Computer Simulations of Planar Sports Motions

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INTRODUCTION

The computer simulation and the associated problem of the optimization of sports motions is a comparatively new field of biomechanical research. Until recently, the majority of investigations were concerned with the analysis of specific attributes of a certain discipline, usually neglecting all other facets of the investigated phenomenon. This view has now changed in favour of a more holistic one.

However, very little experience has been gained up to now in the field of computer simulation of sports motions. One of the reasons for this lack is certainly to be found in the high degree of mathematical sophistication required to deal with the intricacies associated with the computer simulation of the human neuromusculoskeletal system. Only a team of mathematicians, numerical analysts and computer scientists is in a position to develop the necessary algorithms and computer programs.

In this paper we shall present an overview of some of the major problems relating to the computer simulation of planar (2-D) motions and give an example of a long jump simulation. We shall deal mainly with the skeletal subsystem of the total neuromusculoskeletal system since a discussion of the complexities of the muscular and neural subsystem is beyond the scope of this presentation.

MODEL OF THE SKELETAL SUBSYSTEM

The skeletal, or executor, subsystem consists of the assemblage of limb segments which are acted upon by internal active and passive forces (moments) and by external driving and reaction forces (moments).

An anthropomorphic (human-like) physico-geometrical model of the skeletal subsystem will be termed a *hominoid*. Such a model of the segmented human body is essential for the simulation of gross body dynamics. The morphology of the hominoid defines the number f of mechanical degrees of freedom of the (unconstrained) model, as well as the shapes and inertial properties of the individual segment models.

Hominoids of widely varying complexity have been reported in the literature, beginning with the impressive work of O. Fischer (1906). Some time ago, several authors (Hemani et al., 1973; Hemani and Golliday, 1977; Vukobratovic and Juricic, 1969) have used three- and four- link body models that could conceivably still be classified as anthropomorphic. These models consist of a three- or four- segment assemblage of uniform bodies and were used for investigations into the stability of bipedal gait. It is, however, highly questionable whether models with two stiff legs, without feet or knee joints, can yield results that are applicable to actual human gait.

The inadequacy of these oversimplified models was soon recognized and hominoids comprising from 11 (Morecki et al., 1975) to 17 segments (Hatze, 1977, 1980a) were proposed for simulating and analyzing more complex motions of the human neuromusculoskeletal system. Surprisingly, however, the shoulder segments, which clearly constitute dynamically separate entities, are almost always considered part of the upper trunk except in the model of Hatze (1977), where they are included as separate segments. The latter 17-segment hominoid is displayed in Figure 1.

