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The need for a common taxonomy and benchmarks to achieve "human-like" performance in bipedal robot locomotion

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***Abstract*— A common taxonomy for the term "human-like locomotion" is essential to enhance the progress in the field of bipedal robot locomotion. In literature widespread use of this term can be found implying that human motion is optimal and worthy of imitation. However, a common basic understanding of the fundamental principles and characteristics of human locomotion is yet to be completed. In this talk we review various interpretations of this term in the literature and elaborate briefly on the most relevant characteristics of human motion trajectories. Further, essential methods from modeling and simulation to locomotion performance evaluation are discussed. We present a possible definition for "human-like locomotion" and a general concept for a better comparability of human and robot locomotion performance. The expressed ideas are supported by interim results obtained within the BioBiped project.**

I. The Importance of a Common Taxonomy for the Term "Human-like Locomotion"

Achieving bipedal robot locomotion performance that comes close to that of the biological counterpart is still a major and challenging research topic in the field of humanoid robotics which is not only due to the complexity of the problem requiring the know-how from various disciplines. Rather, a common taxonomy for the term "human-like locomotion" is missing. Today we have a wealth of different concepts for the actuation and motion control of humanoid robots and different views for the locomotion performance evaluation without a generally accepted understanding of the neuromechanics and core functionality underlying human locomotion.

The overwhelming majority of authors take a general but not rigorously specified understanding of "human-like locomotion" for granted, but in fact it is associated with very individual interpretations and definitions. A common taxonomy is expected to enormously enhance the progress in the field of bipedal robot locomotion and allow a better and valid comparability of results among the different research groups.

II. Literature Review

The overwhelming majority of authors take a general understanding of "human-like locomotion" for granted and do not even attempt to explain the use of this term in their papers. Some exemplary uses are as follows. In [1] snapshots of the robot motion sequence are presented and the robot model's and author's step frequency are compared to assess the human-likeness.

Visual comparison of snapshots is a popular tool also in [2], accompanied by statements such as: "The periodic running motion looks very natural, (compare the corresponding animation at our website)". Also, biomechanical gait characteristics such as duty factor, step length, ground reaction forces (GRF) and the vertical center of mass (COM) trajectories are computed and compared to those known from a human.

In addition to the GRF and COM trajectories, sagittal joint angle histories obtained from the simulation and real robot model are compared to human joint kinematics in [3]. Self-stabilization of a gait is seen as a further important property of human locomotion.

Also, walking with stretched knees and heel-contact and toe-off are considered as important characteristics of human walking [4]. As proof of concept it is shown that the GRF of the robot agree very well in pattern and peaks with those collected from a human subject.

In [5] the well known cost of transport is introduced as a measure to rate the degree of human-likeness. A robot walking at low cost of transport, like the Cornell biped, is regarded as quite "human-like".

For the authors of [6], a characteristic of "natural human-like motion" in general is the exploitation of the passive body dynamics.

These various interpretations suggest that a generally accepted catalog of all relevant characteristics of human locomotion and their measurement tools is an essential requirement for progress in the field of bipedal robot locomotion.

III. Key Characteristics of Human Locomotion

Human motion capture data offers a wealth of data ranging from GRF patterns to Electromyography (EMG) and kinematic data. Most of these data contain redundant information. For instance, the GRF not only provide information about the ground reaction patterns and impact forces. The GRF for walking and running have typically camel-back and single-hump pattern, respectively. The GRF let us also derive the course of the COM and consequently reveal the altitude difference of the COM. The COM and GRF data play an important role in biomechanics studies involving simple models such as the spring loaded inverted pendulum (SLIP) model. Analyses of the torque-angle courses or the leg's force-length curves are often applied by biomechanists to obtain a more detailed notion of the inherent so called global

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leg dynamics. A constant slope or almost constant slope in the leg force-length relation, which is also referred to as the leg's work loop, is regarded as linear stiffness [7]. Another biomechanical gait property is the duty factor that can be directly derived from the GRF. The duty factor, however, does not necessarily identify the corresponding gait type.

EMG data capture the electrical activity of skeletal muscles. But EMG data are not considered as reliable source of information to be used for realizing similar motions on robots, because it is not possible to estimate from EMG data the forces produced by the muscles.

Another very popular opportunity, often applied in robotics and graphics research, is given by the use of kinematic data.

The main questions to be answered by the biomechanics and robotics community are

- Which of all these reference data actually capture the core functionality of the human locomotor apparatus to be transferred to robots [8]?
- Further, how are the relevant features embodied and related to each other [8]?

IV. Methods and Challenges

The challenging problem of a missing taxonomy directly relates to the problem of benchmarks to compare different bipedal robots with respect to the overall and human locomotion performance. In order to answer the previously posed questions and approach the problem of achieving improved locomotion performance, a catalog of methods is necessary.

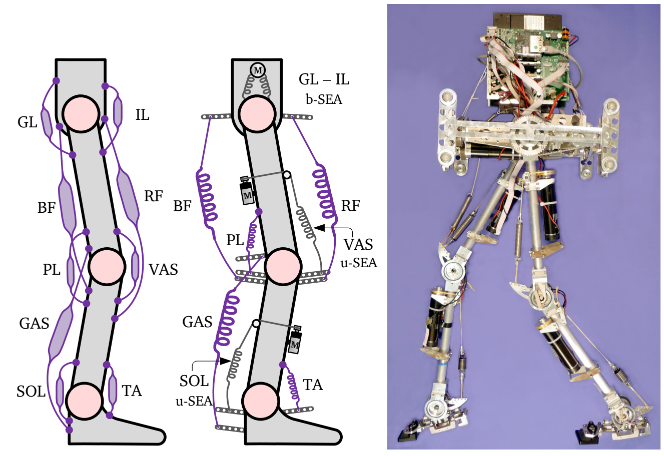
Modeling and simulation techniques are essential to represent both the human and robot platform. Here different levels of detail and the relations of these models need to be defined. The biomechanics community mainly uses conceptual models whereas the robotics community considers more complex segmented dynamics models on actuation level. Therefore, a central research question of high interest to both communities is how templates such as the SLIP relate to complex segmented legs actuated by muscles. It also needs to be ensured that the chosen template represents sufficiently well human locomotion behavior.

On the other hand, various criteria are necessary to evaluate the locomotion performance which can consist of several components. For example, the cost of transport serves only as criterion for the energy consumption. It can be used to rate human-likeness and to evaluate the motion performance among different robots. In general it is assumed that the importance of a criterion varies for different gaits. This also raises the question of the central locomotion capability.

Appropriate motion control methods and optimization or learning techniques are further essential tools to define a common taxonomy and benchmarks.

V. This Talk

Due to the open issues already outlined and the missing knowledge of the truly underlying mechanisms of human locomotion it can be agreed upon that it is still a long way to go before a motion can be claimed being human-like. Instead, the current goal should be to demonstrate improved



(a) (b) (c)

Fig. 1. Technical realization of BioBiped1's three-segmented leg actuation: (a) Main muscle groups in human legs. (b) Technical realization of the bi- and unidirectional elastic structures in the legs of BioBiped1. The passive structures in purple are detachable. (c) Real BioBiped1 platform.

locomotion performance and to present novel insights by studies in different related areas. In this talk we discuss the above questions in more details and highlight important relationships, such as that of the global to the internal leg function. The goal of the talk is to share and discuss our understanding of the term "human-like locomotion". In this context we also introduce the BioBiped project [9], [10] and the so far achieved milestones.

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