Simulation of Complex Human Movement Through the Modulation of Observed Motor Tasks

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Abstract. A method for the simulation of human movements driven by real data and correlated with modification of constraints in the external environmental is presented. It was applied to the simulation of the car ingress changing the configuration of the doorway to check early on in the design the man-machine-interface requirements for choosing the best ergonomic solution among different alternative solutions without the physical construction of prototypes. The method for the simulation of the movement is based on the modulation of a real measured performance recorded through an opto-electronic system for motion analysis. The algorithm implements a multifactorial target function to solve the redundancy problem. The reliability of the method was tested through the comparison of simulated and real data showing promising developments in ergonomics.

Keywords: movement, simulation, pattern modulation, ergonomics, virtual prototyping.

1 Introduction

The Central Nervous System (CNS) controls any human motor performance by setting sequences of muscular activation in respect of the several constraints (environmental as well as biomechanical) acting on the human [1], [2], [3]. Controlled by the CNS, the biomechanical system is characterised by a very high degree of complexity so that the mechanical structure is redundant thus allowing for different motor strategies in realising the same motor task [4], [5]. These strategies may have completely different joint motion patterns, or may represents slightly different modulations of a recognisable unique motor strategy. The study of the neural control of human movement aims to identifying the criteria assumed by the CNS in the design of the muscle activation patterns [1], [5]. These studies have considered mostly simple movements (i.e. movements involving few anatomical segments, the joints connecting them and the muscles acting on that part), but the same concepts have been adopted in the explanation of complex movements of the whole body.

The quantitative approach in the measurement of human motion as well as the mechanical modeling of the human body lead to a mathematical interpretation of the

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CNS criteria [2], [6]: some "cost functions" have been defined and it is assumed that the CNS controls the several Degrees of Freedom (DoF) in the anatomical structure in order to minimise those costs through a sort of optimisation algorithm.

The contribution of the several authors consisted in explicitly introduce in those cost functions all the elements that are thought to be determinant in the definition of a motor strategy: the anthropometric features, the physiological/pathological conditions, the level of motor ability, a preliminary phase of specific training, the energetic cost, the respect of the implicit and explicit constraints, the feedback [3], [7], [8], [9], [10]. In particular, in synthetic generation of the movement the three main categories of ill-posed problems can be identified: the simulation of trajectories, the inverse kinematics and the inverse dynamics. For the system redundancy previously described, in human motion simulation, the main problem to face is that the solution to the problem is not unique. The simplest approach to solve and to find an unique solution is the introduction of a target function with a performance index to be optimized. The criterions for the optimization of this performance index are based on the characteristics of the motion or on the mechanical properties of the muscle-skeletal system implementing one of the followings functions [8], [9], [10], [11], [12], [13], [14]: a) minimum jerk; b) minimum spatial deviation; c) minimum change of the muscular tension; d) minimum torque change.

In the present paper a real data-driven method for the simulation of complex motor tasks (when many approaches fail) is presented through the application example of the analysis of the car ingress-egress movements.

2 Materials and Methods

The method requires the availability of an experimental measure of a reference similar movement: the simulation of the new movement according to virtual new constraints is performed by modulating the measured movement.

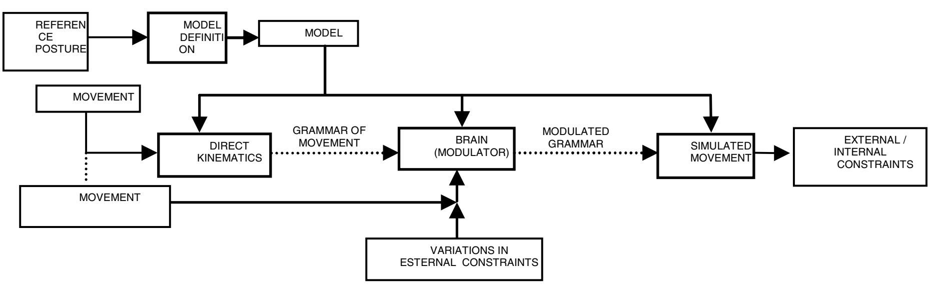

Fig. 1. The flow-chart diagram of the method for the virtual synthesis of the movement

The approach we propose here for the simulation consists in the modulation of the experimental grammar of movement, i.e. the set of vectors of all the kinematic variables describing the observed movement. This means that the simulation is the modification of a reference recorded movement according to new virtual constraints, through an algorithm that finds the solution of the redundancy problem by minimizing a target function. The purpose is to obtain a synthetic movement to be coherent with all the given intrinsic (i.e. the DoF of the model) and extrinsic (i.e. external obstacles) constraints, and indistinguishable from the correspondent movement performed in the reality for an external observer.