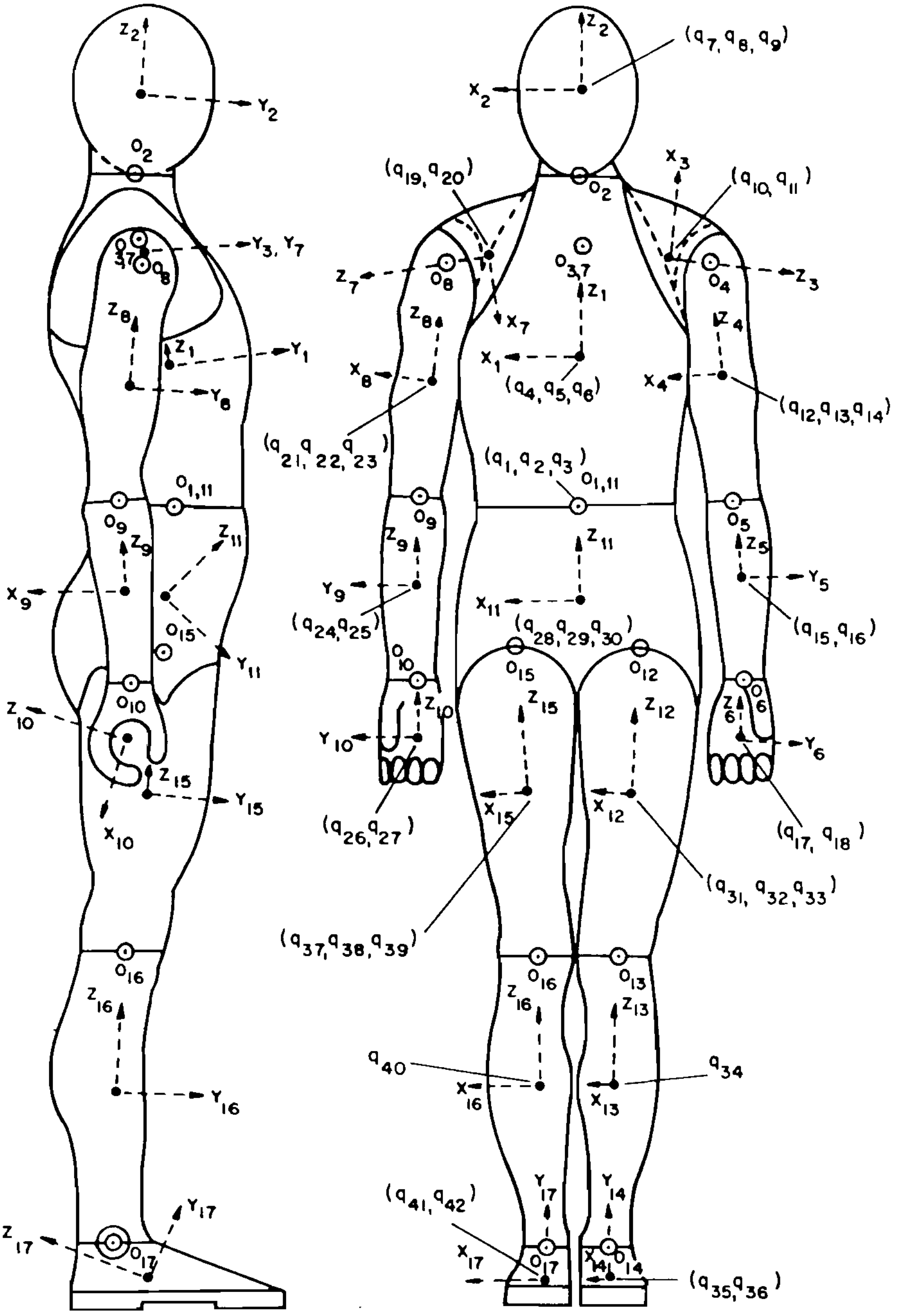

Fig. 1 Morphological appearance of the 17-segment hominoid. The local segment coordinate systems are also shown.

The number f of mechanical degrees of freedom of the body models discussed varies from five (three-segment model in planar motion) to 44 (for three-dimensional motions of the hominoid depicted in Fig. 1). If used for the simulation of planar motions, the latter 17-segment hominoid has only 21 degrees of freedom. The planar model and its 21 configurational coordinates q_1, ..., q_{21} are shown in Figure 2.

