The HuMAnS toolbox, a homogenous framework for motion capture, analysis and simulation

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Abstract—**Primarily developed for research needs in humanoid robotics, the HuMAnS toolbox (for Humanoid Motion Analysis and Simulation) also includes a biomechanical model of a complete human body, and proposes a set of versatile tools for the modeling, the capture, the analysis and the simulation of human and humanoid motion. This set of tools is organized as a homogenous framework built on top of the numerical facilities of Scilab, a free generic scientific package, so as to allow genericity and versatility of use, in the hope to enable a new dialogue between direct and inverse dynamics, motion capture and simulation, all of this in a rich scientific software environment. Noticeably, this toolbox is an open-source software, distributed under the GPL License.**

Motion capture; Motion analysis; Dynamical simulation; Open-source software.

I. INTRODUCTION

Originally developed for humanoid robotics research, the HuMAnS toolbox (for Humanoid Motion Analysis and Simulation) proposes a wealth of state-of-the-art algorithms from the field of robotics research for the modeling, the analysis and the simulation of human and humanoid motion. These algorithms allow reconstructing efficiently a motion from measures given by multiple sensors. They allow as well simulating precisely human motion, with a muscle model specifically developed for the simulation and control of Functional Electric Stimulation [1], and with a specific emphasis on the precise simulation of the contact between the feet and the ground. They give access then to a variety of tools to analyze the kinematics, kinetics and dynamics of these reconstructed or simulated movements.

Most noticeably, this toolbox is developed on top of the rich (and free!) numerical analysis environment proposed by Scilab [2] (an open-source clone of Matlab™) and architected in order to propose a homogenous and versatile framework, with the idea to enable a new dialogue between direct and inverse dynamics, motion capture and simulation. It is proposed as an open-source software and distributed under the GNU General Public License in order to induce exterior contributions. Now, section II presents the general architecture of the toolbox, and the different dynamical models that it includes so far. Section III focuses then on its motion capture possibilities, presenting the optical sensors that have been modeled so far, and the possibilities for other motion sensors, together with a brief description of the corresponding numerical method for reconstructing a motion from their measures. Section IV is a brief introduction to the kinetic and dynamic analysis facilities, as well as to its simulation capacities, focusing especially on the problem of contacts between the feet and the ground. Section V offers finally a brief conclusion, opened towards the new uses that we hope such a versatile set of numerical tools may offer to the field of biomechanics.

II. PRESENTATION OF THE HUMANS TOOLBOX

A. *General architecture*

First of all, a set of Maple™ algorithms, based on state-of-the-art algorithms described in [3], have been designed to compute efficient analytical models of musculo-skeletal dynamics such as the one presented in the next section, of motion sensors such as the optical sensors discussed in section III.A, and of the different cinematic and kinetic values of interest to the users. These different analytical models are compiled as generic C functions, which are then linked and made available inside Scilab's rich numerical analysis environment.

These models can be interconnected and processed then with the help of Scilab's powerful numerical methods in order to propose in a homogenous framework both their simulation and their analysis. This allows for example capturing a motion from various sensors' measurements, reconstructing some unobserved physical values, and finally simulating additional virtual experiments fed with these different data. An example of such a new dialogue between analysis and simulation is presented in Fig. 1, where the walking pattern measured in [4] is executed by the biomechanical model presented in the next section, but in space, i.e. without gravity and contact forces: we can observe then a rotation of the body, expression of the non-holonomy effects in its dynamics [5] (the same effects that allow cats to always fall back on their legs). Of course, such virtual biomechanical experiments would be far much more costly to realize in real life.

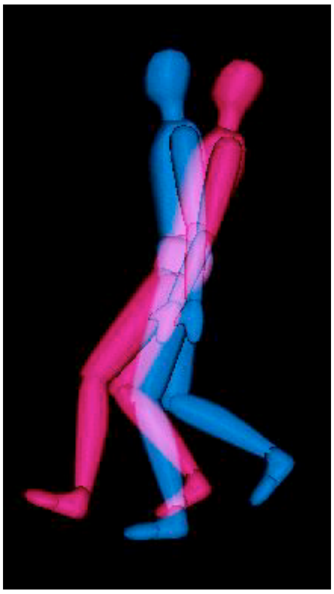

Figure 1. Rotation of the body when executing a walking pattern in space, i.e. without gravity and contact forces.

