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 rhythmic 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.

I. 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. This article discusses the relation between stability of gait patterns and body’s dynamic properties in quadruped locomotion using musculoskeletal quadruped robot.

The quadruped locomotion involves two major dynamic properties: one is that the system is composed of many degrees of freedom with highly nonlinear dynamics including contact motions of the legs and statically unstable system state in locomotion. This property strongly affects the behavior of the system in the gravitational field and dynamically changeable constraints such as leg-ground contacting[1]-[4]. When the control parameter of the system changes, the dynamic behavior will change in terms of stability, flexibility, robustness, etc. But the relation between the control parameters and dynamic properties of the locomotion is not clear. The other is that controllable motions are legs’ periodic motions, whereas statically uncontrollable motion is body’s posture motion in the gravitational field. Therefore, the locomotion is explained as an emergence of dynamic patterns in the nonlinear multi-body system with coordinating many DOF and tuning the control parameters with controllable periodic legs’ motions in the gravitational field. But the dynamic mechanism of emergence in stable locomotion is not clear.

Biological researches give us some clues to overcome such difficulties. Bernstein pointed out that during such rhythmic and steady motion as straight walking, many joints and muscles are organized into a collective unit that is controlled as though it had fewer degrees of freedom (DOFs), even though it still needs to retain the necessary flexibility for changing environments [5]. In order to explain such synergetic control scheme, one crucial architecture for locomotion is rhythm generator with feedback signal from muscles or peripheral nervous system, which is called Central Pattern Generator (CPG) model[6]-[9]. This knowledge has inspired robotics researchers, and a considerable amount of research has been done [10]-[17] on biologically inspired control systems for walking robots that enables them to adapt to variations in the environment based on the CPG model.

The other biological knowledge we focused on is that the stability of locomotion also strongly depends on the mechanical properties of the body mechanism, especially the joint stiffness. Biological studies teach us that the tones(stiffness) are actively and adaptively controlled by the neuronal system during locomotion[18],[19]. This neuronal system stabilizes the posture and also obtains stable gait patterns by controlling the periodic legs’ motions driven by a rhythm generator(CPG). When we consider applying this biological architecture to a robotic system, pneumatic actuators that have changeable elasticity are suitable to change the body’s stiffness[20]-[31].

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 coordination of actuators. The robot has artificial spinal structure with many segments of vertebra and interspinal disk in line. The artificial 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[32]-[34].

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. The system used in this study consists of a rhythmic motion generator and a changeable tones mechanism. The rhythmic motion generator controls periodic motions of the legs. When the body stiffness and the locomotion conditions such as speed and phase difference between the legs’ motions are given, the dynamic interactions between body dynamics and periodic motions of the legs enable mutual entrainments to get a stable gait pattern in quadruped locomotion. But when the conditions...
are not suitable to make an entrainment, the locomotion becomes unstable. 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. In the trot pattern, a parameter set of high body stiffness and considerably high locomotion speed is stable, while in the walk pattern, a set of considerably low body stiffness and low locomotion speed is suitable for stable locomotion.

From the study, we can note that stability of adaptive gait selection or gait transition strongly depend on the matching condition between body’s dynamic property and the dynamic characteristics of leg’s periodic motion in quadruped locomotion.

II. MODEL

A. schematic model

Consider the quadruped robot shown in Figure 1; it has four legs and a main body. Each leg consists of two links that are connected to each other through a one degree of freedom (DOF) rotational joint. The main body is composed of two parts, a fore body and a hind body, that are connected through a multi-segmented spinal structure. Each leg is connected to the main body through a one DOF rotational joint. Legs are enumerated as follows: Left fore = 1, Left hind = 2, Right hind = 3, and Right fore = 4. The joints of each leg are 1 and 2 from the main body toward the end of the leg. We define \( \theta_{i}^{(0)} \) \((i = 1, 2, 3)\) as the components of the Euler angle from the inertial space to the coordinate system fixed on the fore body. \( \theta_{i}^{(B)} \) \((i = 1, 2, 3)\) are defined as the joint Euler angles of the hind body to the fore body. We also define \( \theta_{j}^{(i)} \) as the joint angle of link \( j \) of leg \( i \).

Leg’s joints are driven by geared DC motors. The spine, on the other hand, has no actuator to actuate directly its motion, but the robot has pneumatic actuators to change the trunk’s stiffness through tendon mechanism.

B. Spine model

Figure 2 shows the spinal structure of the robot. The spine is composed of ten vertebrae and nine interspinal disks assembled in line. The tensile force of the steel wire in the spine is adjusted by a winch.

The schematic design of the trunk structure is summarized in Figure 3. This structure consists of artificial spine and eight pneumatic actuators. 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.