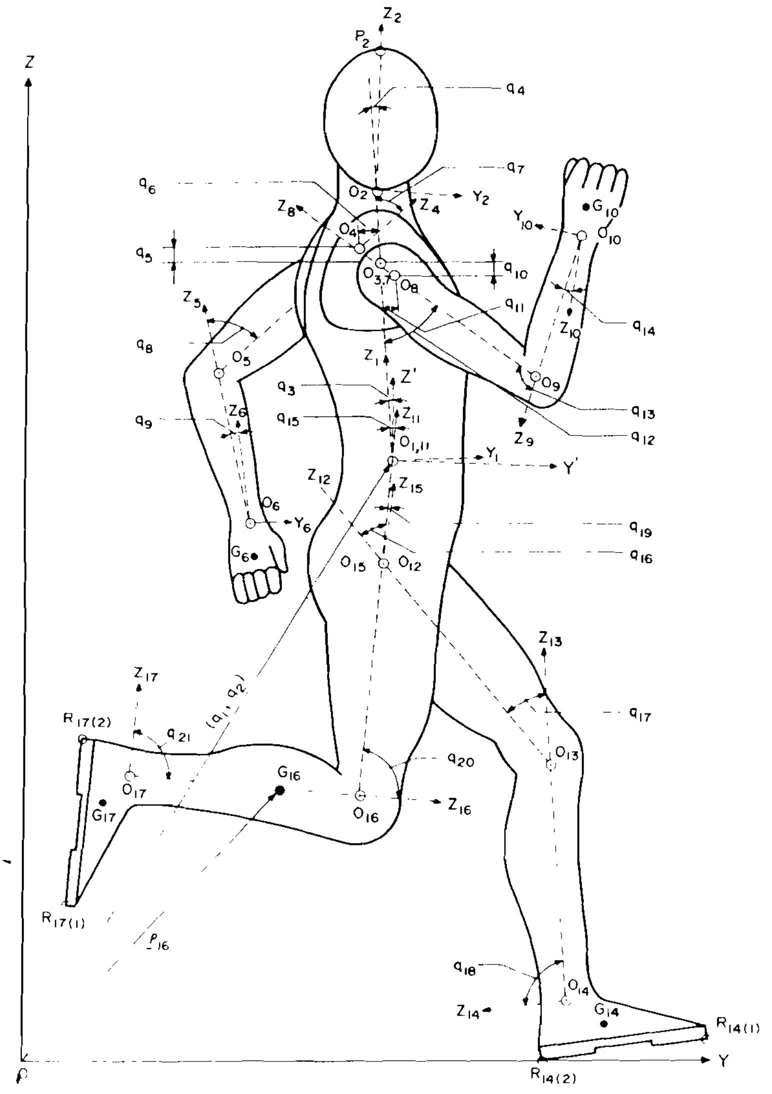

Fig. 2 Seventeen-segment human body model for the simulation of planar motions. The 21 configurational coordinates q_1, ..., q_{21} are also shown.

This model has been found to be adequate for the analysis and simulation of a large variety of planar sports motions. In particular, it has been used successfully in the simulation studies of the long jump to be presented here. However, in order to individualize the general model of the skeletal subsystem, the values of the segmental parameters of a given athlete have to be substituted into it. Methods for the practical determination of these parameter values will now be discussed.

PRACTICAL DETERMINATION OF SEGMENT PARAMETER VALUES FOR A GIVEN ATHLETE

The parameters characterizing the biomechanical properties of the hominoid segments are given by the set

$$\{V_i,\ M_i,\ \overline{I}_{xi},\ \overline{I}_{yi},\ \overline{I}_{zi},\ \overline{X}_i,\ \overline{Y}_i,\ \overline{Z}_i,\ x_i^\circ,\ y_i^\circ,\ z_i^\circ,\ \Theta_i,\ i=1,\ \ldots,\ 17\}, \qquad (1)$$

where the symbols denote, respectively, the segmental volume, mass, the three principal moments of inertia with respect to principal axes passing through the mass centroid, the three components of the position vector locating the mass centroid relative to the local (segment-fixed) Cartesian coordinate system, the three components of the vector locating the origin of the i-th segment relative to the coordinate system of the proximal segment, and the angle(s) of inclination of the principal axes relative to the original segment axes.

While parameters describing segmental lenghts (x_i°, y_i°, z_i°) may be determined by direct measurement on the respective segments of the subject, the experimental determination of the other parameter values creates problems. Dempster (1955), Drillis and Contini (1966), and Clauser et al. (1969) used the immersion method for the determination of segmental volumina, while the computation of the segmental masses from the measured volumina is possible by employing the average density values reported by Dempster (1955) and Harless (1860). Indirect experimental determinations of segmental masses and (or) moments of inertia can be performed by means of the gamma-ray method (Casper, 1971), the reaction change method (Williams and Lissner, 1962), the pendulum method (Hill, 1940), the quick-release method (Fenn, 1938), and the oscillation method (Hatze, 1975). However, experience has shown that all of these experimental methods either yield inaccurate results, or are cumbersome to use.