2.1 The Biomechanical Model

Human body was modeled with 16 anatomical segments: head, arms, forearms, hands, thighs legs, feet, thorax, abdomen and pelvis. Markers were positioned on the head, on the trunk, on the lower limbs while upper limbs were not considered and so they were thought in a rest position along the body. The 11 markers are: for the head, front, vertex and occiput; for the shoulders, right and left acromion; for the hips, the right and left great trochanter; for the knees, lateral condyles of femuri; ankle.

The experimental protocol was integrated by the measurement of some anthropometric parameters: weight (kg); height (cm); arm length; forearm length; sternum height; pelvis width; pelvis height in sitting position; upper iliac crest point height from sitting plane; knee diameter; ankle diameter.

Each segment was characterized by fixed anatomical axes and constant inertial geometric properties: the segment mass was concentrated in one fixed point. The mass of each body segment was estimated by means of regression equations [15]. The total body centre of mass (COM) position was computed as the weighted mean of each body segment centre of mass position.

2.2 The Experimental Protocol

Three-dimensional measurement of human movement is the detection of the trajectories of several points that identify the positions of the body segments in space through a motion capture optoelectronic system (ELITE by BTS, Milan, Italy) recording the position of spherical or hemispherical passive markers fixed onto the body. The vehicle was implemented by a car simulator provided by all the structural elements required to reproduce a real car.

Six healthy subjects (five male and one female), university students, took part in the study (age: 26 ÷ 31 years, height: 170 ÷ 183 cm and weight: 50 ÷ 94 kg).

The protocol consisted in ingress and egress with reference to left back seat. When entering, the subject started in the standing position near the car mock-up and ended when in the sitting position. In the egress, the movement went in the opposite way. The subject chose velocity and strategy of movement. During the experiments, the door height was progressively lowered with steps of 2 cm starting from higher quote of 154 cm into other 8 fixed positions. For every set-up the subject did a sequence of 10 trials, 5 ingresses and 5 egresses, so that in total he made 80 trials. Data of homogeneous trials (same subject, same vehicle set-up) were time normalized and averaged for the statistical analysis.

2.3 The Motor Task Model (Grammar of Movement)

In the case of car ingress, the main consideration is that any subject has to lower the COM while translating from out to the interior of the vehicle. A similar but opposite consideration can be done for egress. The events describing the motor task are the maximum (start) and the minimum (end) of the vertical co-ordinate of the COM; similarly, but in inverse order, for egress.

The grammar of movement is set of n vectors containing the values of the n DoF of the model. These DoF are the angles between connected segments - (n – 6) relative rotations – and the position and the orientation in the 3D space of the segment that is the root of the kinematic chain (6 DoF). A grammar is computed from an observed real movement considering the corresponding model through an optimization procedure minimizing frame by frame the differences between the given experimental points and the positions of the manikin (model).

2.4 The Simulation as a Modulation of an Observed Movement

The model and the grammar of movement converge in the algorithm that integrates the intrinsic limits of the model and the external environmental constraints and mathematically implements the criterions for the solution of the redundancy. A grammar of movement can be divided in its linear and non-linear components (Fig. 2.a and 2.b) defined according to the following equations:

