Promoted Propulsion by Foot Windlass Mechanism in Jumping

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1 Introduction

As a result of millions of years of evolution, the modern human feet have unique and complicated structure compared to our primate relatives [1]. This unique configuration has been widely supposed to contribute to the bipedalism of modern humans [1]. A well-known feature of the modern human feet is the windlass mechanism [2] that includes plantar fascia, medial longitudinal arch, and metatarsophalangeal joints. In toe-off motion, the plantar fascia is stretched thus can pull the calcaneus towards the metatarsal heads [2] [3] [4]. Evidences from fossils suggested that this mechanism emerged in the past millions of years [5] [4], corresponding to the period when ancient human obtained the ability of durable bipedal locomotion [6]. Through the implementation of experiments on humans, several studies have focused on tendons and demonstrated that the elastic tendons contribute to restore and return the energy during stance phase (e.g. [7]). However, little attentions have been paid to the effects of the foot windlass mechanism on active power output.

We hypothesize that the foot windlass mechanism contribute to the active power output in push-off. In the toe-off motion, the plantar fascia is stretched and the tension is increased [8]. This is transferred to the Achilles tendon [2]. It may decrease the contracting velocity of muscles (e.g. triceps surae muscles, including soleus and gastrocnemius) attaching to the Achilles tendon. By considering that a decrease in contracting velocity of a muscle increases its force output [9] (this feature is also present in pneumatic artificial muscles [10]). Therefore, the foot windlass mechanism may promote the tension of triceps surae muscles. Additionally, this phenomenon may influence the propulsion of push-off.

2 Method

In our investigation, we constructed a bio-inspired biped robot with a musculoskeletal body that similar to a human (shown in Fig.1). We also developed a pair of biomimetic feet consists of the phalanges bones, long plantar ligament, metatarsals bones, calcaneus bones and plantar fascia as shown in Fig. 2 by the consideration of physiological studies [2] [3] [4] [8]. This robotic platform allowed us systematically evaluate the effects of windlass mechanism in jumping. Squat jumping experiments were implemented, since squat jumping includes a representative push-off motion. We compared the performance with (WM case) and without (NONE case, by removing the plantar fascia) the foot windlass mechanism. During the experiments, we measured the robotic behaviours such as the joint angles (one jumping trial of each case), force output of triceps surae, ground reaction force, and jumping height (17 jumping trials of each case).

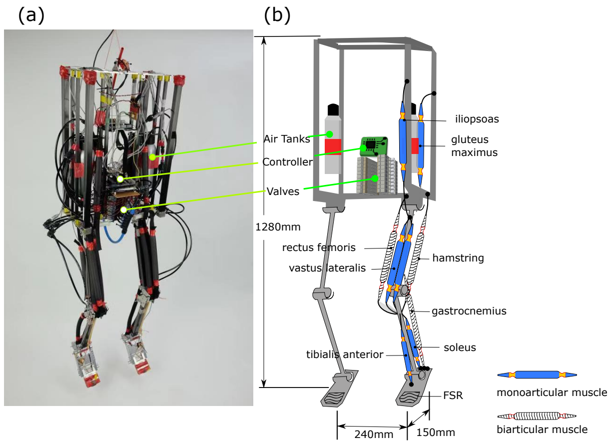

Figure 1: (a) Photo of the robot. (b) The musculoskeletal robot and its equipments.

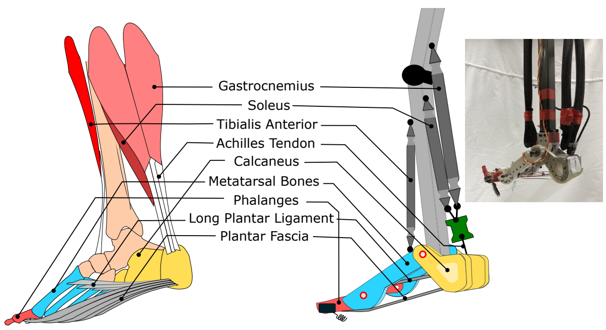

Figure 2: The bio-mimetic foot contains three major bones in human foot, including phalanges, metatarsal, and calcaneus. A artificial plantar fascia connects the phalanges and calcaneus.

