Human-like bipedal robot achieves fast walking gait with mono- and biarticular spring-tendon powered ankle push-off

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1 Introduction

Human bipedal walking is unique in its high efficiency, mobility, and robustness. Current robots and prostheses fall behind human performance due to the missing understanding of human leg biomechanics and control. Impulsive ankle push-off is assumed to be a key event contributing to the high efficiency of human walking. Hof et al., described first how in human walking, the slow energy storage phase is followed by the snap release of energy at the ankle joint in the late stance phase [1] which makes the human leg comparable to a catapult [2]. The observed ankle power peak during push-off is higher than the peak power that the plantar flexor muscles are able to produce [2–4]. The surplus power indicates that additional passive structures store elastic energy during stance that is released and transformed into kinetic energy at ankle push-off [1, 5], which accelerates the stance leg into swing [2]. The three main mechanical components of a catapult are: an elastic element, a block, and a catch with or without escapement. Distinguishing the functional elements of the catapult is challenging due to the convoluted mechanics of the thigh-shank-foot segment chain and the muscle-tendon units (MTUs) spanning the ankle joint. The Achilles tendon, attached to the Soleus (SOL) and Gastrocnemius (GAS) muscles, stores elastic energy during stance and rapidly releases that energy during push-off [3, 4, 6, 7]. The catapult's block is made up of the human foot and the ground. The catapult's catch has not been identified in the human leg yet.

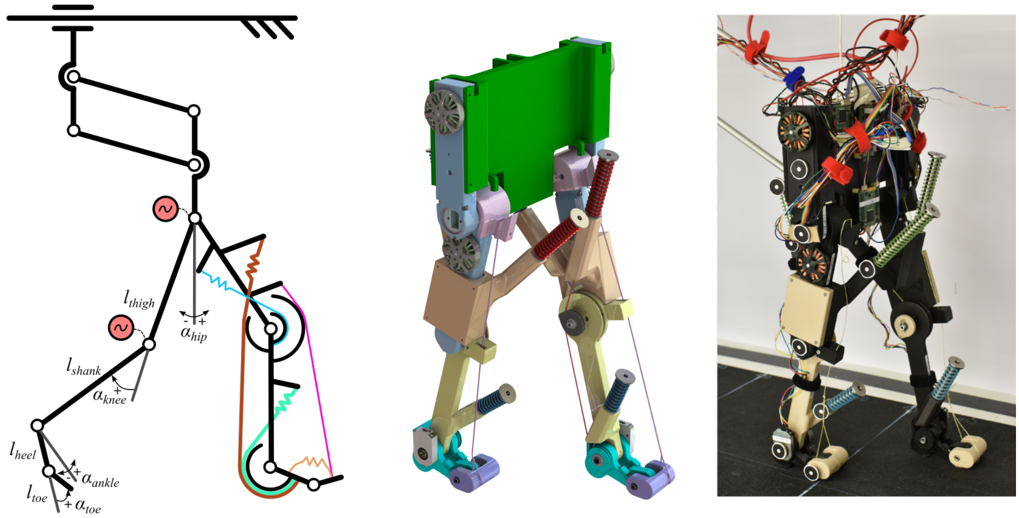
The utilization of the released energy, i.e., the catapult's function, is still open for discussion. In one approach, where the knee joint's buckling just before push-off is not taken into account, the center of mass velocity is redirected by the push-off work of the trailing leg, which in turn reduces the collision losses of the leading leg during touch-down [8]. This view is strengthened by a study where it was shown that positive mechanical push-off work around the ankle increases nearly linearly with an added mass at the center of mass [9]. Yet with another approach, where the knee joint can buckle before push-off, it was shown that only a portion of the push-off energy is transferred to the trunk to redirect the center of mass velocity, and the rest of the energy could rather power the swing of the trailing leg [2]. The biarticular GAS MTU could have a different function from the monoarticular SOL MTU, as parts of the elastic element of the catapult. Before our study [10], the exact role and function of plantarflexor spring-tendons as part of the swing leg catapult during walking was not studied in robots. Functional understanding of the swing leg catapult and its components will help to increase the efficiency of walking for legged robots and could help to improve gait rehabilitation devices and prostheses.

2 Methods

An anthropomorphic bipedal robot representing the lower limbs, the size of a small child, was used for the experiments. The robot's hip and knee joints were actuated and controlled by open-loop central pattern generators [11]. The control patterns follow anthropomorphic joint trajectories [12]. The robot's ankle joints were not actuated. Further details on the robot design, control and experimental setup can be found in our previous study [10].

3 Results and Conclusion

We showed that the monoarticular SOL MTU has a different function from the biarticular GAS MTU as the elastic elements of the human leg catapult [10]. Specifically, we showed that the SOL spring-tendon provided ankle power amplification, presumably allowing lower cost of transport and higher walking speed. The GAS spring-tendon could have a role in the movement coordination between ankle and knee joints during push-off.



(a) (b) (c)

Figure 1: a) Schematic of the robot with spring-tendon routing. For segment length and weight ratios see [10]. b) Rendering of the bipedal robot. c) Picture of the bipedal robot. The robot's trunk can only translate in the sagittal plane, and the trunk is fixed against all rotations. The four-bar guide slides freely forward and backward. (Figure modified from [10])

4 Future plans and research questions

Actuated hip and knee joints were used in our previous study [10] to disengage the human leg catapult's elastic elements. However, to reach natural human swing leg dynamics, actuated catapult disengagement might not be necessary. We are currently working on our hypothesis that natural swing leg motion could be reached without active knee flexion in push-off and swing. We would like to take the opportunity to discuss these research questions with the AMAM community: Is active knee flexion needed for push-off and swing? What impact does minimal knee activation during push-off and swing have on gait parameters? What is the role of the feet [13] in the human leg catapult disengagement?

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