

Human-like motion generation for a virtual manikin

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Abstract: An algorithm for both the *human-like* motion generation and the joint torques computation for a *virtual manikin* is addressed in this paper. This goal has been achieved using some techniques derived from robotics. In particular, the so-called *augmented Jacobian* has been used to solve the inverse kinematics problem with a single *closed loop inverse kinematics* algorithm. Furthermore, a position control for the center of mass of the kinematic chain, and for its projection on the support plane (*Center of Pressure*), has been implemented. Thus, the inverse kinematics can be solved taking into account the static balance of the manikin. Moreover, the proposed algorithm allows simulating quite complex tasks, which involve the motion of the whole manikin, by means of only few task-related control points. The resulting movements are quite natural even for complex tasks. Finally, the joint torques can be computed thanks to the kineto-statics duality: the results are in accordance with biomechanical analyses.

Key words: Virtual humanoid, Human-like motion generation, Kinematic control, Kineto-static duality, Low-back biomechanical analysis.

1- Introduction

Over the years, manufacturing companies have considered the man adaptability as a basic parameter of quality for their products; an increasing attention has been therefore devoted to ergonomic analyses, even from the early stage of design [DL1], [CD1], [CD2], [DP1].

In order to meet this demand, a great deal of research has been done for building a digital substitute of a human being in a virtual environment [M1], [D1] also for predicting human-product and human-process interaction. This has given birth to the digital human modeling (DHM) which led to the development of several software [SJ1], [MS1] whose main goal was to reproduce as closely as possible the human behavior.

These so-called *virtual manikins* are essentially kinematic chains consisting of several segments and joints. The lengths of segments, as well as the mass distribution, are derived from anthropometric databases, (e.g. [N2], [KS1]) which can be queried with respect to different percentiles in the population.

However, these software tools are generally too complicated to be handled. The human behaviour simulation often becomes a very time-consuming task, mainly because of the difficulty in controlling the kinematic chain of the virtual humanoid. In fact, the customary key-frame animation techniques generally can be very time demanding. In addition, the accuracy of the resulting simulations is strongly related to the experience of the operator. Even though these software tools implement the inverse kinematics (IK) algorithms, they generally manage only a limited number of links at time. From the above, it is clear that it would be very useful to have a software tool allowing simple kinematic control of the entire humanoid by means of only few control points.

The humanoid model proposed in this paper is deliberately simpler than others; in fact it has just 39 degrees of freedoms (DoFs) because the idea is to build a model which is simple to control while providing good results in terms of simulation.

The proposed algorithm, despite the simplicity of the kinematic structure of the humanoid, allows performing quite complex tasks by forcing physical constraints and some optimality criteria.

2- Kinematic modelling

The approach presented in this paper is based on the idea of controlling a highly redundant kinematic structure, such as a humanoid, by means of few control points which can move on its structure [DA1], [DP2], [DS1]. This goal has been achieved using the serial robots modelling techniques [DG1]. In fact, once determined an inertial base frame, the *Denavit-Hartenberg* (DH) method determines position and orientation of a frame attached to the control point. Usually, this control point is the end-effector. However, changing the value of some DH parameters in a proper sequence results in obtaining another kinematic equation of another manipulator whose end effector is located before the real one: that is equivalent to move the control point along the structure. The symbolic form determined for DH allows identifying an arbitrary point as a virtual end-effector of a smaller manipulator considered for the control. An arbitrary number

of such control points can be considered that can be fixed or moving.

Related to the humanoid, different kinematic chains will be considered. In addition, during the execution of certain tasks, the posture taken by humans largely depends on balancing and mechanical issues that are only partially related to the considered task. This implies the need for an additional posture control. For this purpose, the goal has been to develop an inverse kinematics algorithm with a limited number of task-related control points, without the need of specifying the DoFs of the chain for posture control.

