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Foot Sensor Module of Musculoskeletal Legged Robot for Vertical and Horizontal GRF with Elastic Metacarpophalangeal Joint

Michihisa Oohara[1], Hiroaki Tanaka[1], Ojiro Matsumoto[1], Shinpei Arikawa[1], Takumi Kawasetsu[1] and Koh Hosoda[1]
[1]Graduate School of Engineering Science, Osaka University, Japan
oohara.michihisa@arl.sys.es.osaka-u.ac.jp

1 Introduction

In the control of legged robots, vertical and horizontal components of the ground reaction force (GRF), which generate propulsion and support the body, are measured for adapting to various terrain [1] and for adjusting moving speed [2]. To this end, force sensors are fixed at the foot to measure each component of GRF. In general, the posture of the force sensors dynamically changes depending on the motion of the legged robot. Therefore, accurate posture estimation of the force sensors and translation of the coordinate system based on that estimation are required for the measurement each component of GRF.

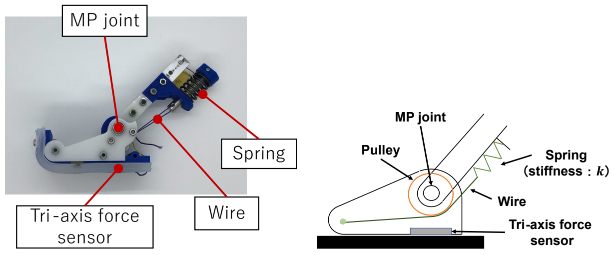
On the other hand, a bio-inspired legged robot that has an elastic metacarpophalangeal (MP) joint can passively maintain the footpad in a specific posture even as the legged robot moves dynamically [3]. This study focuses on such elastic MP joints and propose a sensor module that can estimate both components of GRF without estimating the posture of the foot. We also implement the sensor module in musculoskeletal quasi-quadruped robot and conduct walking experiments.

2 Material and Method

Figure 1 provides an overview of the proposed sensor module. To maintain a fixed posture of the footpad passively, an elastic tendon structure is utilized at the MP joint. This structure of the MP joint is based on the work by Sprowitz et al [3], in which a wire fixed to the toe connects to a spring in the leg through a pulley. Additionally, a tri-axis force sensor [4] is placed on the footpad to measure vertical and horizontal components of the GRF during stance.

To support the body weight on the foot while keeping the footpad on the ground during stance, it is essential to design the stiffness of the MP joint appropriately. Accordingly, we developed several sensor modules with different stiffness (spring stiffness k in Fig. 1(b)) and compared their ground contact performance through walking experiments. Based on these results, we determined the appropriate stiffness.

To assess the ability of the sensor module, we developed a legged robot (Fig.2) that incorporates the proposed sensor module. The robot is 640 mm long, 400 mm high, 290 mm wide, and weighs 5.15 kg. The leg structure is based on a robot that imitates the musculoskeletal structure



(a) Side view (b) Schematics of elastic MP joint

Figure 1: Proposed sensor module

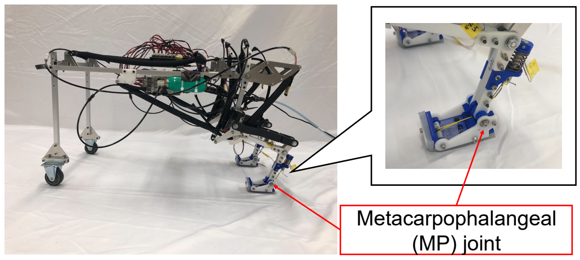


Figure 2: Musculoskeletal legged robot (left) and proposed sensor module (right)

of the hindlimbs of quadrupeds [5]. The robot has four degrees of freedom (DoFs) in one hindlimb, with one being the MP joint. Five pneumatic artificial muscles and one spring are used to drive the other three DoFs. We conduct walking experiments on a force plate and compared the sensor values with the actual GRF applied to the foot. In these experiments, we adopted feedforward control and generated an alternating gait [5].

3 Result and Discussion

3.1 Foot posture

Figure 3 shows snapshot series of walking experiment. Figure 4 shows the variation of the angle (θ) between the footpad of the right hindlimb and the ground for each spring stiffness k. The gray area in the figure indicates the stance phase determined by the video analysis.

