Quasi-quadruped robot with a powerful and compliant musculoskeletal spine

Ojiro Matsumoto* and Koh Hosoda*
*Graduate School of Engineering Science, Osaka University, Japan
matsumoto.ojiro@arl.sys.es.osaka-u.ac.jp

1 Introduction

Feline animals are good at high-speed running, and they repeat flexing and extending their spine during running [1]. There are some functions of quadruped animals' spine [2,3]: the spine transformation changes the position of the hip joint so that they expand their foot stride length, the musculoskeletal spine enables them to store elastic strain energy to realize efficient running. Several researchers developed robots with a motor-driven spine structure. However, it is difficult to realize that motion during running, considering the required driving force and compliance.

We propose adopting biorobotic muscle actuators into spine structure. Quadruped animals actuate their spine structure by antagonistic muscles that provide compliance. The compliance allows the spine structure to transform easily by the external force (e.g. ground reaction force, inertial force, and gravity) and to cause more extension of muscles along the spine. That enhances the initial tension of muscle when it actuates [4]. Therefore, we built the hypothesis that the compliant spine enhances the driving force during running by utilizing its shape transformation that external force causes. The more the running speed increases, the more external force the spine structure receives, but we consider the spine structure described above can exchange the external force to the driving force that maintains the running speed.

In this research, we verified the hypothesis by a musculoskeletal robot that has a compliance spine structure actuated by antagonistic muscles. We measured the spine angle and the foot trajectory of the robot during two different situations where the robot received different external forces: in-air and on-ground running.

2 Spine-hindleg musculoskeltal robot

We designed a spine-hindleg musculoskeletal robot (Figure 1). The size and the motion range of each joint are based on the domestic cat [2, 5]. The body length, height, and width of the robot are 540, 375, and 235 mm, respectively, and its weight is 3.9 kg. The robot mainly consists of POM (polyoxymethylene) plates, aluminum square tubes, and metal shafts. We adopted a pneumatic artificial muscle that has a similar relationship of length and force to muscles [4].

The spine structure consists of one degree of freedom linkage mechanism and a pair of antagonistic muscles. The linkage referred to in a previous study [6] simulates the change in the pelvis position and angle relative to the torso so that its transformation expands the foot stride length. One degree of freedom structure makes it easy for a pair of antagonistic muscles to transform the spine. The longissimus (LO) and the rectus abdominis (RA) as a dorsal muscle and an abdominal muscle connect the torso and pelvis (Figure 2) and work as antagonistic muscles.

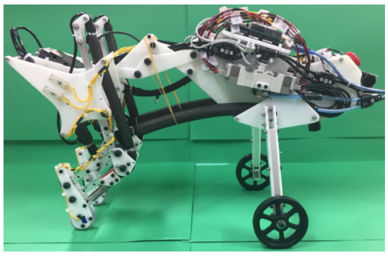

Figure 1: The spine-hindleg musculoskeletal robot

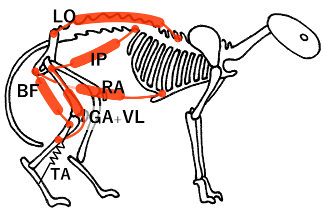

Figure 2: The muscle arrangement

We adopted a pantograph linkage as hind legs, and implemented muscles and a tension spring: iliopsoas major (IP), biceps femoris (BF), gastrocnemius and vastus lateralis (GA+VL), and tibialis anterior (TA). The robot has wheels instead of the front legs that support the body.

3 Experiments

We measured the spine angle and the foot trajectory of the robot during in-air and on-ground running. To calculate the spine angle and the foot trajectory, we set the position of point C and the angle OAB shown in Figure 3. Figure 4 shows the actuation pattern of muscles based on preliminary experiments and previous studies [2,7]. We placed transparent plastic plates on either side of the robot so that it keeps running straight and the robot realizes bound gait running on a treadmill. A camera placed on the side of the treadmill captured the points mentioned above. In the next section, we show the data when the robot realized stably and faster running.

