A Study on Trunk Stiffness and Gait Stability in Quadrupedal Locomotion Using Musculoskeletal Robot

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Abstract: In this study, a feasibility study on the stability of gait patterns with changeable body stiffness is reported. The periodic motions of the legs are generated as a rhthmic motion. The stability of locomotion strongly depends on the mechanical properties of the body mechanism, especially the joint stiffness. In this report, the muscle tone of the robot motion at the trunk is changeable by using the changeable elasticity of the pneumatic actuators. The stability of quadruped locomotion in crawl, trot and pace patterns with changeable body stiffness was evaluated with hardware experiments.

Keywords: Quadruped locomotion, Musculoskeletal robot, Body stiffness, Stability

1. INTRODUCTION

Locomotion is one of the basic functions of a mobile robot and the important topic to develop a new control strategy for nonlinear multi-modal system. Therefore, a considerable amount of research has focused on controlling the motion of legged locomotion robots[1],[2]. This article discusses the relation between stability of gait patterns and body's dynamic properties in quadruped locomotion using musculoskeletal quadruped robot.

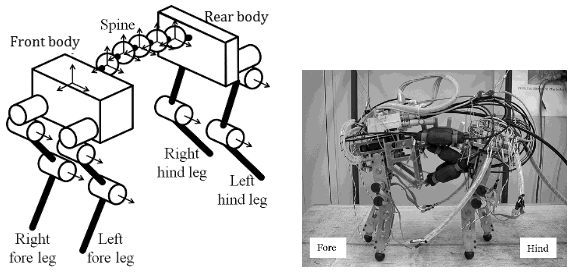
In this study, the first topic is development of musculoskeletal structure of the robot's trunk to imitate the animal's kinematical structure and physical properties in terms of stiffness(visco-elasticity). We can change the stiffness of the trunk through the balanced adjustment of the elasticity in coordiations of pneumatic actuators[3],[4]. The robot has artificial spinal structure with many segments of vertebra and interspinal disk in line. The articifial spine plays a role of structural member of the system and also becomes a passive device to be a dynamic damper with its visco-elasticity property[5],[6].

In this article, we focused on the point that the stability of quadruped locomotion in crawl, trot and pace patterns with changeable body stiffness through artificial musculoskeletal mechanism was evaluated with hardware experiments. We evaluated the relation between body stiffness and stable gait patterns. In hardware experiments, the stability is checked by evaluating the deviations of body motions in angular velocities. The results show there is appropriate parameter set of body stiffness and locomotion speed for each gait pattern in terms of stability.

2. MODEL

2.1 schematic model

Consider the quadruped robot shown in Figure 1; it has four legs and a main body. The main body is composed of two parts, a fore body and a hind body, that are connected through a multi-segmented spinal structure. Leg's joints are driven by geared DC motors. The spine, on the other hand, has no acturator to actuate directly its motion, but the robot has pneumatic actuators to change the trunk's stiffness through tendon mechanism.



Schematic model Hardware model

Fig. 1 Models of the musculoskeletal robot

2.2 Spine model

The schematic design of the trunk structure is summarized in Figure 2. This structure consists of artificial spine and eight pneumatic actuators. The spine is composed of ten vertebras and nine interspinal disks assembled in line. The tensile force of the steel wire in the spine is adjusted by a winch. The alignment of the actuators and geometrical scale of structure is designed to imitate usual size of living cats. The pneumatic actuators to change the trunk stiffness are enumerated as shown in the figure. Robot's total length and height are 0.41[m] and 0.35[m], respectively.

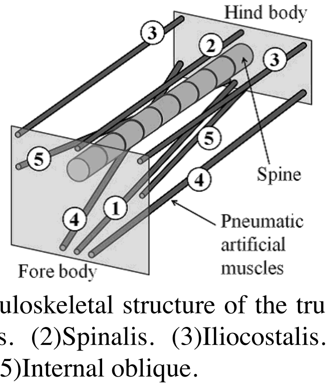


Fig. 2 Musculoskeletal structure of the trunk (1)Rectus abdominis. (2)Spinalis. (3)Iliocostalis. (4)External oblique. (5)Internal oblique.

3. HARDWARE EXPERIMENTS

The pneumatic actuators are controlled to change the stiffness of the trunk. The stiffness of each actuators are controlled in two states; 0.40 [MPa] and 0.15 [MPa]. The combination of the actuators' determines the trunk stiffness. The trunk stiffness is experimentally measuerd for each combination. The value of trunk stiffness changes from 0.1[Nm/rad] to 2.9 [Nm/rad].