The position of the center of mass (CoM) of the humanoid has then been taken into account: it is calculated on-line and always kept consistent with the balancing issues of the mechanical structure. In fact, the time-varying CoM is considered as an additional moving control point. It is worth noticing that the control points on the humanoid can be also selected automatically depending on the task and the environment, giving a very powerful tool for simulation. Moreover, in order to take advantage of the systematic approaches typical of serial robots, the humanoid has been modelled as the combination of four kinematic chains, which share the same starting point, called *root*.

In addition, describing the position and orientation of the humanoid with respect to an inertial frame is not immediate because, unlike serial robots, there is a variable configuration of constraint for the support plane, like, e.g., single support on one foot or double support on both feet. Such a kind of reference frame periodically changes during the walking, thus we apparently cannot identify a fixed base where the base frame for the DH method can be located (Figure 1). It can be seen as a so-called *free flying kinematic chain*. To overcome this problem the *virtual joints* approach has been used [Y1]. Namely, the virtual manikin has been conceived as connected to the ground plane through a virtual manipulator consisting of three prismatic and three revolute joints, which characterize its position and orientation. It is worth noticing that, obviously, the actuation torques (so that the static torques) would be always zero for the virtual joints because simply they “do not exist”.

With this approach, the hands and the feet (and even any other control point) are simply end-effectors that can be controlled with velocity references. The resulting model is the hierarchical structure shown in Figure 2.

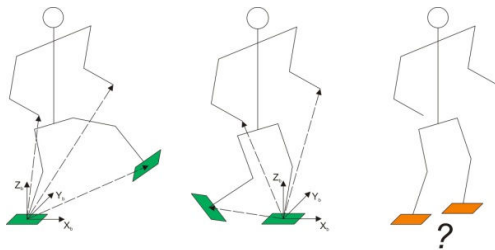


Figure 1: Which reference frame?

Starting from this graph, it is possible to build up the DH model of the whole kinematic chain (Figure 3). In particular, we can define a number of direct kinematic equations, with respect to the root reference frame. One or more control points on the provided chains can be selected, by considering the

proper set of DH parameters that specify such points. Thus, the considered kinematic structure has 39 DoFs in all. This kind of modelling has the advantage of simplicity, but generally it may cause a physical consistency problem, since some links (as well as all the virtual links) are shared among different kinematic chains.

For instance the “back” of the virtual humanoid is shared between its right and left arms. Some strategies have been adopted to avoid this problem. More in general, optimality criteria can be adopted for solving redundancy.

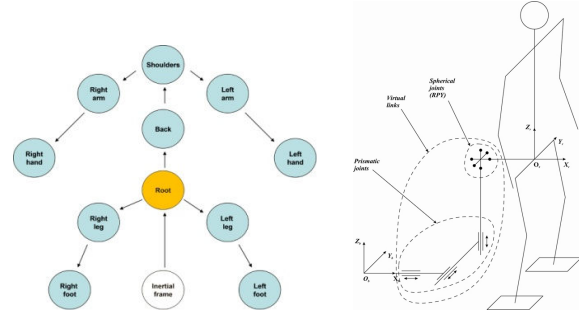


Figure 2: Hierarchical model of the virtual manikin (left) and virtual joints (right)

Moreover, the presence of multiple end-effectors (two hands and two feet and so on) implies the need to describe the position and orientation of many frames, differently from industrial robots, in which the kinematic chain has only one end-effector.

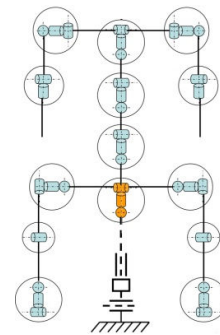


Figure 3: Kinematic structure of the virtual manikin

In other words, the posture of the virtual humanoid is completely specified by the following joint variables vector:

$$\mathbf{q} = [\mathbf{q}_r^T \quad q_1 \quad q_2 \quad \dots \quad q_n]^T \quad (2.1)$$

where $\mathbf{q}_r$ identifies the joints in the root.