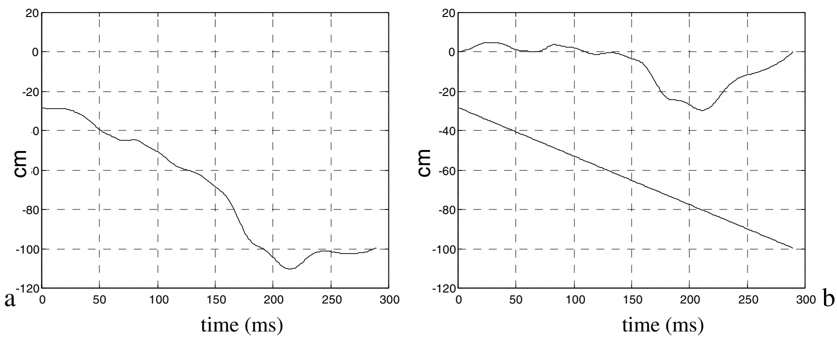

Fig. 2. The separation of a variable Y (a) in its the Linear Component YL and Non-Linear Component YNL (b)

Grammar of movement: $Y_i = YL_i + YNL_i \qquad \forall i \in [1, N]$ (1)

linear component: $YL_i = Y_1 + \frac{Y_N - Y_1}{N-1}(i-1)$ (2)

non linear component: $YNL_i = Y_i - YL_i$ where i is the time i = 1, ,T. (3)

The separation of the linear and non-linear components is consistent with the consideration that in general a movement does not modify the starting and final posture such as in the example of the ingress/egress to a vehicle in which a variation of the geometry of the doorway does not modify the initial (standing) and final (sitting) positions, but it influences the intermediate trajectory. In this sense, the informative content of the reference grammar is exclusively in its non-linear component because, during the simulation, the linear component is defined while the non-linear component is modulated. The only requirement for the reliability of the presented method is that the conditions of the reference grammar should be similar to those of the virtual conditions that are going to be verified.

The simulation of the movement is realised as follows: considering the general kinematic variable Z^s of the simulated movement, the linear component ZL^s_i is the same one of the observed data ZL^o_i: $ZL^s_i = ZL^o_i$

To simulate a movement modulating the non-linear component of its grammar of movement means to define a constant multiplying factor of the reference non-linear component YNL_i:

$$ZNL^s{}_i = k \cdot ZNL^o{}_i \qquad i = 1,..,N \tag{4}$$

and, finally it is possible to obtain the simulated vector of values of the variable Z through the sum of the two components:

$$Z_i = ZL^s{}_i + ZNL^s{}_i = ZL^o{}_i + k \cdot ZNL^o{}_i \tag{5}$$

Therefore, the three unknown parameters of the function are the extremes of the linear component, and the coefficient of the non-linear component to be computed considering the constraints along the trajectory. But, given the starting and final postures from the observed movement, the problem of the simulation of the movement is reduced to the calculation of the vector of the coefficients k_i K = [k_1… k_i … k_n], i.e. of the multiplier factors for each non-linear component of all the DoF.

The algorithm for the virtual synthesis of the movement integrates information about the subject, that is the model and its intrinsic limits (DoF and RoM); the new geometry of the environment (the car in the proposed application); the grammars of movement, i.e. the experimentally observed motor patterns.

The target function consists in the product of simple sub-functions that singularly implement the following different aspects:

f_1: clearance, e.g. no interference between subject and environment;

f_2: constraints on the absolute positions of segments, e.g. respect of environmental constraints;

f_3: constraints on free coordinates, e.g. respect of RoM;

f_4: attraction towards a reference posture, e.g. the standing.

Therefore, the global target function F is:

$$F = \prod_{j=1}^{4} f_j \tag{6}$$

The algorithm finds the n values k_i that minimize the function F.

After the calculation of the coefficients k_i of the non linear component, the algorithm provides the vectors of the new DoFs (i.e. the virtual or simulated grammar) to be imposed to the biomechanical model to obtain the simulated movement.

3 Results

The validation of the procedure of simulation of the movement was realized using the central configuration (corresponding to the real condition in the commercial car model) as reference for the extraction of the grammar of movement. Subsequently tests of ingress and egress movements with the roof respectively lowered of 6 cm and raised up of 8 cm were used for comparison with the simulated movements. Then the kinematic data of the variables, and the trajectories of the COM were compared (Fig. 3.a and 3.b).

Also by visual inspection it is evident how the algorithm did not change the global motor strategy adopted by the subject when in presence of non-extreme constraints, as in the verified situations that represent general and common situations of typical cars' doorways of the market central segments (Fig. 4). Data analysis did not reveal differences between the two joint angular patterns (simulated and real ones).