Because of these shortcomings, methods were devised which use certain anthropometric measurements as input data to segment models that permit an approximate computation of the segmental parameter values. We shall call these techniques anthropometric - computative methods. In the Hanavan model (Hanavan, 1964), simple geometrical bodies (ellipsoids, right elliptical cylinders, etc.) are used to approximate the shapes of the actual body segments. Miller and Morrison (1975) and Jensen (1978), have commented on some of the inaccuracies associated with the identification of anthropomorphic segments with simple geometrical bodies. In 1980, a new anthropometric - computative method and computer algorithm was introduced by the author (Hatze, 1980a) in which the individual segments are decomposed into finite elemental units of known geometrical structure. By the use of triple integration over element boundaries and subsequent summation of integrals, the volume, mass, the coordinates of the mass centroid, the principal moments of inertia, and the orientation of the principal axes of a given segment may be obtained. Each individual elemental unit is assigned its own density, and in this way the varying mass distributions across and along segments are taken into account. Some of the integrals involved cannot be solved analytically, and a special subroutine performing the numerical quadrature is supplied in the computer program ANSEPA for this purpose. The morphologies of the individual segment models can be seen from Fig. 1.

In creating this finite elemental unit model and the associated computer program ANSEPA, the following requirements had to be satisfied:

1) The model should permit a differentiation between male and female subjects (exomorphic differences mass distributions, density functions, etc.);
2) the actual shape fluctuations of all the individual segments should be fully taken into account;
3) varying densities, both across the cross-section of a segment (where necessary) and along its longitudinal axis should be accounted for;
4) the densities of some segmental elements (buttocks, lateral sections of upper thighs, etc.) should be automatically adjustable by the program according to the value of a special subcutaneous-fat indicator;
5) asymmetries of segments (abdomino - thoracic segment, abdomino - pelvic segment, hands, feet, etc.) should be fully taken into account and the necessary principal axes transformations performed by the program;

6) all changes in body morphology due to age, obesity, pregnancy etc. should be accounted for;
7) the overall accuracy for all parameters and segments should be better than 3%;
8) all segmental parameter values for a given subject should be computable from a set of anthropometric measurements taken directly from the subject thus obviating the introduction of errors to which photo-image techniques are subjected.

The final model and associated algorithm fulfilled the above requirements so that the computer program ANSEPA was considered adequate for the determination of the segmental parameter values of the 21-year old male subject whose long jump motion was to be simulated.

SIMULATION MODEL

The dynamical model used for the simulation of planar motions is described in detail by Hatze (1977, 1980b, 1981a, 1981b) and Hatze and Venter (1981). In the present paper, a simplified version of the general model will be discussed. The simplification consists of the exclusion of the excitation and contraction dynamics of the model muscles, i.e. the control inputs to the simulation model are not the neural controls stimulation rate and rate of motor unit recruitment of the respective muscles, but directly the time functions of the muscle moments generating the motion. In this case, the dynamics of the executor (skeletal) subsystem is given by the nonautonomous, nonlinear, ordinary first-order differential system

$$x = A^{-1}(x)[B(x)+Q^{M}(t)+Q^{L}(x)+Q^{E}(x,t)+Q^{C}(x)], \quad x(0)=x_0, \qquad (2)$$

where

$$x = (q_1, q_2, \ldots, q_{21}, q_1, q_2, \ldots, q_{21})^T \qquad (3)$$

is the 2f-dimensional (in the present model 42-dimensional) state vector consisting of the 21 configurational coordinates (see Fig. 2) and their first derivatives; A(x) denotes the 2fx2f inertia matrix containing also the segment parameter values; B(x) is a 2f-vector of gravitational, centrifugal and other inertial forces; and $Q^M(t)$, $Q^L(.)$, $Q^E(.)$, and $Q^C(.)$ denote respectively the vectors of the muscle moments, joint range limitation torques, external non-contact moments or forces, and the moments (forces) resulting from external constraints, such as ground reactions on the feet. The constraint moments $Q^C(x)$ are computed automatically by the simulation program upon activation of the constraints. The symbol x_0 in (2) denotes the initial state vector.

