Bio-inspired Musculoskeletal Robotics Foot with Toe Joint and Plantar Intrinsic Muscle in Tiptoe Motion

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1 Introduction

The human foot is a remarkable structure that combines biomechanical efficiency with exceptional adaptability, through the coordination of several components, including the toe joint and the plantar intrinsic muscle (PIM). The toe joint provides the necessary flexibility and range of motion to enable the foot to perform various tasks with heel-off posture [1]. Meanwhile, the plantar intrinsic muscle, located in the sole, allows for dynamic adjustments to the foot's shape, actively changing the foot stiffness [2], enhancing push-off force [3], improving athletic performance [4], or improving foot stability [5]. As a result, these structures of the human foot contribute to the adaptability, that is outstanding in bipedal locomotion, allowing us to move efficiently and effectively in various environments.

This study presents the consequences of changing the stiffness of the toe joint at different timing in the tiptoe motion, which is the most fundamental motion involving heel-off posture, by controlling the plantar intrinsic tension force with PIM made of pneumatic artificial muscles (PAMs).

2 Robotics Foot with Plantar Intrinsic Muscle

The design of the musculoskeletal robotics foot has the purpose to enhance the functionality and performance of feet with its biomechanical features. The robotics foot with plantar intrinsic muscles (see Figure 1) made of PAMs were designed to mimic the natural functioning of human muscles. These muscles working along with the flexibility of the toe joint, have been studied to find their contributions to aid push-off and help improve forefoot stability. The PAMs allow feed-forward control to manipulate the stiffness of the toe joint by controlling torque and tension force, which is crucial for executing motion and maintaining stability.

3 Relationship between Plantar Intrinsic Muscle, Torque, and Activation Time

3.1 Torque Generation from Activation of PIM

Other than the activation of the soleus muscle (SOL) causing the tiptoe motion, the plantar intrinsic muscle will also activate in response to the tiptoe motion. The torque generate from PIM (τ_{PIM}) has two ends; the heel-end and the toe-end (see Figure 2).

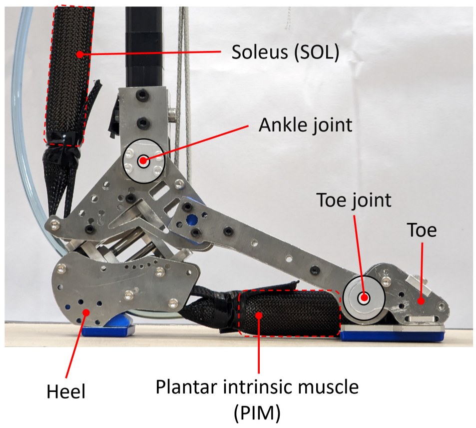

Figure 1: The musculoskeletal robotics foot with two DOFs (ankle and toe joint) have two PAMs (SOL and PIM) to activate the joints during the tiptoe motion experiment.

While τ_{PIM} on the heel-end could suppress torque generated from SOL (τ_{SOL}), it could also generate push-off force to enhance the push-off on the toe-end. Therefore, if timed correctly, the PIM could be used as either a suppressor or an enhancer of distal foot movement.

3.2 Activation Time of Plantar Intrinsic Muscle

In a dynamic motion, the impulsive force generated from PAMs will be affected by various factors such as; gravity and inertia. The addition of the plantar intrinsic tension force of PIM into the motion could also change the behavior of the overall motion. As a result, the activation timing of PIM should have different outcomes for the motion.

4 Experiment and Result

In the experiments, a 9-axis IMU (BWT901CL) was installed on the toe to measure toe-lifting angle θ_T, and a force

Table 1: Activating conditions of PIM in response to SOL used in the experiment.