Moreover, virtual joints technique makes unnecessary the management of closed kinematic chains, e.g. during the phase of double support. Indeed, this condition becomes merely equivalent, from a kinematic point of view, to imposing a null velocity reference to the feet. Each chain has its own kinematic function; therefore a Jacobian matrix can be computed for a generic control point of the structure. Generally, considering n control points we can define the following set of equations:

$$\begin{aligned} \mathbf{v}_1 &= \mathbf{J}_1 \dot{\mathbf{q}} \\ &\vdots \\ \mathbf{v}_i &= \mathbf{J}_i \dot{\mathbf{q}} \\ &\vdots \\ \mathbf{v}_n &= \mathbf{J}_n \dot{\mathbf{q}} \end{aligned} \quad (2.2)$$

where the generic element $\mathbf{J}_i$ is the Jacobian matrix related to a specific control point i . It is understood that, if the generic joint variable $\mathbf{q}_i$ does not affect $\mathbf{v}_i$, it is $(\mathbf{J}_i)_{kj}=0$ (where k is the generic row of $\mathbf{J}_i$). This set of equations can be summarized as

$$\mathbf{v} = \mathbf{J}_{AU} \dot{\mathbf{q}} \quad (2.3)$$

where $\mathbf{J}_{AU}$ is the so called *augmented Jacobian*. On one hand, this approach allows us to solve the IK problem with only one CLIK algorithm, i.e.,

$$\dot{\mathbf{q}} = \mathbf{W}^{-1} \mathbf{J}_{AU}^T \left(\mathbf{J}_{AU} \mathbf{W}^{-1} \mathbf{J}_{AU}^T \right)^{-1} \mathbf{v}_e \quad (2.4)$$

In particular, if $\mathbf{W}$ is the identity matrix

$$\dot{\mathbf{q}} = \mathbf{J}_{AU}^\dagger \mathbf{v} \quad (2.5)$$

where

$$\mathbf{J}_{AU}^\dagger = \mathbf{J}_{AU}^T \left(\mathbf{J}_{AU} \mathbf{J}_{AU}^T \right)^{-1} \quad (2.6)$$

is the so called *right pseudo-inverse* of $\mathbf{J}_{AU}$.

On the other hand, the trajectories defined for the control points will be all considered as tasks with the same priority (primary tasks), unlike other solution methods do, such as null-space based approaches [N1], [SS1].

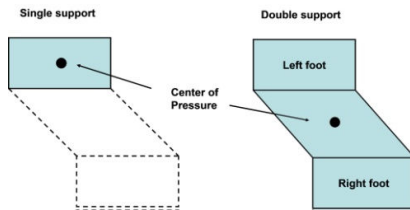


Figure 4: Support polygon

In particular, in order to define the structure of $\mathbf{J}_{AU}$, the joint velocities vector $\dot{\mathbf{q}}$ must be properly sorted. Since the humanoid structure is composed by four kinematic chains, we can write four different vectors of unknowns:

$$\begin{aligned} \dot{\mathbf{q}}_1 &= \begin{bmatrix} \dot{\mathbf{q}}_r^T & \dot{\mathbf{q}}_{rl}^T \end{bmatrix}^T & \text{right leg} \\ \dot{\mathbf{q}}_2 &= \begin{bmatrix} \dot{\mathbf{q}}_r^T & \dot{\mathbf{q}}_{ll}^T \end{bmatrix}^T & \text{left leg} \\ \dot{\mathbf{q}}_3 &= \begin{bmatrix} \dot{\mathbf{q}}_r^T & \dot{\mathbf{q}}_b^T & \dot{\mathbf{q}}_{ra}^T \end{bmatrix}^T & \text{right arm} \\ \dot{\mathbf{q}}_4 &= \begin{bmatrix} \dot{\mathbf{q}}_r^T & \dot{\mathbf{q}}_b^T & \dot{\mathbf{q}}_{la}^T \end{bmatrix}^T & \text{left arm} \end{aligned} \quad (2.7)$$