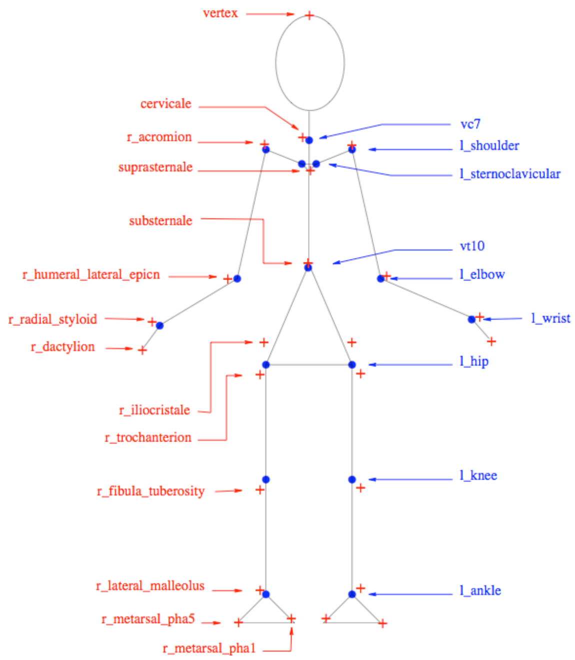

Figure 2. The biomechanical model included in the distribution of the HuMAnS toolbox proposes 16 joints (blue dots) for 36 degrees of freedom, and 24 canonical optical markers (red crosses).

B. The different dynamical models proposed so far

The musculo-skeletal dynamics are essentially split in the HuMAnS toolbox, between the dynamical behavior of the muscles on one side, and the "skeletal" dynamics of the body masses and joints on the other side. Of course, those two dynamics are closely interconnected, with forces generated by the muscles acting on joint movements, and joint movements stretching more or less the muscles in return. This separation allows however to develop independently new muscle models and new mechanical models of the body, interconnecting them at will later.

Since the HuMAnS toolbox has been primarily developed for humanoid robotics research, most of the models proposed so far in the distribution are models of humanoid robots [6], [7], with electric motor models instead of muscle models, but one biomechanical model of a complete human body is also included. This model proposes 16 joints, as shown in Fig. 2, representing 36 degrees of freedom (with 6 additional degrees of freedom for the translation and rotation of the whole body in space), with masses and lengths based on [8] and [9].

The only muscle model presently proposed in the HuMAnS toolbox is the model primarily developed for the simulation and control of Functional Electric Stimulation of paralyzed muscles in [1]:

$$\begin{cases} \dot{k}_c = -\left(|u| + |\dot{\varepsilon}_c|\right) k_c + \alpha\, k_0 |u|_+ \\ \dot{F}_c = -\left(|u| + |\dot{\varepsilon}_c|\right) F_c + \alpha\, F_0 |u|_+ + k_c\, L_{c0}\, \dot{\varepsilon}_c \\ \dot{F}_c = k_s \left(L_0\, \dot{\varepsilon} - L_{c0}\, \dot{\varepsilon}_c\right) \end{cases} \quad (1)$$

This model integrates the stiffness k of the muscles and the forces F they generate with respect to their length ε and the level of calcium ions u received by way of neural control. All details concerning this muscle model can be found in [1]

III. Motion Capture from Multiple Sensors

A. Optical sensors and other motion sensors

Optical sensors such as Vicon™ or OptoTrak™ devices sensors have been modeled in the HuMAnS toolbox, but as presented in section II.A, the toolbox provides algorithms to derive new models of motion sensors if necessary.

The optical sensors are supposed to give the 3D position of a set of markers attached to different parts of the body. Their output depends therefore solely on the position and orientation of the different joints of the body. Note that the biomechanical model included in the HuMAnS toolbox readily proposes 24 canonical markers, as shown in Fig. 2, which are sufficient to reconstruct completely the posture of the body.

B. The reconstruction process

We can observe that no subset of the optical markers presented in Fig. 2 allows to deduce directly and simply the position and orientation of any specific part of this biomechanical model. Yet, this whole set of markers allows to deduce the complete 3D posture of the body thanks to redundancy in the information present in this whole set of 3D positions.

The intelligent use of such redundancy in the sensors' measures can only be realized by a global approach, making use of all the knowledge available both in the measures and in the model (what degrees of freedom, oriented in which directions…). A simple way to do so is to represent the whole 3D reconstruction process as a general nonlinear least-squares problem. Powerful algorithms such as the FSQP algorithm [10] can efficiently solve such nonlinear problems and propose reliable reconstructions even when some of the measures are missing, for example because of occlusions. Even real-time treatment is not out of reach: prototypes have already been developed and successfully tested, though not included yet in the toolbox.

