Locomotor sub-functions for design and control of locomotion

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1 Introduction

In this study we focus on bio-inspired legged locomotion concepts. A primary goal of comparative biomechanics is to understand the fundamental physics of locomotion within an evolutionary context. Such an understanding of legged locmotion results in a transition from copying nature to borrowing strategies for interacting with the physical world in design and control of bio-inspired legged robots or robotic assistive devices. Inspired from nature, legged locomotion can be composed of three locomotion sub-functions which are intrinsically interrelated: **Stance**: redirecting the center of mass by exerting forces on the ground. **Swing**: cycling the legs between ground contacts. **Balance**: maintaining body posture.

With these three sub-functions, one can understand, design and control legged locomotion with formulating them in simpler separated tasks. Coordination between locomotion subfunctions in a harmonized manner looks as an additional problem which is absent while considering legged locomotion as one (more complex) problem. However, Biological locomotors show that appropriate design and control of each subfunction prevents suffering from complex coordination step.

2 Methods

Our separate treatment of locomotion sub-functions allows interrogation of key functional features at each of level of legged locomotion (mechanics, actuation, sensing and control). Let's first describe locomotion sub-functions and their relation. Stance function describes the repulsive function of the stance leg (in contact with the ground) to counteract gravity. Leg swinging is mainly a rotational movement combined with a complementing axial leg movement to avoid foot scuffing on the ground. Because a major part of the body mass is located at the upper body, the human body is an inherently unstable system unless a controller is continuously keeping balance. Therefore, balancing or body posture control is considered to be a third locomotion sub-function required to accomplish stable gaits especially in bipeds.

Template models [10] which have a high level of abstraction provide a very useful tool to understand how these subfunctions are controlled and coordinated, in both nature [1] and legged robots [11]. For stable legged locomotion, control architecture is required to employ the locomotion concepts. Hence, we need to know the corresponding control concepts and how to learn from biology to simplify control.

Based on realizing legged locomotion with the aforementioned trilogy, we have investigated different bioinspired control approaches on human experimental data, conceptual models and finally robots and exoskeletons. Applied methods and the test cases are described in the next section. In summary, we have developed the following analysis and control approaches for different locomotion sub-functions:

Stance: (1) Mimicking leg elastic behavior using SLIP model [6, 5] e.g., implemented by VMC (Virual model control) (2) energy transferring by biarticular muscles [7]

Swing: (1)VBLA (Velocity based leg adjustment) [6, 8], (2) spring (muscle) equipped pendulum-like swing leg behaviour, with biarticular muscle [9, 7]

Balance: FMCH (force modulated compliant hip) model (1) to describe human gaits [13] (2) modeling [12] (3) implementation on robot and exoskeleton [7, 3]

In [13], we have considered all sub-function in human walking and analyzed how they contribute to walking speed.

3 Results

For stance leg control, our template model is SLIP for bouncy gaits, such as hopping and running. In [5], we have implemented the SLIP-based stance leg control on MARCO-Hopper-II robot to mimic human like vertical hopping. VMC and energy-management were two approaches to implement this control strategy. Similar features were found between human hopping, the robot model and the hardware setup.

In [6], the same approach was implemented on the detailed simulation model of BioBiped robot for forward hopping. In addition to apply VMC for SLIP-based control of the stance leg, we employed the VBLA [8] for swing leg adjustment. Stable forward hopping was achieved with this combination of two sub-functions while the upper body was balanced using mechanical constraints.

For swing leg control, in addition to VBLA which gives the desired leg angle based on the CoM velocity vector and the desired speed, we have developed other pendulum-based swing leg control models [9]. Here, the swing leg is modeled by a regular pendulum, but without additional torques (e.g., produced by muscles) it cannot generate stable gait. In [9], we have considered a double pendulum equipped with biarticular hip muscles (rectus femoris and hamstrings). It was shown that stable walking can be achieved without energy consumption for leg swinging. Using SLIP for modeling the stance leg, we have shown that appropriate tuning of the rest lengths are the only parameters required for swing leg adjustment. Fig. 2 illustrates similarity between muscle force patterns of the model and human subjects. In [7], the same control approach was successfully implemented on BioBiped model for

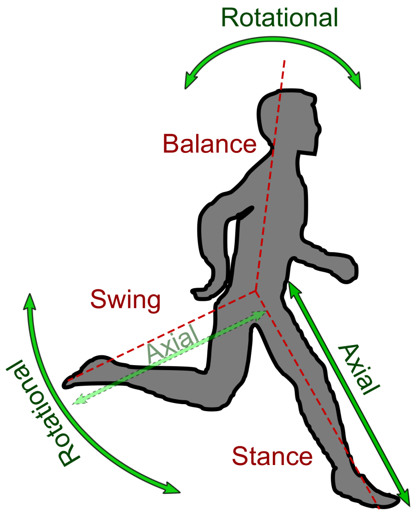

Figure 1: Main locomotion sub-functions; i) axial stance leg function, ii) rotational swing leg function and iii) balance for maintaining posture.

forward hopping instead of VBLA.

Based on the bioinspired VPP (virtual pivot point) concept, introduced in [4], we have developed the FMCH model, in which adaptable hip springs are considered for balancing while the spring stiffness is modulated by leg force. We have shown that this control approach results in VPP using conceptual models [12]. In [13], hip torques in single support of human walking at different speeds were predicted by this model with sufficiently high precision. Finally, in a new experiment we have implemented the FMCH-based controller on a lower-extremity powered exoskeleton (LOPES II) and demonstrated that it can effectively assist humans during walking [3]. In addition to reduction in different muscle activities, the oxygen consumption is reduced by 11%.

4 Conclusion and future work

In this paper, we have presented a short summary of different studies preformed based on the concept of dividing legged locomotion to three sub-functions. Modeling and control of legged locomotion suffer from nonlinearity, hybrid dynamics, uncertainties, dynamic coupling, etc. Splitting this complex problem to smaller sub-problems, helps better understand, design and control legged locomotion. We have supported this hypothesis by several studies resulting in (i) acceptable prediction of different features in human gaits, (ii) stability analysis of the developed models and (iii) successful implementation on hardware setups such as BioBiped, MARCO-Hopper-II and LOPES. We believe that this can be a useful tool for simplification of the complicated legged locomotion problem.

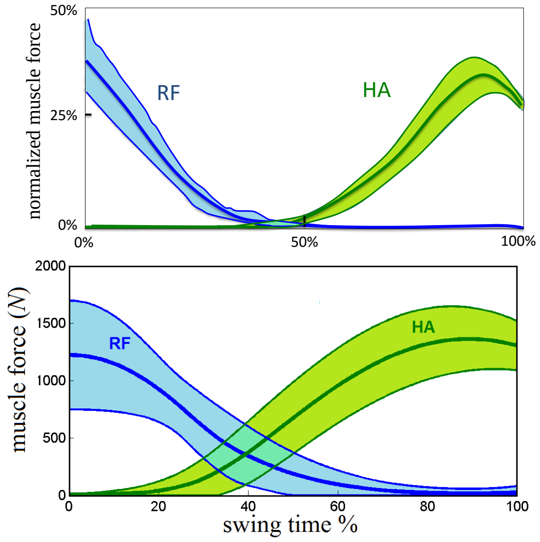

Figure 2: Biarticular thigh muscle forces during swing phase of walking (top) at speed 1.8 m/s of human experiment (data adopted from [2]) (bottom) at speed 1.55 m/s of stable simulations with different combinations of rest length and stiffness for RF and HAM. The mean values and standard deviation are shown with solid and thin lines, respectively.

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