1	Active (fast)	0 msec after SOL
2	Active (slow)	100 msec after SOL
3	Passive	Always supply

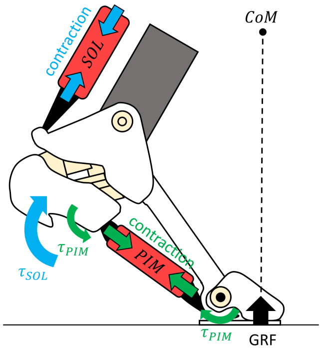

Figure 2: The tiptoe foot posture and the torque τ_{SOL} and τ_{PIM}, generate from the muscle contraction force by SOL and PIM, respectively, with ground reaction force (GRF) between toe and ground.

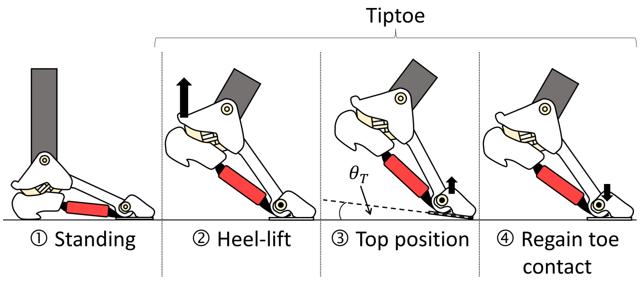

Figure 3: The tiptoe motion from; standing position, heel-lifting, reaching top position (with toe-lifting angle θ_T), to regaining toe contact as each curve represents in Figure 4.

plate (TF-3040) was placed under both of the robot feet to collect the GRF data. In this study, the various PIM activating conditions in response to the activation of SOL executing the tiptoe motion used in the experiment are shown in Table 1. While the passive PIM indicates a fixed amount of air pressure supplied to the muscle prior to the tiptoe motion.

The robot was able to realize tiptoe motion in a short duration, which we separate into four different phases as described in Figure 3. Figure 4 shows the changes in the GRF curves, where the active PIM reduced the GRF curve, which was clearly shown in the faster activation of PIM. Comparing the maximum θ_T in Figure 5, the slow-activating PIM (middle) performs a better foot contact to the ground, compared to the faster activation of PIM (left) which seems to over-actuated toe joint, while the passive PIM (right) is underactuated, causing less consistent data.

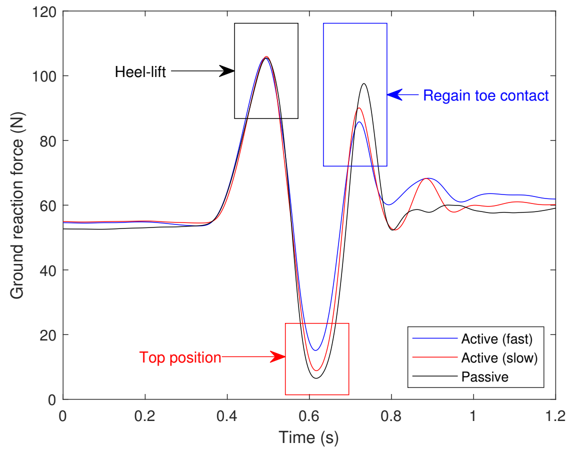

Figure 4: The ground reaction force.

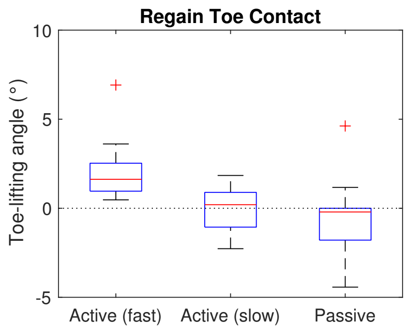

Figure 5: The maximum θ_T during the regaining toe contact phase.

5 Conclusion

The PIM activates in different time duration will affect the motion differently. The faster activation of PIM is shown to suppress the GRF curve into a more steady curve, possibly cause due to the antagonistic torque τ_{PIM}, generates around the ankle joint by PIM, activating simultaneously with τ_{SOL} similar to the capability to deaccelerate the motion of the muscle. Meanwhile, the slow activating PIM shows a more stable θ_T during the regaining toe contact phase might indicate improved forefoot stability adapting to the ground.

In the future, the activation of PIM right after the robot reaches the top position could be realized to study the enhancing push-off force of the toe in tiptoe motion.

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