The equations (2) and all other algorithms necessary for their integration are coded in FORTRAN77 and combined in the computer program ANDYMO (Hatze, 1981a).

Of particular interest for the simulation on the computer of the differential system (2) are the inputs of muscular moments $Q^M(t)$. Given the segmental parameter set (1) of a specific athlete, an initial state x_0, moment functions $Q^L(x)$ and $Q^E(t)$, and muscular control moment inputs $Q^M(t)$, the system (2) may be integrated and the resulting motion

$$\Omega: = \{q_i(t_k),\ \tau;\ t_k \in \tau,\ i=1,\ldots,21,\ k=0,1,\ldots,N\} \qquad (4)$$

of the hominoid may be displayed on an electronic screen in the form of successive configurations of a human figure. This procedure will now be demonstrated on the example of a long jump simulation.

COMPUTER SIMULATION OF THE LONG JUMP

In order to simulate on the computer a planar long jump motion of a specific athlete, the 17-segment hominoid shown in Figures 1 and 2 was chosen. To obtain an initial estimate of the muscular control moment function vector $Q^M(t)$ for the take-off phase, the following technique, termed ANSYN (ANalysis - SYNthesis) approach, was devised.

A 21-year old made athlete, 187 cm tall and having a mass of 85.30 kg, performed a series of long jumps (left leg jumper). The take-odf phase was filmed with a Photosonics Biomechanics 500 high speed camera at 500 fps. The ground reaction forces were measured by a Kistler force plate, synchronized with the film, and recorded on tape.

A complete 2-D motion analysis was then performed using the recorded data. The computer program MORECO was used for the high precision object space reconstruction from the manually digitized film images of the body markers fixed to the subject.

First, the program automatically smoothed the time sequences of the digitized point coordinates and removed outliers. Next, it performed automatic calibration by correcting for all linear and nonlinear distortions in the whole optical train, using a modified DLT-approach with a spatial reconstruction accuracy of better 0.7 mm. Finally, the program performed the object space reconstruction of the whole take-off motion yielding both, the time functions of the spatial marker coordinates and of the configurational coordinates $q_1(t_k)$, i=1,...21.

The latter coordinate sequences were fed into the computer program HOM2D2, together with the ground reaction force histories and the athlete's segmental parameters as determined with the aid of program ANSEPA. Program HOM2D2 then automatically performed the optimal smoothing of the data sequences $q_i(t_k)$, i=1,...,21, k=0,1,...,N and the computation of their optimally filtered first and second time derivatives, and computed all kinematic and kinetic characteristics of the observed motion (the histories of all shear and compressive joint loads, the histories of the passive and muscle moments, the histories of the segmental and the total linear and angular momenta, energies, and powers, and the histories of the position and velocity of the body center of mass).

The output file of the analysis program HOM2D2 therefore contained the muscle moment functions $Q^M(t)$ required as input for the simulation program ANTOR which program constitutes a simplified version of the general 2-D simulation program ANDYMO. Further inputs to program ANTOR were the segmental parameter values as computed by program ANSEPA, and the smoothed initial state vector

$$x(0) = [q_1(0),\ldots,q_{21}(0),q_1(0),\ldots,q_{21}(0)]$$

taken from the respective file of program HOM2D2. All input and output files of the various programs communicate directly thereby facilitating easy data handling.

For the simulation of the long jump, the vector $Q^E(x,t)$ of external non-contact moments (forces) appearing in (2) is a zero vector, while the vector $Q^C(x)$ of external constraint moments is automatically computed by program ANTOR upon activation of one or more constraints. The respective algorithm has been described in Hatze and Venter (1981).

