Role of Multibody Dynamics Based Simulation in Human, Robotic and Hybrid Locomotion Benchmarking*

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Abstract— **Multibody dynamics has provided methods for simulating vehicles and machines since the seventies, thus helping in the design of such systems as their behavior can be anticipated before having a physical prototype. Those methods can also be applied today to the study of locomotion, but different challenges arise depending on whether the system is human, robotic or hybrid. This work attempts to point out the challenges that must be faced in each case to carry out a simulation, and the advantages that can be obtained by exchanging results for the three types of systems.**

I. Introduction

Locomotion is a topic of great relevance in current research for a number of fields. For the medical sector, locomotion is both a mean for illness diagnosis, as long as illnesses may have effects on it, and an activity to be restored or improved in patients that lost mobility. For the robotic sector, locomotion is a key factor for the successful development of human-like robots, those expected to help humans in the next future. Moreover, there is a place where both sectors meet, i.e. the prosthetic and orthotic sector, characterized by robotic devices thought to rehabilitate and assist patients in their locomotion. Multibody dynamics based simulation can be a useful tool for the three mentioned sectors dealing with locomotion. In the next sections, particularities raising in each field to carry out simulations will be described, and benefits from cooperation among fields will be highlighted.

II. Human Locomotion

The human body can be considered a multibody system and, in principle, methods from multibody dynamics could be applied to study its motion in the same way that it is done for machines or vehicles. However, there is a main difference with them: the unknown nature of inputs. Indeed, the excitations sent by the central nervous system to muscles are not known, and this prevents from running forward dynamic simulations to predict the locomotion (or any other motion) of subjects. Anyway, multibody dynamics techniques are still applicable in the following two approaches:

A. *Real Motion Analysis*

The most popular use of multibody dynamics is the analysis of real motions. The motion at position level of some reflective markers placed on the subject is optically captured through synchronized cameras while the ground contact forces are measured by dynamometric plates. After appropriate signal processing, inverse dynamics can be applied to a model animated with the acquired motion, yielding as result the joint drive torques that generated it. However, there is a number of drawbacks related to this approach:

- The captured motion is noisy due to limited camera resolution and motion of reflective markers relative to the skin (skin motion artifact).
- The computational model of the human body to which the acquired motion is applied may be more or less detailed, being uncertain the values of geometrical and inertial data, as well as the exact locations of markers.
- The indeterminacy problem arising in the external reactions when there are two or more simultaneous contacts of the subject with the ground (double stance).
- When descending from joint to muscle level, muscle redundancy requires optimization to estimate forces, which entails uncertainty in cost function election, muscle origin and insertion points, muscle path, muscle model parameters, passive forces, etc.
- Lack of dynamic consistency, as each time instance is considered separately, so that muscular activation and contraction dynamics are not accounted for.

The last problem can be overcome if the real motion analysis is performed through forward dynamics instead of inverse dynamics. In this way, a true simulation is carried out, but the resulting motion is known. Therefore, it can be perceived as an intermediate step towards motion prediction, as the uncertainty is limited. Both optimization and control methods have been used. Control methods, more efficient, can adopt two forms: a) controllers in all the model degrees of freedom to track the acquired motion [1]; b) controllers in the actuated model degrees of freedom only [2], along with foot-ground contact models [3,4]. This second form is closer to reality, as the human body is an underactuated system.

B. *Motion Prediction*

The true simulation of human body motion is known as motion prediction, aimed at anticipating the locomotion (in this case) of a subject under some specific conditions, e.g. after a certain surgical intervention. This problem represents a great challenge, currently being a topic of intensive research. Methods developed so far, based on optimization, can be grouped as follows:

- Inverse dynamics based methods [5]. The design variables are the histories of model coordinates. The

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function evaluation implies the solution of the model inverse dynamics, which is computationally cheap.

- Forward dynamics based methods [6]. The design variables are the histories of forces, and the function evaluation implies the solution of the model forward dynamics, with a high computational cost. Many function evaluations risk to result in the fall of the model, due to the unstable character of gait.
- Predictive dynamics methods [7,8]. They aim to gather the positive aspects of the two previous ones by stating an optimization problem where both the motion and the forces are design variables, while the equations of motion are considered as constraints. The solution of the model forward dynamics at each iteration is avoided, thus reducing the computational cost. There is also a hybrid version [9] that employs a real motion as reference, imposing more or less convergence to it.

All the described methods are optimization based, which makes them very complex and leads to highly uncertain results. It would be strongly desirable to develop control based methods for gait prediction [10], for which progress in the understanding of the operation rules of the human nervous system during walking will be extremely valuable [11,12].

III. Robotic Locomotion

Humanoid robots are machines and, hence, unlike the case of humans, the inputs provided to them are perfectly known. Therefore, methods of multibody dynamics can be applied to simulate their motion as for any other machine [13]. However, practical difficulties can appear due to the unstable nature of gait and the use of foot-ground contact models.

IV. Hybrid Locomotion

This type of locomotion is the one of humans using robotic devices for rehabilitation or assistance purposes. Such devices are either prostheses, in the case of amputees, or orthoses, in the case of patients having suffered stroke, spinal cord injury or other illnesses or causes limiting their walking ability. In hybrid locomotion there are both known (robot) and unknown (human) inputs, and the interaction between them should be considered. Therefore, everything said for human locomotion is applicable here, with some additional difficulties arising, as the potential redundancy in actuation (human and robot), the uncertainty on disability modeling (actuation, cost function in optimization approaches), or the subject's evolution during the process of adaptation to the device.

V. Benefits From Comparison

Comparison of simulations of the three mentioned types of locomotion may be beneficial in several ways.

For humanoid robots, the obtained kinematic and kinetic magnitudes can be compared with those coming from the inverse dynamic analysis of human locomotion, so as to search for indicators of human-like walking. Also, controllers designed for humanoid locomotion can be compared with those proposed for human motion prediction, thus giving ideas to improve robotic controllers and a better understanding of the operation rules of the human nervous system.

For hybrid locomotion, kinematic and kinetic results from the inverse dynamic analysis of human locomotion can help in the design of prosthetic and orthotic controllers, as well as in the evaluation of devices and patients' adaptation to them. Moreover, if the motion analysis is carried out by forward dynamics, muscle dynamics can be considered too, and the interaction forces between subject and device can be estimated. Finally, motion prediction can be helpful to study the effect of modifications in the design and/or control of the devices on subjects' gait.

VI. Conclusion

Simulation of human, robotic and hybrid locomotion cannot be carried out in the same way for the three cases. However, multibody dynamics proposes methods to address each of them and, even if some of the methods should be improved to provide higher added value, current developments are useful tools in the particular fields and can streamline cooperation among them, thus contributing to their global progress.

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