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Effect of Flexible Spine Motion on Energy Efficiency in Quadruped Running

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Abstract

Energy efficiency is important in the performance of quadruped robots and mammals. Flexible spine motion generally exists in quadruped mammals. This paper mainly explores the effect of flexible spinal motion on energy efficiency. Firstly, a planar simplified model of the quadruped robot with flexible spine motion is introduced and two simulation experiments are carried out. The results of simulation experiments demonstrate that both spine motion and spinal flexibility can indeed increase energy efficiency, and the curve of energy efficiency change along with spinal stiffness is acquired. So, in order to obtain higher energy efficiency, quadruped robots should have flexible spine motion. In a certain speed, there is an optimal spinal stiffness which can make energy efficiency to be the best. Secondly, a planar quadruped robot with flexible spine motion is designed and the conclusions drawn in the two simulation experiments are verified. Lastly, the third simulation experiment is carried out to explore the relationship between the optimal spinal stiffness, speed and total mass. The optimal spinal stiffness increases with both speed and total mass, which has important guiding significance for adjusting the spinal stiffness of quadruped robots to make them reach the best energy efficiency.

Keywords: bionic quadruped robot, flexible spine motion, spinal stiffness, energy efficiency, locomotion experiment

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1 Introduction

Relying on the ascendant movement performance of quadruped mammals, robotic researchers give more and more attention to quadruped robots. The research about quadruped robots originated from the 60 s of last century when the walking quadruped robot was the main focus of study. The most typical example is the "Walking Truck" made by Mosher[1]. From the 1980s, robotic researchers started researching the dynamic quadruped robot; Raibert is the father of the dynamic quadruped robot. When working at the MIT lab, Raibert[2,3] clearly expounded the balance of the dynamic quadruped robot from the dynamics view. Afterwards, Raibert *et al*.[4] developed a dynamic quadruped robot for the U.S. Army on the basis of his theory. This dynamic quadruped robot was called BigDog and its movement performance was amazing. After Raibert's study, many aspects of the dynamic quadruped robot have been studied deeply. Spröwitz *et al*.[5] researched the self-stabilizing behavior of the dynamic quadruped robot. Poulakakis *et al*.[6] studied how to make the dynamic quadruped robot run with a bounding gait. In 2010, some robotic researchers found that the body of the dynamic quadruped robot studied before was stiff, but spine motion is usually apparent in the running of quadruped mammals (especially the cheetah). So the quadruped robot with non-flexible spine motion was gradually studied. Çulha and Saranli[7] proposed a planar simplified model for the quadruped robot with non-flexible spine motion. The body of the planar simplified model has an actuated spine joint. With the planar simplified model, they studied the effect of non-flexible spine motion on speed. And in Refs. [8,9], the effect of non-flexible spine motion on stability was studied. In order to further improve movement performance, now the quadruped robot with flexible spine motion is the main focus of study. Because spine motion not only exists but also is flexible in the running of quadruped mammals. Çulha[10] also proposed a planar simplified model for the quadruped robot with flexible spine motion. The body of the planar simplified model had an actuated spine joint and there was a linear

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torsion spring in the spine joint. With the planar simplified model, Çulha[10] studied the effect of flexible spine motion on speed. Pouya *et al.*[11] derived the dynamics of the quadruped robot with flexible spine motion based on the planar simplified model proposed by Çulha[10]. And Pouya *et al.*[11] studied the effect of flexible spine motion on stability. Folkertsma *et al.*[12] designed a mechanical structure for the spine of the quadruped robot with flexible spine motion. The spine structure is actuated by a differential gear and can change its spine stiffness.

Besides speed and stability, energy efficiency is also important for quadruped robots. High energy efficiency can make quadruped robots operate in a power autonomous fashion for extended periods of time. The effect of speed on energy efficiency is the first to be researched. Hoyt and Taylor[13] presented that energy efficiency increased with the increase of speed. The effect of non-flexible spine motion on energy efficiency has also been deeply studied. Leeser[14] developed a planar quadruped robot with no-flexible spine motion and studied the problem through prototype experiments. Haueisen[15] proposed a multi-body dynamic model for the quadruped robot with non-flexible spine motion and studied the problem through simulation experiments. These studies all show that energy efficiency of the quadruped robot with flexible spine motion is higher than that of the quadruped robot with stiff spine. But the studies about the effect of flexible spine motion on energy efficiency, which can be seen now, are all made by biologists. Alexander *et al.*[16] found that there were many elastic structures in the body of quadruped mammals. So they considered the body's elastic structures could improve energy efficiency as the elastic structure was able to store energy. Gray[17] measured the energy changes of the running Greyhound and found that the body's elastic energy could help the transformation from leg explosive force to kinetic energy. So Gray[17] presented that flexible spine motion could improve energy efficiency, compared with non-flexible spine motion. Quadruped mammals, after all, are very complex systems, making it difficult to focus on studying the effect of flexible spine motion on energy efficiency. For example, it is difficult to get the curve of energy efficiency change along with spinal stiffness using quadruped mammals. In conclusion, the effect of flexible spine motion on energy efficiency has not been researched thoroughly and systematically.

In this paper, we introduce a planar simplified model of the quadruped robot with flexible spine motion and design a planar quadruped robot with flexible spine motion to study the effect of flexible spine motion on energy efficiency. Firstly, we carry out two simulation experiments with the model to study the curve of energy efficiency change along with spinal stiffness. Secondly, corresponding to the two simulation experiments, we conduct two prototype experiments with the robot to verify the conclusions of the two simulation experiments. Lastly, the third simulation experiment with the model is carried out and the relationship between the optimal spinal stiffness, speed and total mass is obtained. The relationship between the optimal spinal stiffness, speed and total mass has important guiding significance for adjusting the spinal stiffness of quadruped robots to make them reach the best energy efficiency.

2 Model and simulation experiments

2.1 Model description

A planar simplified model of the quadruped robot with flexible spine motion, proposed by Çulha[10], is shown in Fig. 1. In this paper, we use the model to conduct simulation experiments. The model has two main parts: a body and two legs. The body consists of a front torso and a rear torso connected by a spine joint. In the spine joint, there is a linear torsional spring (spine spring). The two legs are both massless compressed springs (spring legs). The spring legs are passive. The spine joint and the two hip joints are all active.

2.2 Control method

To make the model reach a stable periodic motion, a proper controller is necessary. Now, Central Pattern Generator (CPG) is the most popular controller for

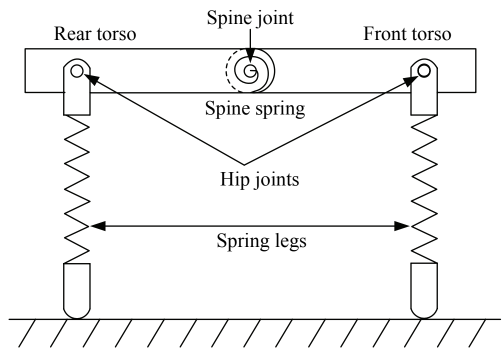

Fig. 1 Planar simplified model of the quadruped robot with flexible spine motion.