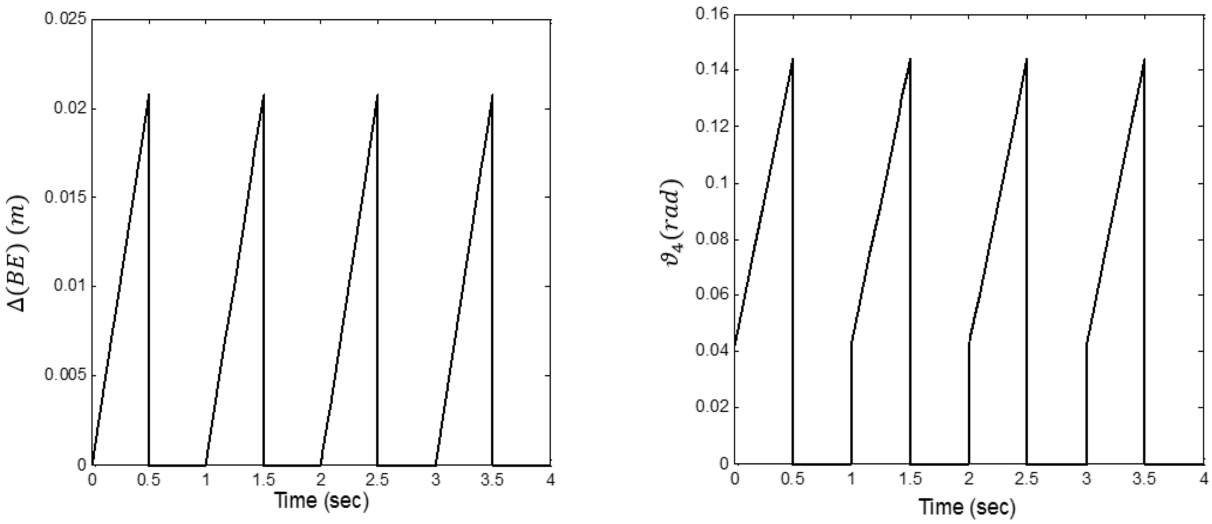

Fig. 12-The reaction force parameters generated in the muscle gastrocnemius (GAS)

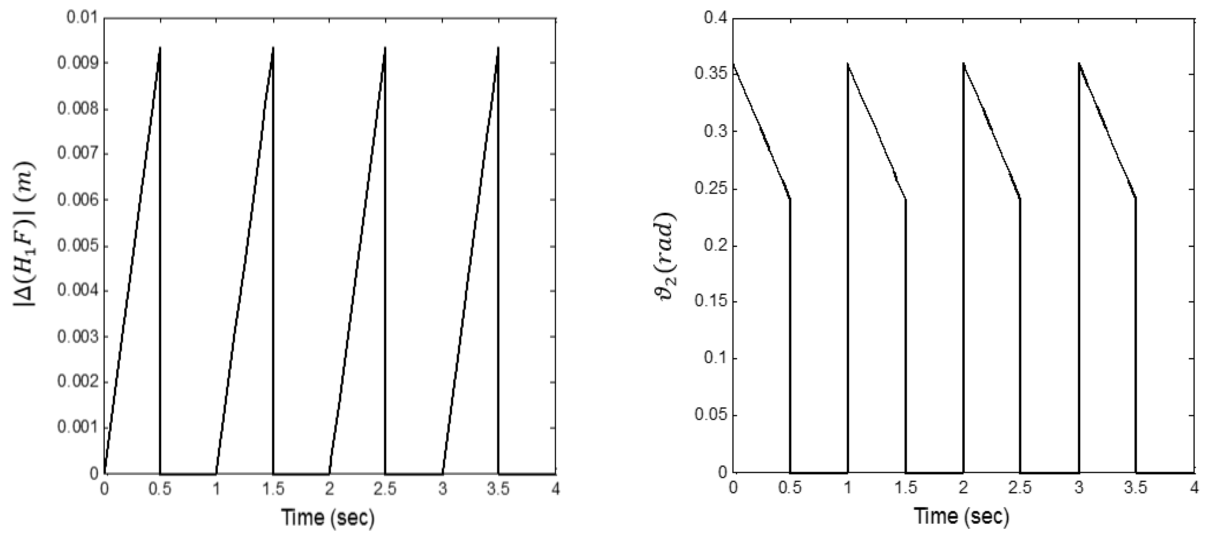

Fig. 13-The reaction force parameters generated in the muscle bicep femoris (BF) case (1)