where $\dot{\mathbf{q}}_r$ is the vector of the virtual joint velocities that are shared among four kinematic chains. These vectors can be summarized in only one vector of unknowns

$$\begin{aligned} \mathbf{q} &= \begin{bmatrix} \mathbf{q}_r^T & \mathbf{q}_{rl}^T & \mathbf{q}_{ll}^T & \mathbf{q}_b^T & \mathbf{q}_{ra}^T & \mathbf{q}_{la}^T \end{bmatrix}^T \\ &= [\mathbf{q}_1 \quad \mathbf{q}_2 \quad \dots \quad \mathbf{q}_{39}]^T \end{aligned} \quad (2.8)$$

The matrix $\mathbf{J}_{AU}$, with the proposed humanoid model, has 39 columns, while the number of its rows depends on the number of considered control points. Unlike industrial manipulators and, more generally, non-legged robots, bipedal robots must explicitly address balance control while performing any task. If this does not happen, obviously, the robot would lean over and fall. Moreover, humanoid robots are inherently hyper-redundant, having a much higher number of joints than traditional industrial robots. Consequently, there are many postures that achieve the same position for its body terminals, corresponding to control points. Also, taking into account the balancing issues allows the humanoid to attain more natural postures, similar to those of human beings. For this, the proposed approach, with multiple Virtual End-Effectors (VEEs), has been implemented also with respect to the CoM of the digital humanoid, which becomes a further control point for the kinematic chain. In particular, the trajectory of the CoM can be defined in such a way that the center of pressure (CoP) belongs to the stability polygon formed by the feet (Figure 4). It is worth noticing that the constraint about the CoP will be treated as a primary task, as well as the other tasks. The basic idea is to obtain a differential relationship like

$$\mathbf{v}_G = \mathbf{J}_G \dot{\mathbf{q}} \quad (2.9)$$

where $\mathbf{J}_G$ is a $3 \times n$ matrix, called Center-of-Mass Jacobian. Then, Equation (2.9) will be inserted in the equations set (2.2) as a further control point. For this purpose, we can calculate the position of the CoM for a kinematic chain composed of n links as

$$\mathbf{p}_G = \frac{\sum_{i=1}^n m_i \mathbf{p}_{Gi}}{\sum_{i=1}^n m_i} \quad (2.10)$$

Deriving the equation (2.10) with respect of time we obtain the CoM's velocity

$$\mathbf{v}_G = \frac{\sum_{i=1}^n m_i \mathbf{v}_{Gi}}{\sum_{i=1}^n m_i} \quad (2.11)$$

Since the center of mass of each link can be considered as a VEE it is always possible to write the differential relationship

$$\mathbf{v}_{G_i} = \mathbf{J}_{G_i} \dot{\mathbf{q}} \quad (2.12)$$

where the Jacobian is

$$\mathbf{J}_{G_i} = \begin{bmatrix} \gamma_{x,1} & \cdots & \gamma_{z,1} & 0 & \cdots & 0 \\ \gamma_{y,1} & \cdots & \gamma_{z,1} & 0 & \cdots & 0 \\ \gamma_{z,1} & \cdots & \gamma_{z,1} & 0 & \cdots & 0 \end{bmatrix} \quad (2.13)$$

Indeed, if the vector $\dot{\mathbf{q}}$ has been properly sorted, $\mathbf{v}_{G_i}$ can be affected at most by the first i links of the chain. Now, equation (2.11) can be written, placing $m = \sum_{i=1}^n m_i$, as

$$\mathbf{v}_{G_i} = \left[\frac{1}{m} \sum_{i=1}^n m_i \mathbf{J}_{G_i} \right] \dot{\mathbf{q}} \quad (2.14)$$

By comparing Equations (2.14) and (2.9), we can finally assume

$$\mathbf{J}_G = \frac{1}{m} \sum_{i=1}^n m_i \mathbf{J}_{G_i} \quad (2.15)$$

Given $\mathbf{J}_G$, the CoM becomes a further control point for the kinematic chain. Thus, we can insert the kinematic relation (2.9) in the equations set (2.2).