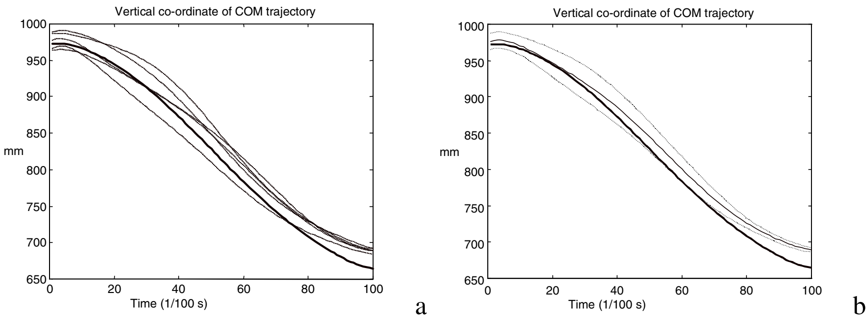

Fig. 3. a) vertical co-ordinate YCOM trajectories for a subject of 176 cm in 5 observed tests (dotted lines) and in the simulation (solid line) of the car ingress with the roof height lowered of 6 cm; b) the average and standard deviation of the vertical co-ordinate COM trajectory for the same subject in the 5 trials (solid and dotted lines) and in the simulation (solid wider line)

In the last part of the movement a lowering is observed for the vertical coordinate of the COM in the simulation in comparison with the observed tests: probably it happens because the modulation coefficient is constant along all the movement so that to pass through the doorway and under the superior region of the doorway, all the body is somehow lowered also in the intermediate positions and therefore the COM reaches lower final values. With a more detailed model of the environment with the seat and of the human body with the ‘muscular envelope’ a better results could be achieved. Also the 20 mm threshold for the clearance factor could be over-estimated as shown in the figure 4 where in correspondence of the instant of maximum head interference in the real movement the head is closest to the doorway than the set value.

To quantify the correspondence of the simulated movement to the real one we introduced a statistical index of coherence computed for the two main kinematic variables of the movement we analysed (vertical co-ordinate of COM - YCOM and Left Hip Flexion – LHF). Defined the range of natural variability of a generic variable X as the interval average ± 2 standard deviations computed on 5 observations of the same movement, the PIX index is computed as follows:

$$PI_i = \begin{cases} 1 & \text{if the simulated angle is in the range of the natural variability} \\ 0 & \text{if the simulated angle is not in the range of the natural variability} \end{cases} \quad (7)$$

and finally $PI_X = \sum_{i=1}^{100} PI_i$ where i is the normalized time. (8)

