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Challenges in the use of multibody dynamics for the study of human body motion in medical applications

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Abstract

The greatest contribution of multibody dynamics with respect to previous non-computer-based techniques, was to provide the ability of carrying out forward dynamic simulations of machines, mechanisms and vehicles. In the general case (presence of closed loops), writing the equations of motion of the mechanism was unfeasible, and even more was their time integration.

A good example of what has been mentioned is the application to the automotive field, one of the first and main boosters of multibody dynamics development. Having the option of running a simulation of the multibody model of a car provided enormous advantages to manufacturers for the design process. Initially, the inputs to the car (steering, throttle, brake) were introduced through functions or tables. Later, control algorithms were implemented to mimic human driving (smart drivers) and hardware peripherals (steering wheel and pedals) were included to enable real human driving (human-in-the-loop simulation). Multibody dynamics made it possible that the dynamic behavior of a car could be studied during the initial stages of the design process, being still far from having the first physical prototype.

Today, there is a growing interest in another application of multibody dynamics, i.e. the study of human motion dynamics, with practical impact in several sectors, like medical and sports. Focusing on the medical field, musculoskeletal surgery and orthoprosthetic design are examples of activities which could benefit from multibody dynamics.

Establishing a parallelism with the automotive case, since a car and the human body are both multibody systems, it could be expected to be able to run forward dynamic simulations of human exercises, e.g. gait, so as to anticipate the result of surgery, or to virtually test prosthetic or orthotic devices which only exist in digital form. This would undoubtedly provide as great advantages to surgeons and orthopedists (and, ultimately, to their patients) as those provided to car manufacturers many years ago. However, the forward dynamic simulation of human motion is not that simple as it is for a car, the reason being the unknown nature of the inputs in the human case. For example, it is not possible to simulate in a conventional way the gait of a healthy subject, even if a reasonably detailed computational model of the subject has been developed, since the excitations sent by the central nervous system to the subject’s muscles for him to walk are not known. One could think of developing a smart walker, similar to the smart driver for cars, but this time difficulty is many orders of magnitude greater.

Such a situation motivated that the use of multibody dynamics techniques for human motion followed a different path. From here on, the work focuses on gait, since the author landed in the biomechanical field due to a project devoted to the design of active knee-ankle-foot orthoses aimed at assisting the gait of spinal cord-injured subjects [1] and, hence, has mostly paid attention to walking activity. However, the content can be generalized to other motions.

Initially, inverse dynamics was the adopted approach [2]. The motion of the target subject was optically recorded, and applied to a subject’s computational model (geometry and inertia) the development of which is a first non-trivial challenge, so that an inverse dynamic analysis could be carried out to yield the external reactions (foot-ground force and moment) and the joint drive torques. The problem here is the indeterminacy in the external reactions when there is more than one simultaneous contact of the subject with the environment, e.g. during the double support phase for normal gait or in the assisted gait of disabled or elderly subjects (canes, crutches, etc.). Furthermore, when the forces exerted by the muscles are of interest, which is usually the case, not only because this information has intrinsic medical value but also because joint reactions cannot be determined unless muscle forces are calculated, an additional problem arises, since joints are overactuated by muscles and the force share is not uniquely determined.

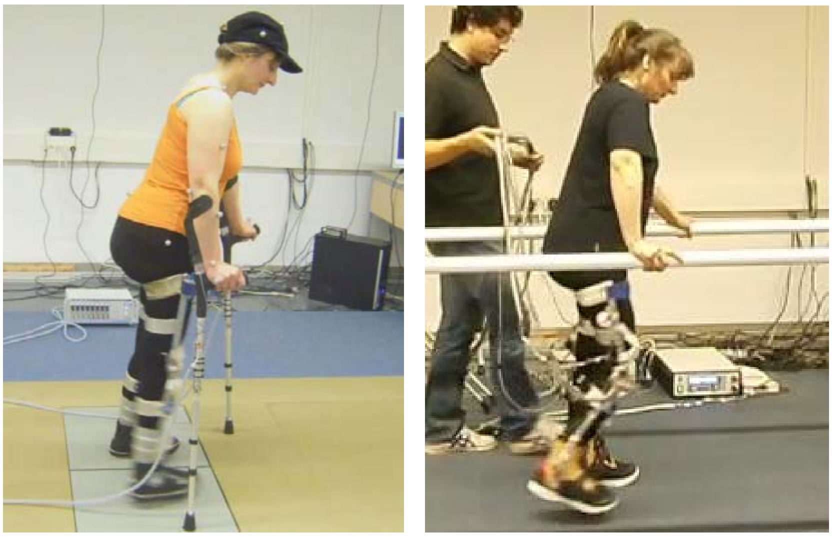

Figure 1: Passive (left) and active (right) knee-ankle-foot orthoses.

The inverse dynamics approach suffers from another drawback, which is the lack of dynamic consistency, since each time instant is considered separately. This is problematic when muscle action is taken into account, as muscle dynamics must not be ignored. The mentioned fact motivated the adoption of an alternative approach: the use of forward dynamics to analyze an optically recorded motion [3]. This approach can be addressed by means of optimization or control techniques. The control alternative is much more straightforward, since the equations of motion must be integrated in time only once, while in the optimization option they must be integrated at every iteration. Forward dynamics requires contact modeling, typically of the foot-ground interaction and of other possible contacts, like crutch-ground or orthosis-leg in disabled subjects. Although this represents an additional issue, it has also the advantage of providing contact forces as a result, which is not the case with inverse dynamics if more than one contact exists, as the accuracy of motion capture is not enough to derive contact forces from displacements.

And, finally, the problem of motion prediction was faced. The human motion community has relied on optimization techniques to address this problem through the three following basic approaches: the inverse dynamics approach [4], in which the parameters defining the motion are the design variables; the forward dynamics approach [5], in which the parameters defining the actuating forces (or any of their generating magnitudes as muscular excitations or muscular activations) are the design variables; and the so-called predictive dynamics approach [6], in which both the parameters defining the motion and the forces are the design variables, being related by the equations of motion that are considered as equality constraints of the optimization problem.

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