III. GENERATING LOCOMOTIONS

A. Design of the trajectories of the legs

The position of the tip of the leg where the transition from the swinging stage to the supporting stage occurs is called the anterior extreme position (AEP). Similarly, the position where the transition from the supporting stage to the swinging stage occurs is called the posterior extreme position (PEP).

We determine the nominal trajectories that are expressed in the coordinate system which is fixed on the main body.

First, we define the nominal PEP \( r_{eP}^{(i)} \) and the nominal AEP \( r_{eA}^{(i)} \). The index \( * \) indicates the nominal value.
The nominal phases of the legs’ motion at landing and lift off are determined as follows:

\[ \phi^{(i)} = \hat{\phi}^{(i)} \text{ at landing}, \quad \phi^{(i)} = 0 \text{ at lift off} \]  

(1)

The nominal trajectories for swinging stage \( r^{(i)}_{eF} \) (a cycloid curve) and for supporting stage \( r^{(i)}_{eS} \) (linear trajectory) are given as functions of the phase \( \phi^{(i)} \) of the oscillator and are alternatively switched at every step of the nominal landing and lift off points.

\[
\dot{r}^{(i)}_{eS}(\phi^{(i)}) = \begin{cases} 
\dot{r}^{(i)}_{eF}(\phi^{(i)}) & 0 \leq \phi^{(i)} < \hat{\phi}^{(i)} \\
\dot{r}^{(i)}_{eS}(\phi^{(i)}) & \hat{\phi}^{(i)} \leq \phi^{(i)} < 2\pi 
\end{cases} 
\]  

(2)

The nominal duty ratio \( \beta \) for leg \( i \) is defined to represent the ratio between the nominal time for the supporting stage and the period of one cycle of the nominal locomotion.

\[ \beta = 1 - \frac{\hat{\phi}^{(i)}}{2\pi} \]  

(3)

Joint angles \( \theta^{(i)}_j \) are calculated by inverse kinematics on eq.(2).

B. Gait patterns

We describe the nominal gait patterns as the phase difference of the rhythm generators. There are three gait patterns in which two legs support the main body at any instant during locomotion. In the trot pattern, legs 1 and 3 form one pair and legs 2 and 4 form the other pair; in the pace pattern, legs 1 and 2 form one pair and legs 3 and 4 form the other pair; finally in the bounce pattern, legs 1 and 4 form one pair and legs 2 and 3 form the other pair. In such patterns, the phase difference of the rhythm generators in a pair is zero, and the phase difference between the pairs is \( \pi \).

On the other hand, there are two gait patterns in which the three legs support the main body at any instant during locomotion. One is crawling in which legs 1, 2, 3, and 4 touch the ground in this order.

The gait pattern is coded as a phase difference of the rhythm generators. By changing the phase difference between rhythm generators, gait patterns are changeable. When a stable phase difference can be sustained, the corresponding gait pattern is stable[16].

The rhythm generators can be expressed in the following equations:

\[ \phi^{(i)} = \phi^{(k)} + \gamma_{ik} \]  

(4)

where \( \gamma_{ik} \) is the nominal phase difference between rhythm generator \( i \) and \( k \), \( \phi^{(k)} \) is a time dependent value and a function of duty ratio \( \beta \) that determines the ratio of the stance phase during the total time period for the walking cycle; i.e., this parameter controls the locomotion speed:

\[ \phi^{(k)} = \int_0^{2\pi(1-\beta)} \frac{2\pi(1-\beta)}{T_f} dt \]  

(5)

where \( T_f \) is the nominal time period for the swinging stage, and it is constant.

The gait patterns and phase differences are summarized in Figure 4.

C. Muscle tones of the trunk

In this study, the muscle tone at the trunk is changeable. It is difficult to directly and precisely control the stiffness of each actuators in a real robot system, which changes if we change the supplied air pressure or inspiration/expiration time of the air.

The stiffness of the trunk is changed by controlling the combinations of active actuators at the trunk as follows:

\[
K_m = \begin{cases} 
K_{m}^{\text{max}} & \text{fully air-inspired condition} \\
K_{m}^{\text{min}} & \text{air-expired for a given time duration from fully air-inspired condition} 
\end{cases} 
\]  

(6)

where \( K_m \) is the stiffness of the actuator \( m \) in the musculoskeletal mechanism of the trunk. \( K_{m}^{\text{max}}, K_{m}^{\text{min}} \) are maximum and minimum values of \( K_m \).

Each actuator’s stiffness is evaluated by using experimental data in advance. Figure 5 shows the relation between length and load for a pneumatic actuator. We can find that the actuator has linear characteristics in its stiffness. Using this experimental data, we estimated the trunk’s stiffness of the robot.