During the stance phase, the foot force sensors should maintain a specific posture on the ground, thus θ should remain stable at around 0°. When k is 3.9 N/mm, the variation of θ from 0° is small during the stance phase. When k is too large, θ increases in the late stance phase and largely deviates from 0°. When k is too small, θ stays near 0°. However,

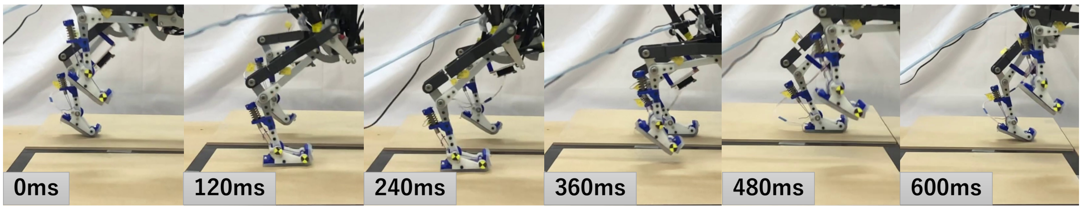


Figure 3: Snapshot series of walking experiment ($k = 3.9$ N/mm). Gait cycle is 620 ms.

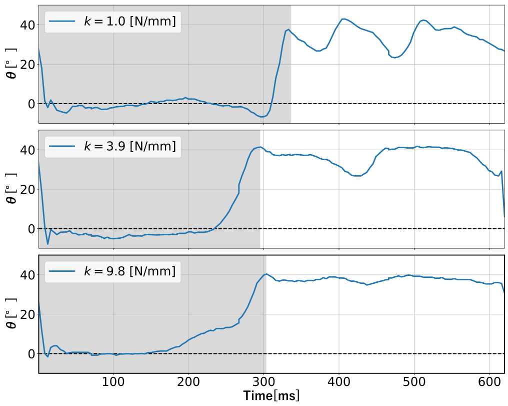
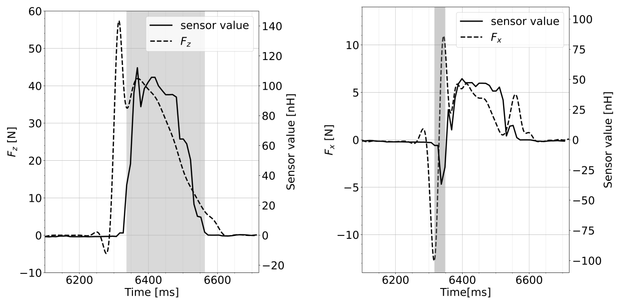


Figure 4: The angle θ between the footpad and the ground during walking. The gray area indicates the stance phase. The dashed line shows 0°. The time range is one step (620 ms) from the moment the right hindlimb touches the ground.



(a) Vertical (b) Horizontal

Figure 5: Comparison of sensor values and GRFs. In (a) and (b), the period when the sensor values exceeded and fell below the threshold values are shown as gray area, respectively.

θ is negative around 300 ms, indicating that the toe is floating. Because of this, the robot cannot move forward.

From Fig.3 and 4, when k is 3.9 N/mm , the proposed sensor module can maintain the footpad in a specific posture during stance. In this study, we determine that 3.9 N/mm is the appropriate stiffness for MP joints, and we used this parameter in the following experiments.

3.2 Vertical and horizontal components of GRF

Figure 5 shows the comparison of the sensor value whose unit is [nH] [4] and the variations of vertical and horizontal components of GRF (F_z and F_x) whose unit is [N] during one step. We applied a low-pass filter with a cutoff frequency of 20 Hz to F_z and F_x.

Figure 5(a) shows the variation of F_z. To assess the estimation ability of F_z based on the sensor values, we define the period when the sensor values exceed the threshold value (2.0 nH in this paper) as the gray area. The gray areas correspond approximately to the period when F_z is positive. On the other hand, in Fig. 5(a), there is a period when F_z is positive before and after the gray area. One possible reason is that only the toe was grounded and the GRF was not applied to the force sensor placed the middle part of the footpad. These results indicate that the proposed sensor module can estimate the tendency of the vertical component of GRF, while the footpad is on the ground.

Figure 5(b) shows the variation of F_x. To assess the estimation ability of F_x based on the sensor values, we define the period when the sensor values fall below the threshold value (-3.0 nH in this paper) as the gray area. In this period, we can detect the negative peak at landing, i.e. the braking force. Moreover, both variation show the positive values in the mid-stance phase. These results indicate that the sensor values and F_x show the same tendency.

However, there are periods when there are error between the sensor values and both components of GRF. One possible reason is the stiffness of MP joint. In order to eliminate this error, it is necessary to search for a more appropriate stiffness for MP joint in the future.

4 Conclusion

In this study, aiming to apply the vertical and horizontal components of GRF for control of legged robot, we developed a foot sensor module with elastic MP joint and a musculoskeletal legged robot equipped with this module. By appropriately designing the stiffness of MP joints, we could maintain the footpad in a specific posture during the stance phase. As a result, we could estimate the tendency of vertical and horizontal components of GRF applied to the foot without estimating the posture of the foot.

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