3 Results

The results demonstrate that with the windlass mechanism (WM case), the longitudinal arch raises in the end of push-off phase, and the contracting velocity of triceps surae

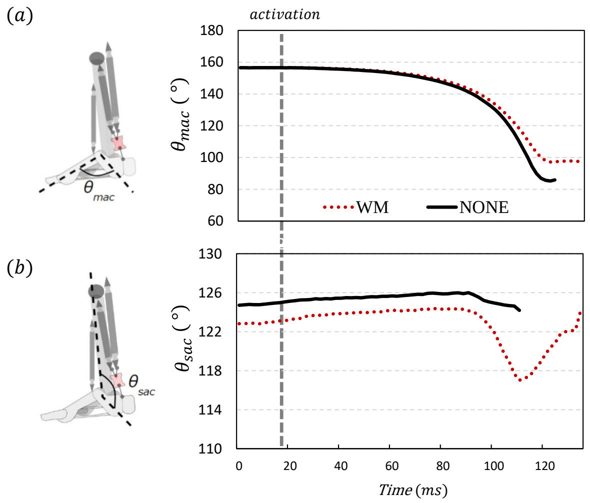

Figure 3: Kinematic behaviour of selected trials from WM and NONE cases. (a) angle of metatarsal–ankle-calcaneus (θ_{mac}), and (b) angle of shank–ankle-calcaneus (θ_{sac}). In (a), compared to the NONE case, the WM case displays a decrement of θ_{mac} and indicates the raise of longitudinal arch in the end of push-off phase. In (b), the WM case shows a inhibited rotation of θ_{sac} and suggests that the decreased contraction of triceps surae.

muscles decreases compared to NONE case (shown in Fig. 3). Moreover, the force output of triceps surae muscles and ground reaction force get increased in the end of push-off phase by the windlass mechanism and displayed in Fig. 4(a) and (b). Finally, the WM case demonstrates increased jumping height compared to NONE case in Fig. 4(c).

4 Disscussion

Physiological studies have widely identified the kinematic effects of foot windlass mechanism in locomotion [2] [4]. Similar to these studies, we observed that the dorsiflexion of phalanges pulled the calcaneus towards the metatarsal heads and activated the windlass mechanism in jumping and shown in Fig. 3(a). A step further, in Fig. 3(b) we confirmed that the foot windlass mechanism inhibited the contraction of triceps surae muscles in the end of push-off phase. Then, we measured the tension of triceps surae muscles in Fig. 4(a) and demonstrated that the foot windlass mechanism promoted the force output of these muscles. In Fig. 4(b) and (c), we observed that the GRF and jumping height also get promoted in the end of push-off phase. Our results suggests that the foot windlass mechanism contribute to promote the active force output of triceps surae muscles and the generation mechanical energy in push-off.

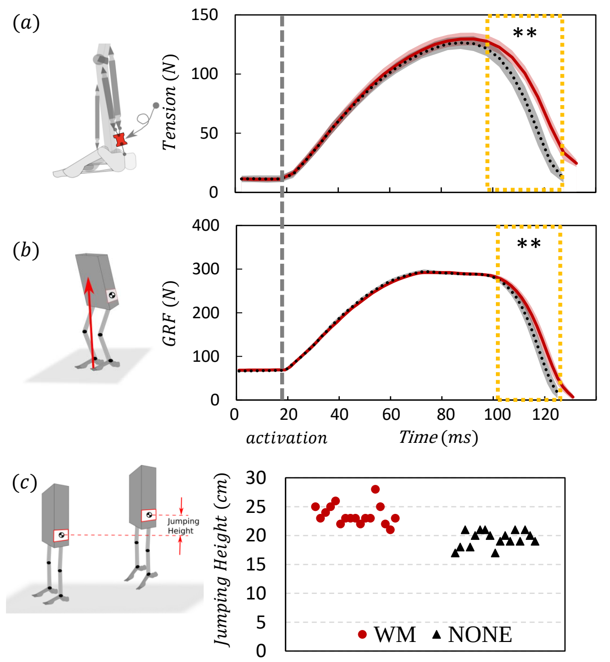

Figure 4: Comparisons of (a) force output of triceps surae muscles, (b) ground reaction force, and (c) jumping height from 17 trials from both WM and NONE cases. Compared to the NONE case, the WM case demonstrates promoted force output of triceps surae muscles, and ground reaction force in the end of push-off phase. Moreover, the WM case behaves higher jumping than NONE case.

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