As a result, we will have an augmented Jacobian matrix with two more rows that are related to the components of $\mathbf{v}_G$ projected on the current support plane (CoP's velocity). As mentioned above, the implemented inversion algorithm assures that a constraint on CoM velocity becomes a high-priority task to be achieved, without using null-space projection.

3- Biomechanical modelling

The formulation of the IK problem for a virtual manikin in terms of a single CLIK algorithm suggests also the possibility of computing the torque at the joints of the humanoid by means of KSD [SS2]. The main feature of the proposed model is the possibility of implement multiple-point kinematic control for a humanoid using a single CLIK algorithm (something like the serial robots), through the $\mathbf{J}_{AU}$ matrix. Thus, the torque joints related to a force applied to a generic point of the structure will be:

$$\boldsymbol{\tau}_i = \mathbf{J}_i^T \mathbf{f}_i \quad (3.1)$$

Where $\mathbf{f}_i$ is the generalized vector of forces applied at generic point of the structure, $\mathbf{J}_i$ is its Jacobian matrix and $\boldsymbol{\tau}_i$ the resulting torque joints vector.

In the dynamic biomechanical model of lifting described in [CA1] the moment at the hip can become quite large, especially when a load is lifted far from the body. In particular [T1] proposed that the load moment about the lumbosacral disc L5/S1 should be used for setting the limit for lifting and carrying loads of various sizes in order to avoid muscle fatigue in the erector spinal muscle group.

From a biomechanical point of view the fact that large moments are created raises the question on the internal forces that must be present to stabilize the spine while incurring such load moments.

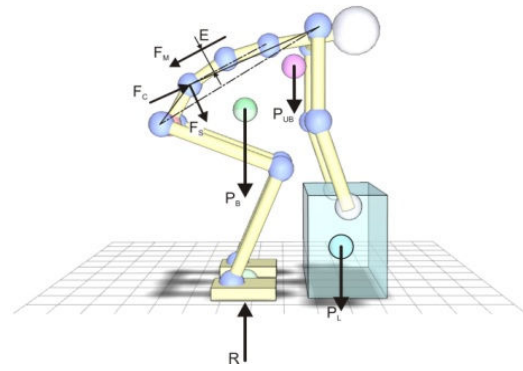


Figure 5: Forces applied to the manikin for the biomechanical analysis

A simple static model was proposed by [ML1] in which it is assumed that two kind of forces are involved. One is produced by the extensor erector spinal muscles which exert their action approximately at 5cm posterior to the center of rotation in the spinal discs; the second, due to the abdominal pressure acting on the diaphragm [B1].

This model showed also that while the load is lifted a large compression forces raises in the spinal column that acted to compress the disc. The existence of this compression was also later confirmed experimentally by [NE1]. A simple static analysis, without taking into account the abdominal pressure, can be made first identifying the relevant forces involved, shown in Figure 5 where $\mathbf{P}_L$ is the load due to the lifted weight, $\mathbf{P}_B$ is the weight of the whole humanoid, $\mathbf{P}_{UB}$ the weight of the body part located above the L5/S1 level, $\mathbf{R}$ is the reaction of the plan, $\mathbf{F}_M$ is the force produced by the extensor erector spinal muscles, $\mathbf{F}_C$ and $\mathbf{F}_S$ are, respectively, the compression and the shear force acting on the lumbosacral discs L5/S1. In particular $\mathbf{P}_L$, $\mathbf{P}_B$, $\mathbf{P}_{UB}$ and $\mathbf{R}$ are external forces and $\mathbf{F}_M$, $\mathbf{F}_C$ and $\mathbf{F}_S$ are internal forces.