![Fig. 5. Relation between length and load](attachment:image.jpg)
IV. HARDWARE EXPERIMENTS

Figure 6 shows the musculoskeletal quadruped robot with pneumatic actuators to change its stiffness. In the figure, we can see the artificial spine and some pairs of actuators in the trunk. Legs’ joints are actuated by geared DC motors (maxon RE-max 20W).

Physical parameters of the robot is summarized in Table 1.

<table>
<thead>
<tr>
<th>Physical parameters of the robot</th>
<th>[m]</th>
<th>[kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>0.132</td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>0.350</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>0.413</td>
<td></td>
</tr>
<tr>
<td>Length of legs</td>
<td>0.225</td>
<td>4 × 0.657</td>
</tr>
<tr>
<td>Total</td>
<td>5.610</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7 shows the architecture of the hardware system. The CPU on the host computer is an Intel Xeon 3.0 [GHz], and the sampling frequency is 1.0 [kHz]. The signals from the contact sensors are input to 12 bit A/D converters and sent to the host computer. The control commands for the actuators are calculated on the host computer in real time using our proposed control method and sent to actuator drivers (iXs Research Corp., iMCs03) by USB. The electric valves (SMC Corp., SYJ3340-6M-M5) control the air supply from an air compressor (Jun-Air International, 3-4 Minor) to the actuators. The pressurized air, which is supplied at 0.4 [MPa] through a φ 8 [mm] tube from the compressor to the multi-port valves, is distributed through a φ 4 [mm] tube from the valves to the actuators. Each pneumatic actuator (φ 20[mm], L =100 [mm]) change the stiffness of the trunk in combination.

The pneumatic actuators are controlled to change the stiffness of the trunk. The stiffness of each actuators are controlled in two states; High air-pressure mode (0.40 [MPa]) and Low air-pressure mode (0.15 [MPa]). The combination of the actuators’ states is shown in Table 2, for example. In this case number of high stiffness actuators is three, and the trunk is estimated three times as stiff as the case when no trunk-actuator is active (stiffness comes from just spinal mechanism).

<table>
<thead>
<tr>
<th>Table 2 Example of trunk stiffness parameter</th>
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<tbody>
<tr>
<td>Muscle number</td>
</tr>
<tr>
<td>Trunk stiffness</td>
</tr>
<tr>
<td>Binary expression</td>
</tr>
</tbody>
</table>

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. Figures 8–11 show the results of the hardware experiments, the difference between roll and pitch angular velocities of main body ($\dot{\theta}_{1}^{(0)} - \dot{\theta}_{1}^{(B)}$). The robot can continue stable locomotion in both the trot and pace patterns (Figures 8 and 10). There are slight deviations from the limit cycle due to ground conditions. But they are in steady states without tumbling. 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 cannot match the natural mode of posture motion, the locomotion also becomes unstable (Figures 9 and 11). In figure 9, the rolling motion of the body rapidly became unstable. In figure 11, the difference between the fore and the hind bodies became larger and larger. The difference between the motion of the fore and the hind bodies oscillated by the spinal mechanism. The natural frequency of the spinal mechanism is determined by its stiffness and the oscillation is excited by periodic motion of the legs with phase differences based on nominal gait pattern. Therefore, 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.

Second, the stiffness of the trunk is changed in the crawl, trot and pace patterns, and the locomotion stability is investigated. The control parameters are also the trunk stiffness, gait patterns and time period of walking cycle.

Figure 12 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.

Figures 13 and 14 are the snapshots of the robot during
locomotion in stable case and in unstable case, respectively.
In the stable case(Figure 13), the robot makes a limit cycle in
leg’s periodic motion and posture motion. But, in the unstable
case(Figure 14), the fluctuation on posture motion becomes
larger and larger during locomotion, and through tottering
motion, the robot finally falls down.

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.

V. CONCLUSION

We developed a musculoskeletal quadruped robot with an-
tagonistic pairs of pneumatic actuators which are changeable
in body stiffness. We investigated the stability of locomotion
by changing the stiffness at the trunk in crawl, trot and
pace patterns. The stability when the body stiffness changes
were evaluated with hardware experiments. The results show
that there is appropriate parameter set (body stiffness and
locomotion speed) for each gait pattern in terms of stability.
We can note that stability of locomotion strongly depends
on a well balanced effects of the synchronization and effec-
tive damping between oscillatory motion of the spine and
periodic leg’s motion. The adequate gait pattern emerges
satisfying the condition that makes synchronization of the
motions and effective passive damping.

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