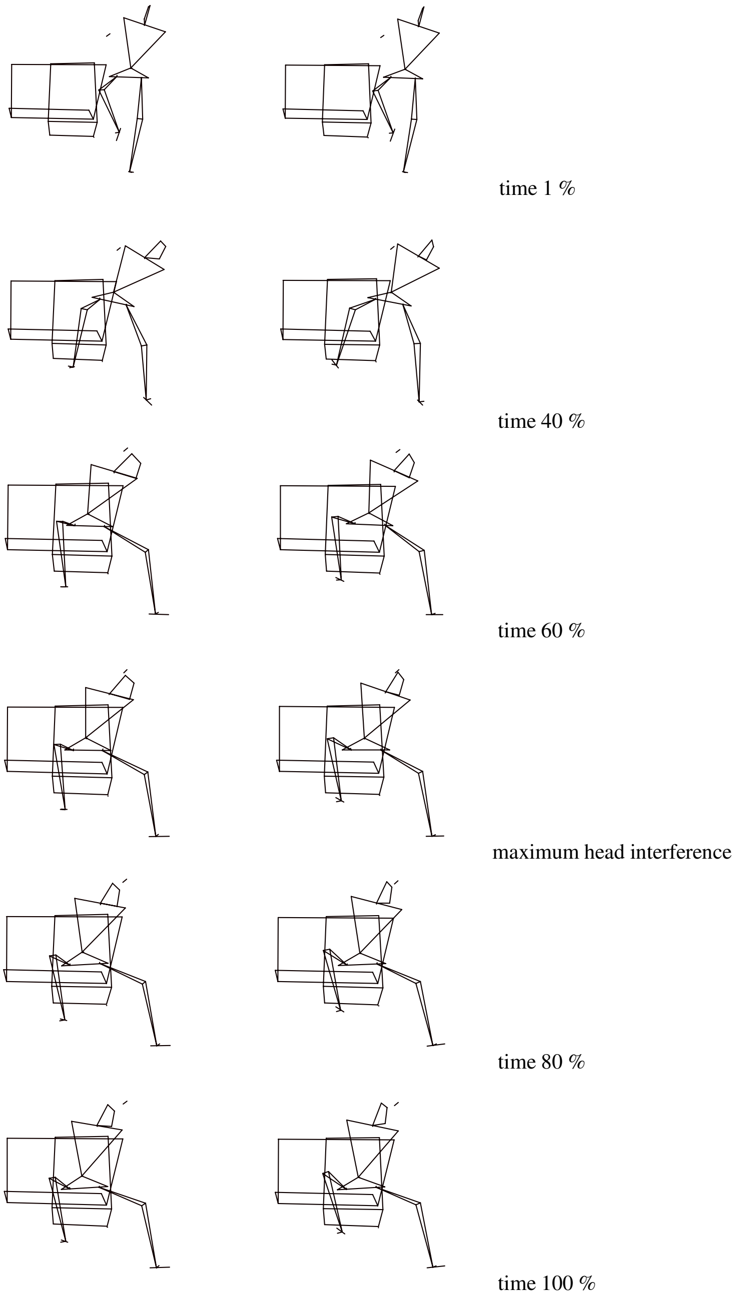

Fig. 4. Comparison of the simulated (on the left) with the observed movement (on the right)

Table 1. The coherence index of the simulation with respect to the actual movement ant its natural variability for the two main kinematic variables: YCOM = vertical co-ordinate of COM, LHF = Left Hip Flexion

Subject	PIYCOM (%)	PILHF (%)
1	76	89
2	80	93
3	79	91
4	81	88
5	87	94
6	83	90
m ± sd	81,0 ± 3.7	90.8 ± 2.3

The aim is to verify how much the simulation is in the range of the natural movement repetition of the same task. The results are shown in table 1.

However, the simulated data were in the natural variability of real movements for 91% of their execution concerning the anatomical angles and 81% of the vertical co-ordinate of COM trajectory: so we can say that the algorithm provides a correct and likely simulation of the motor task.

4 Discussion

The obtained movement is intrinsically similar to real movements already observed, thus looking like a real movement. In the spirit of the proposed methodology, the new grammar has not been already observed but, at the same time, is not strictly virtual. It can be concluded that a simulation realized starting from an observed and then modified grammar is virtual, or it has not been ever observed, but it has characteristics of likelihood and naturalness proper of the observable movements, or it could be observed in the future.

The algorithm was developed and validated for the ingress-egress movements to vehicle, but it is possible to calculate the simulation of any movement given a biomechanical model and the observed behaviour in experimental conditions similar to those to be simulated (to conserve the qualitative behaviour), as demonstrated by the application in the simulation of reaching tasks.

Because of the proper sizing of the movement with the anthropometry of the subject, the reference grammar of the movement must be used for simulations of movement of manikins or subjects with a biomechanical model that is anthropometrically similar to the original experimental subject. Therefore it is opportune to have available many different models of movement, each one from an experimental analysis on subjects of different heights (percentiles).

5 Conclusions

In the presented approach for human motion simulation seems to be sufficiently strong and reliable, and to allow an on-line verification of the human-car interaction early on in the design of virtual prototypes or new models.

The main field of application of the method developed in this research is the ergonomic design of environments and products. The simulation of the movement based on real motor strategies that are adapted to a new virtual space configuration, could assume a relevant importance for the on-line ergonomic evaluation during the design process of environments and objects [16], 17], [18], [19], [20]. In fact our approach proposes that the simulated movement has to be not only congruent with the biomechanical model and its constraints but that also with the qualitative human behaviour (i.e. the different motor strategies that can be adopted by different subjects or by the same subject in modified conditions, speed and accelerations, continuity of the movement). So this concept is implemented and mirrored by the built reliable and likely simulation of what happens in the reality, i.e. a faithful reproduction of the man-machine-environment interface.

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