The analysis of the forces acting on the L5/S1 discs begins with the computation of the second member of equation (3.2) by using the KSD,

$$\mathbf{M}_{L5/S1} = \sum_i \mathbf{M}_i \quad (3.2)$$

Known the average moment arm E between the erector spinal muscles and the lumbosacral discs L5/S1 it is possible to compute the muscular effort $\mathbf{F}_M$ as:

$$\mathbf{F}_M \cdot E = \sum_i \mathbf{M}_i \quad (3.3)$$

For the compression and shear stress it is enough to project $\mathbf{P}_{UB}$ along the directions perpendicular and parallel to the sacral cutting plane. The shear and compression forces can be then calculated through a static equilibrium equation.

4- Applications

In this section, some simulations, related to the task of lifting a weight, are reported. It is worth emphasizing that the CLIK algorithm always takes into account the constraint about the CoP.

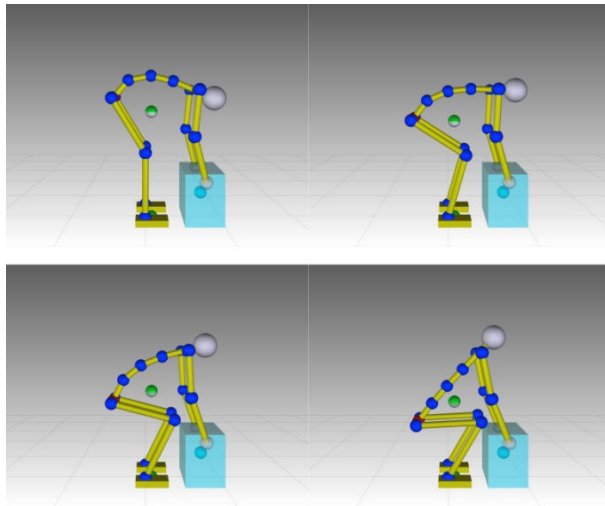


Figure 6: Different behaviours related to the task of lifting a weight

In Figure 6 it is shown how it is possible to obtain different behaviours for the same task. In particular, it can be accomplished either through some optimal criteria or by using a weighted pseudo-inverse or both.

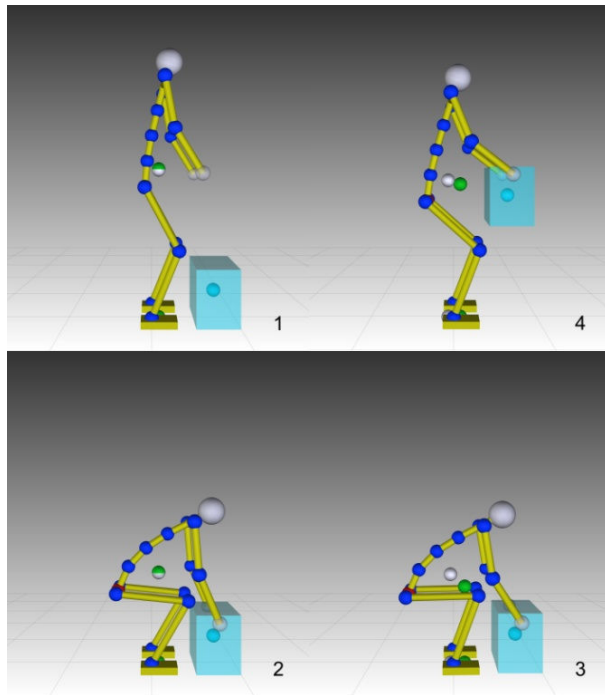


Figure 7: The manikin lifts a box while keeping balance

The CoM control is always active. In Figure 7 it is shown a humanoid lifting a box. It is worth noticing some aspects: first, the motion is imposed only at the hands while holding the feet and keeping the CoP belonging to the support polygon; second, it is interesting to see how, although a few control points are controlled, the resulting motion is quite natural. The algorithm takes into account the load, when lifted, and the humanoid changes its postures accordingly with CoM variation in such a way that a total CoP still belongs to the support polygon.