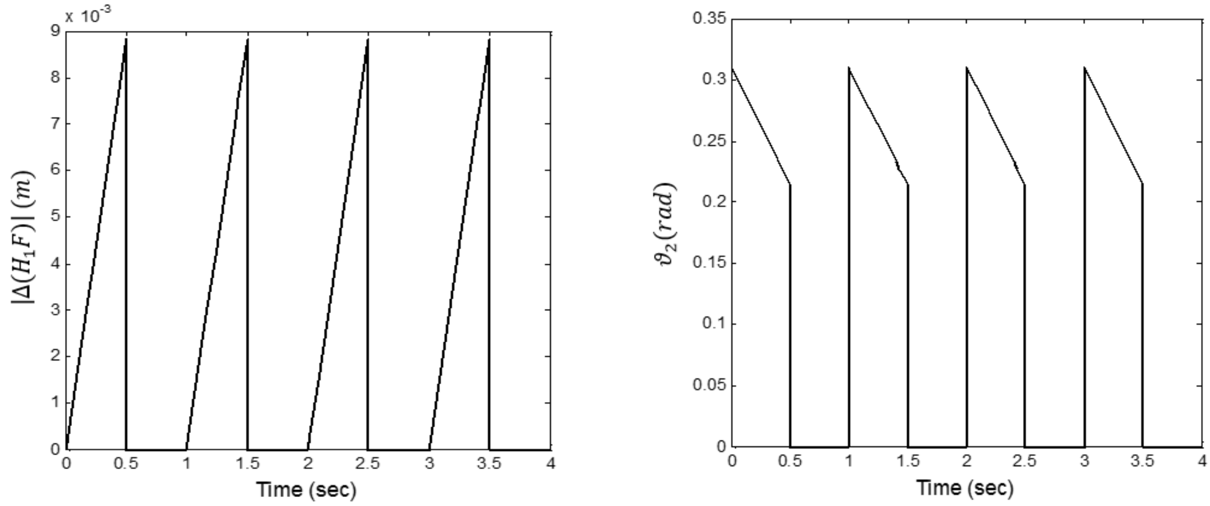

Fig. 14-The reaction force parameters generated in the muscle bicep femoris (BF) case (2)

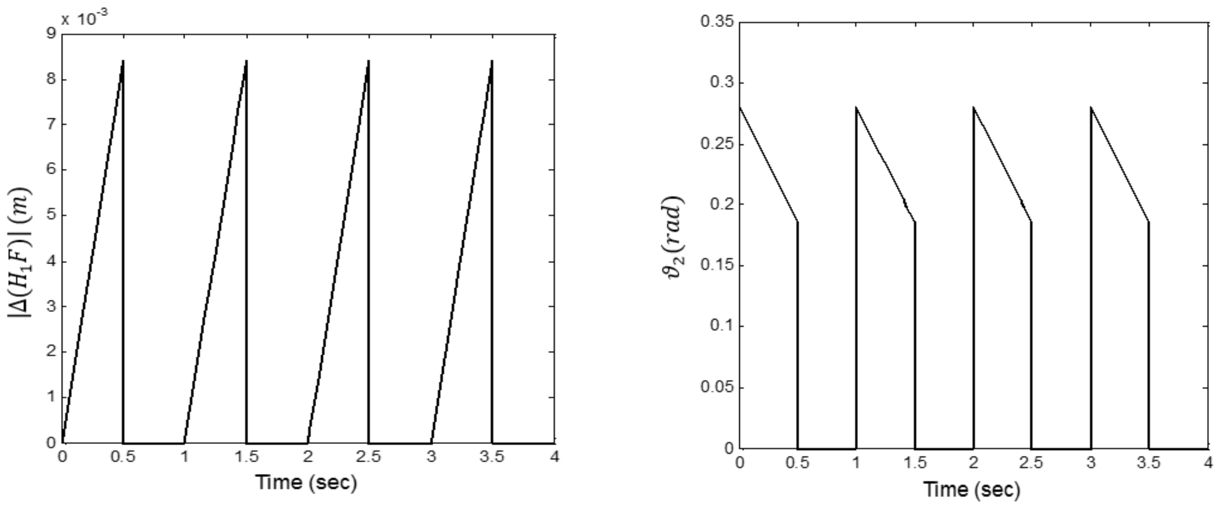

Fig. 15-The reaction force parameters generated in the muscle bicep femoris (BF) case (3)

The results from Fig.10~Fig 15 are obtained by modeling and simulation the walking bipedal robot by using SolidWorks (2015) as shown in Fig.5 and import the model to SimMechanics.