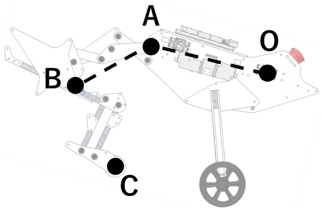

Figure 3: Points O, A, B, and C: represent the origin, the first spine joint, hip joint, and foot

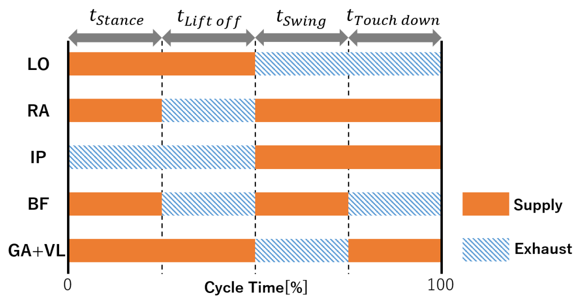

Figure 4: The actuation pattern of each muscle

4 Results

The robot achieved a 5.0 km/h (about 1.4 m/s) running (Figure 5) when the supplied air pressure was 0.65 MPa and t_{Stance}, $t_{Liftoff}$, t_{Swing}, and $t_{Touchdown}$ were 100, 100, 100, and 30 ms, respectively. Figure 6 and Figure 7 show the spine angle and the foot trajectory during each running. In Figure 7, the graph origin is point O and the horizontal axis, X, gives the on-ground travel direction of the robot, and the vertical axis, Y, gives the direction perpendicular to the travel direction. The red circles show the foot trajectory of on-ground running. The blue triangles show that of in-air running, and we applied coordinate transformations to each in-air point so that line OA of in-air matches that of on-ground with the same sample number.

5 Disucussion

We can find that the robot realized running with the transformation of its spine structure from Figure 5 and Figure 6. Figure 6 indicates that the range of the spine angle changed depending on the presence or absence of the ground reaction force. That means the spine structure has compliance. Moreover, the ground reaction force expanded the range of the spine angle and, it approached the structural limit angle (about 185 degrees) at on-ground data. At that time, the abdominal muscle extended enough. Therefore, the initial tension of the muscle should become bigger, and also the muscle should contract more quickly when the spine started flexing. In fact, as shown in Figure 7, the on-ground running realized the quick swinging of the foot. The results described above suggest the hypothesis is correct about the abdominal muscle in the swing phase. Since the spine flexed to its structural limit angle (about 131 degrees) both on-ground and in-air, mainly due to the effect of gravity, we could not confirm the same effect for the dorsal muscle in this experiment. To confirm the hypothesis for the dorsal muscle in other phases, we need additional experiments.

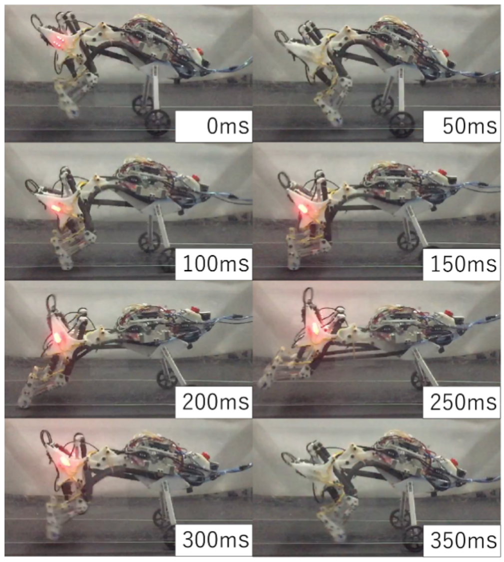

Figure 5: The snapshot of the on-ground running

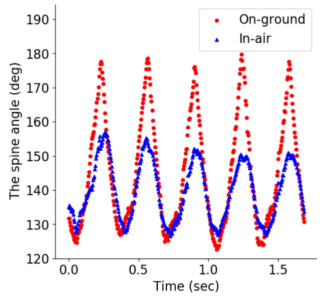

Figure 6: The spine angle with five consecutive cycles

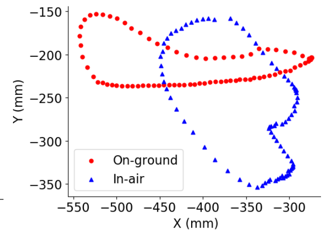

Figure 7: The average foot trajectory of five consecutive cycle

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