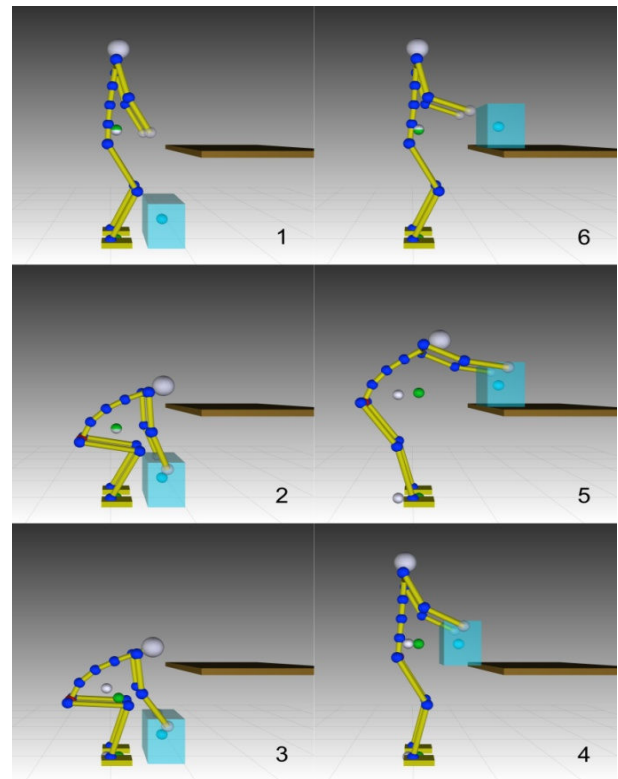


Figure 8: The manikin lifts a box and releases it on a plane

Finally, in Figure 8, a more complex task is simulated, where a humanoid lifts a load from the ground and releases it on a table. Even in this simulation the motion is quite natural and it is evident how the humanoid modifies its posture according to the CoM variation in order to keep the balance. With reference to the task showed in Figure 7 the efforts F_M , F_C and F_S (see Section 3) related to lifting a load have been computed and, then, compared with the *Low-Back Biomechanical Model* results proposed in [CA1]. The results proposed in literature are referred to a single posture of the human identified by torso and knee angle. In spite of the simplicity of the humanoid model proposed, the simulation results, for the posture examined, are in good agreement with the literature data. Finally it is worth emphasizing that the algorithm developed allows plotting the efforts, and any other parameter of interest, throughout the duration of the whole simulation task.

5- Conclusion and future works

The main contribution of the proposed approach is the introduction of an augmented Jacobian matrix that allows specifying trajectories for different control points and solving the inverse kinematics with a single CLIK algorithm. The introduction of the kinematic control for the CoM of the structure has granted quite natural movement to the virtual manikin in spite of the limited number of considered control points. It is worth noticing that these points can move along the humanoid, giving the possibility of controlling nominally every point of its kinematic structure. The symbolic implementation leads to a very fast response of the algorithm with respect to complex simulations in the humanoid

configuration space. Moreover, the algorithm can be adopted for a very huge set of applications. The developed model makes it possible to observe the resulting joint motion simply by planning the trajectory of a limited number of control points. Another field of application could be marker-based motion capture [TT1], where the algorithm can be used in order to limit the number of markers needed to capture human movements. Although the described model is advanced in terms of quality of analysis, it is also computationally efficient. Specifically, a symbolic representation for the kinematics of the digital humanoid has been derived. In this way, it is possible to change in real-time several characteristic parameters of the chain, such as the applied loads, without further computational overload. Finally, the consistency of biomechanical simulation results with literature data raises the interest in a deeper investigation about the biomechanical parameters related to the computation of the effort in a human being from a static analysis. In this scenario, the algorithm developed gives a very powerful and easy to use tool even for biomechanical and ergonomic analyses.

6- Acknowledgements

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