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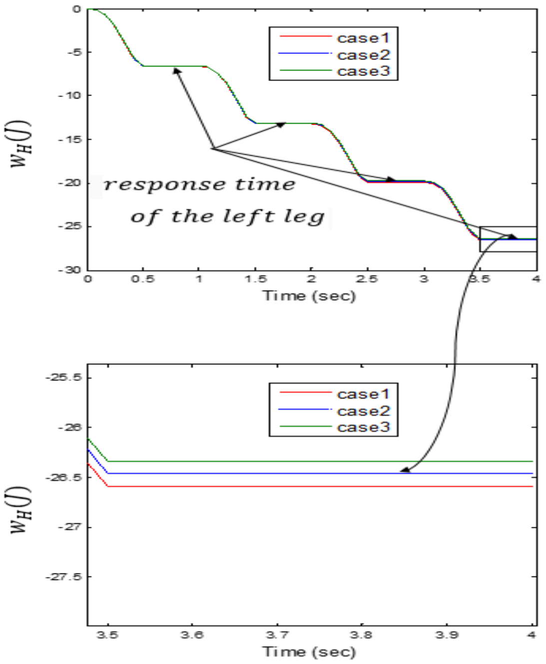

Fig. 16-The works accumulated at the hip joint

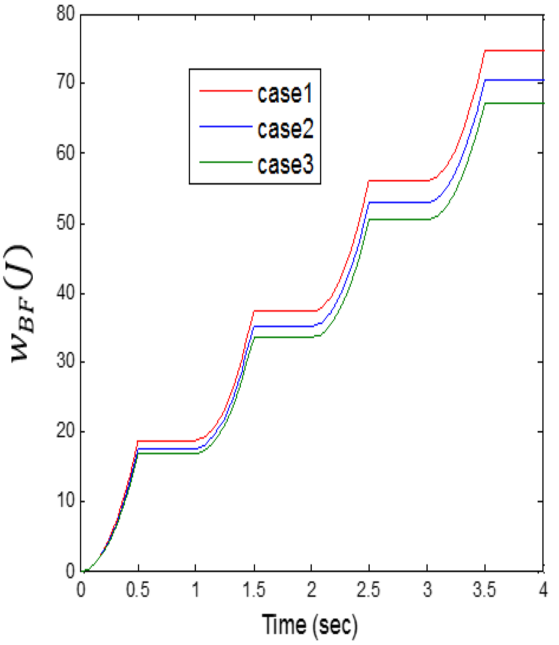

Fig.18 - The works done by the muscle bicep femoris

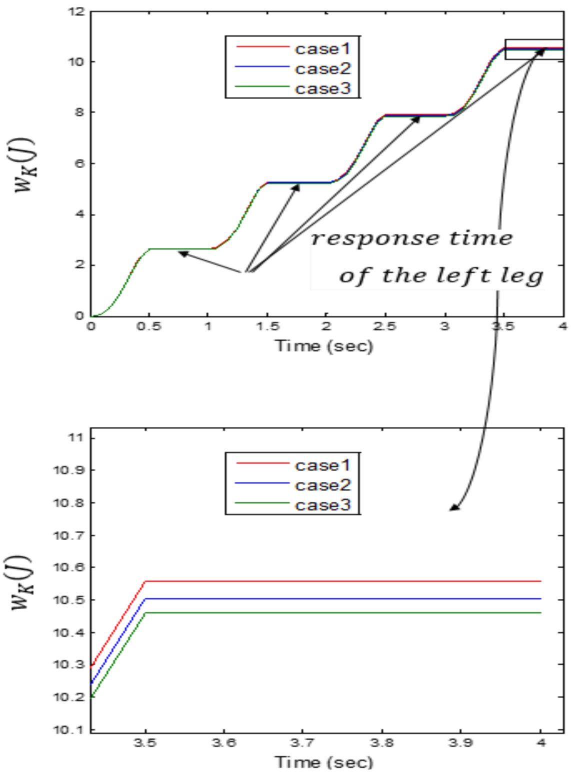

Fig. 17- The works accumulated at the knee joint

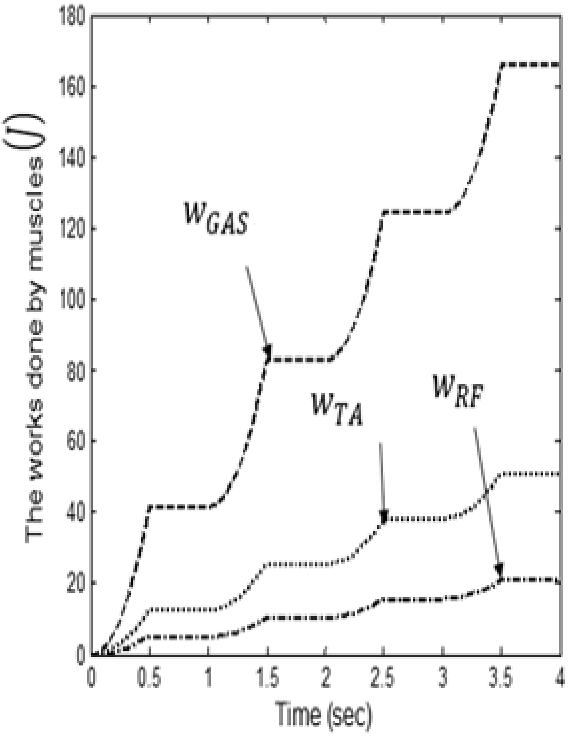

Fig. 19 - The works done by muscles

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It's shown from Figs. 16~19 that the position of the muscle biceps femoris (BF) has a strong impact on the fatigue of leg joints and the fatigue of the muscle itself, where it's found from these figures that using a short biceps femoris (BF) in the walking of bipedal robots contributes to increase the fatigue of leg joints and the fatigue of the muscle itself and using a long biceps femoris (BF) in the walking of bipedal robots contributes to attenuate the fatigue of leg joints and the fatigue of the muscle itself. Additionally, it's found from the results of the works analysis at joints shown in Fig 16 and Fig 17that the hip joint gets tired more than the knee joint during walking. It's also found from the analysis of the works done by monoarticular and biarticular muscles shown in Fig.8 and Fig.19 that in our case,the fatigue level of muscles during the walk periode of bipedal robots can be classified as follows by descending order starting by the most tiring muscle: the muscle gastrocnemius (GAS), the muscle biceps femoris (BF), the muscle tibialis anterior (TA), and the muscle rectusfemoris (RF).

The objective of reducing the fatigue of bipedal robots during walking is not only to ensure a comfortable walking, but also to minimize the power provided by each leg joint which equals to the scalar product of the joint torque and relative angular velocity at joint [13]. Consequently and through this study, we can conclude that using a long biceps femoris (BF) contributes to ensure a power saving of each leg joint during the walk period of bipedal robots. Additionally,another remark shoud be cited in this paper is that ,during the walk period of bipedal robots the works accumulated at joints increase gradually while the power provided by each joint remains stable.This means that the fatigue of joint is basically dependent on the work analysis at joint.

4 Conclusion