First we investigated the motion of the robot selecting three parameters changeable: one is combination of pneumatic actuators' pressure modes to control trunk stiffness; Another is gait pattern and the other is time period of walking cycle T_f. Figures 3∼ 6 show the difference between roll and pitch angular velocities of main body. The locomotions were stable in both the trot and pace patterns (Figures 3 and 5). On the other hand, the robot's locomotion becomes unstable in the case that the trunk's stiffness becomes lower. When the time period of walking cycle could not match the natural mode of posture motion, the locomotion also becomes unstable(Figures 4 and 6). In figure 4 and 6, the rolling motion of the body became unstable. The difference between the motion of the fore and the hind bodies oscillated by the spinal mechanism. The excitation or convergence of periodic rolling motion of the main body depends on the stiffness of the spinal mechanism and muscles of the trunk.

Next, the stiffness of the trunk is changed in the crawl, trot and pace patterns, and the locomotion stability is investigated. Figure 7 shows the results. In the figure, gait patterns are expressed as phase difference, 0.00 for pace, 1.57 for crawl and 3.14 for trot. Trunk stiffness is expressed as multiple number of the stiffness of the spinal mechanism. In terms of the trunk stiffness, in the case of trot pattern, if the stiffness is too small, locomotion itself becomes unstable. However, if we choose appropriate stiffness at the trunk, the robot can continue stable trotting pattern. In terms of the time period of walking cycle, fast locomotion is suitable for trotting pattern, but to the contrary slow locomotion matches the crawl pattern.

These results show that there are different conditions for stable locomotion in each gait pattern, in terms of trunk stiffness and time period of walking cycle. We can note that periodic leg's motion causes excitation of oscillatory motion of the spinal mechanism. The the appropriate trunk stiffness makes effective damping factor to reduce the spine's oscillation excited by periodic leg's motion in the given gait pattern.

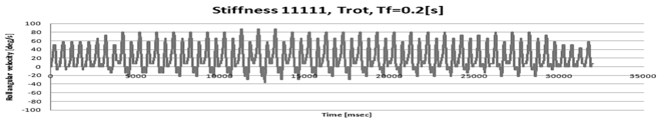


Fig. 3 Trunk stiffness:2.9 [Nm/rad], Trot, Tf=0.20[sec]

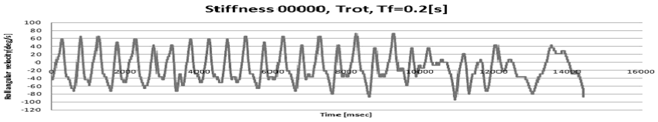


Fig. 4 Trunk stiffness:0.1 [Nm/rad], Trot, Tf=0.20[sec]

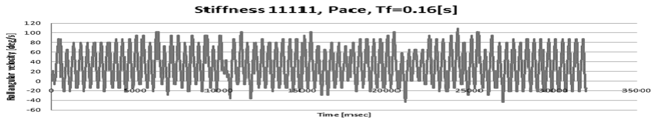


Fig. 5 Trunk stiffness:2.9 [Nm/rad], Pace, Tf=0.16[sec]

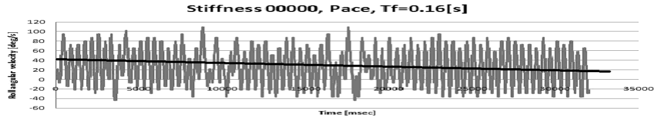


Fig. 6 Trunk stiffness:0.1 [Nm/rad], Pace, Tf=0.16[sec]

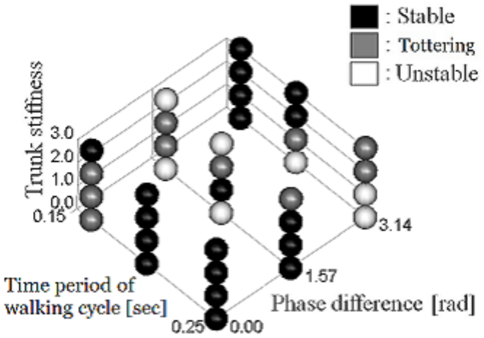


Fig. 7 Stability map: Black point=Stable, Gray point=Tottering, White point=Unstable

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