Such a generic way of treating the 3D reconstruction process in motion capture has proved to be extremely powerful and versatile since missing measures can be dealt with seamlessly, since measures from completely different sensors can be mixed very simply and efficiently, since additional knowledge concerning the motion being captured (canonical multi-segmental coordinations for example, or blocked degrees of freedom) can be introduced straightforwardly.

IV. ANALYSIS AND SIMULATION TOOLS

A. *Kinetics and dynamics*

The motion capture method described in the previous section can be completely derived with the only knowledge of the kinematics of the biomechanical model. But for the purpose of analyzing the motion previously captured or simulating new motions, the HuMAnS toolbox provides many more insights in this model, concerning especially its kinetics and dynamics.

With masses and lengths based on [8] and [9], the toolbox allows to compute kinetic and potential energies in a second, as well as contact forces or joint torques, or more simply the position of the center of mass of the whole body or only of parts of it. Following classical methods from the robotics research field, the complete "skeletal" dynamics of the biomechanical model (remember the distinction presented in section II.B) is represented in the HuMAnS toolbox as a Lagrangian dynamics:

$$M(q)\,\ddot{q} + N(q,\dot{q}) + G(q) = \begin{bmatrix}\tau\\0\end{bmatrix} + C(q)^T\lambda, \qquad (2)$$

where the vector q represents the orientation of the joints of the body, $\dot{q}$ and $\ddot{q}$ their speed and acceleration. The inertia matrix $M(q)$ gathers then in a compact form all the different inertias of the body, with $N(q,\dot{q})$ all the other inertial nonlinear effects (Coriolis and centrifugal forces), $G(q)$ the gravity effects, τ the joint torques generated by the muscles, and $C(q)^T\lambda$ the contact forces. More details on these different terms and how they interact can be found in [11] or in any general robotics textbook. All kinetic and dynamic computations can be based then on this single representation of the complete "skeletal" dynamics. In this framework, for example, the kinetic energy of the whole body would simply be:

$$\frac{1}{2}\,\dot{q}^T M(q)\,\dot{q}. \qquad (3)$$

B. *Unilateral contact forces and simulation of hybrid dynamics*

The computation of the contact forces $C(q)^T\lambda$ can be straightforward in the case of firm grasps: the set of equations (2) is augmented with additional equalities describing the grasp, and this augmented set of equations can be directly solved in order to compute the value of these forces [11]. But the case of contacts with the environment where one can push but can't pull is unfortunately not as straightforward: they can't be described correctly with equalities and need to be described with a complex set of inequalities and complementarity conditions that is generally referred to as a *unilateral contact* [12].

The combination of the set of equations (2) together with this set of inequalities and complementarity conditions takes the form of a Nonlinear Complementarity Problem that can be tricky to solve in the general case [12]. The HuMAnS toolbox is therefore specifically equipped with numerical methods dealing efficiently with this computation, the description of which would go far beyond the scope of this publication: more details on unilateral contacts and how to deal with them can be found then in [12].

Note that on top of the complexity of solely computing these unilateral contact forces, an additional difficulty arises in their evolution with time. Abrupt changes can be encountered each time such a unilateral contact is created or abandoned, for example each time a foot hits the ground or lifts off. This mix of continuous dynamics interlaced with instantaneous abrupt events can be seen as a form of *hybrid dynamics*. The HuMAnS toolbox proposes then a time-integration scheme specifically crafted to simulate precisely and efficiently such hybrid dynamics [13].

The point is that such unilateral contacts leading to hybrid dynamics represent the most usual form of contact between the feet and the ground: they can be observed therefore in almost every human activities. Dealing with them properly from a numerical point of view appears then as a mandatory condition for anybody interested in the numerical analysis of human motion. As we have seen throughout this section, the HuMAnS toolbox appears to be correctly equipped for such a task.

V. CONCLUSION

The HuMAnS toolbox offers tools for the modeling of the kinematics, kinetics and dynamics of human bodies, and for the numerical treatment of these models in motion capture, analysis and simulation. Originating in humanoid robotics research, all of its algorithms are specifically designed for a maximum of precision and efficiency. A specific emphasis of the toolbox architecture is to allow the user to connect the different numerical tools at will through the Scilab programming language, leading to powerful possibilities in mixing different phases of motion capture, analysis and simulation, a simple example of which has been shown in Fig.1. We hope this should allow a rich variety of uses in the future for this toolbox in the field of biomechanics.

A temporary drawback is that the only user interface available so far is at an expert level, implying a good knowledge of both the theory behind motion capture, analysis and simulation, and the technicalities of numerical software environments such as Scilab (similar to Matlab™). A more user-friendly interface is now under development.

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