We can conclude through this study that the position of the muscle biceps femoris (BF) has a strong impact on the fatigue of leg joints and the fatigue of the muscle itself. It's found from this study that, for a same walk period of bipedal robots , the fatigue of leg joints and the fatigue of the muscle (BF) can be mitigated by employing a long biceps femoris (BF) and can be increased by employing a short biceps femoris (BF) this fact fact is clear from the analysis of the works accumulated at joints and the analysis of the works done by the muscle biceps femoris (BF) shown in section 3. Another fact that is revealed from this study which is not shown in this paper is that, by fixing the positions of the muscles (RF),(BF) and (TA), the fatigue of joints and the fatigue of the muscle (GAS) can be mitigated by employing a short gastrocnemius (GAS) and can be increased by employing a long gastrocnemius (GAS) unlike the position's effect of the muscle biceps femoris (BF) on the fatigue of leg joints and the fatigue of the muscle itself. Consequently ,the works analysis at joints and the analysis of the works done by biarticular muscles can be applied to determining a good position of each muscle of biarticular muscles to ensure an excellent comfortable walking and power saving for walking bipedal robots.

The approach used in this paper conducts us to resolve a serious problem which is not treated before is that, how the fatigue of bipedal robots with compliant legs can be mitigated during the walk period. Thus , the challenge and novelty of this study can be summarized as follows: first, the choice of the good position of each muscle of biarticular muscles is able to achieve a human walking with less fatigue. Secondly , the power provided by each leg joint after fatigue mitigation can be alleviated relatively.

The present study shows the two potential roles of the positions variation of biarticular muscles on the walking fatigue of bipedal robots. As a future work , it would be very interesting to study the positions effect of biarticular muscles on the stability of bipedal robots. Thus, the choice of the position of each muscle of biarticular muscles must verify the two factors

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at the same time: stability and comfortable walking during the walk period of bipedal robots.

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