The last entry appearing in (2) and not yet discussed is the vector $Q^L(x)$ of joint range limitation moments. These moments provide a means of quantifying the range of joint mobility of a given individual. For hinge joints (planar motion) the following model proved successful in practical applications:

$$Q^L(\Theta,\Theta) = \frac{c_1}{(\Theta-\Theta_l)^{n_1}} - \frac{c_2}{(\Theta_u-\Theta)^{n_2}} - (b_0+b_1\Theta+b_2\Theta^2)\Theta, \quad \Theta_l<\Theta<\Theta_u \quad (5)$$

where c_1, c_2, n_1, n_2, Θ_l, Θ_u, b_0, b_1 and b_2 denote constants and Θ is the joint angle. The values of c_1, c_2, n_1 and n_2 determine the steepness of the function slopes near the boundaries Θ_l (lower boundary) and Θ_u (upper boundary), while the values of b_0, b_1 and b_2 are the model constants of the factor determining the type of damping present. If, for instance, $b_1 = b_2 = 0$, the damping is a purely viscous one.

An inspection of function (5) reveals that near Θ_l the term containing the factor c_1 dominates and produces a rapidly increasing positive moment as Θ approaches Θ_l from above. A similar situation prevails at the upper boundary as Θ approaches Θ_u, except that the moment produced is negative. Thus, the moments computed are always such as to counteract, in a highly nonlinear fashion, an overstepping of the joint range boundaries, while within the working range of the joint the moments are negligibly small. As an example, Figure 3 displays the joint range limitation torques for the left knee joint of a specific subject. The model constants appearing in (5) were determined experimentally by means of specific methods described in Hatze (1981b).

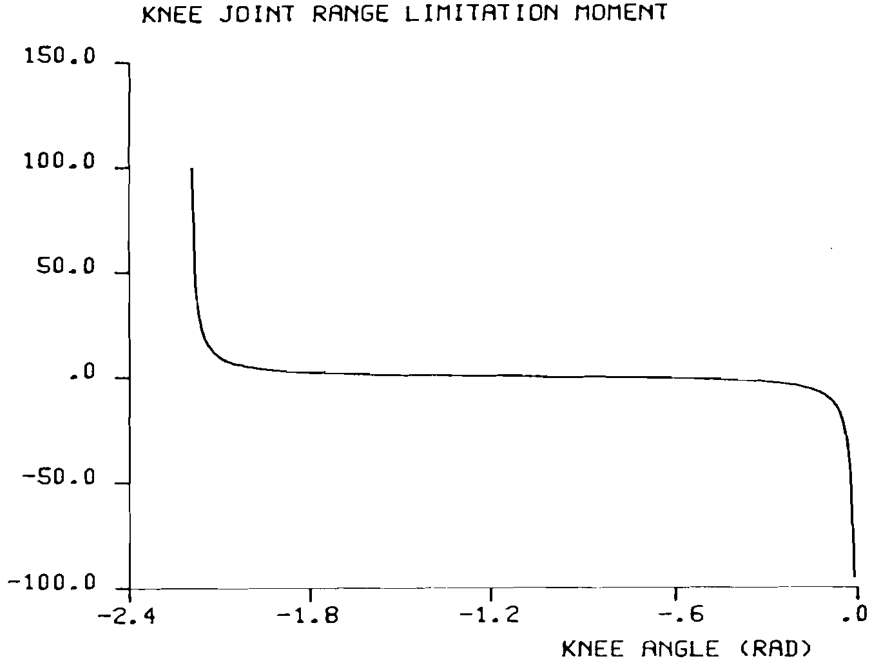

Fig. 3 Joint range limitation moment Q^L for the left knee of a given male subject. The values of the constants are $c_1=1.0$, $c_2=1.0$, $n_1=1$, $n_2=1$, $\Theta_l=-2.20$ rad, $\Theta_u=0.00011$ rad, $b_0=3.01$, $b_1=0.0$, $b_2=0.0$. The function displayed is for $\Theta=0$.

Although functions of the type (5) provide an efficient means of limiting the joint ranges in simulation models of the human neuromusculoskeletal system, they are not without problems. Owing to the steep increase of the functions near the upper and lower boundaries, and due to the presence of the damping term, the functions $Q^L(.)$ introduce inherently stiff components into the model of the executor subsystem. This may lead to excessively small integration steps and hence inefficient simulation if a joint is forced into a limiting position by large inertial and (or) muscular forces. Investigations to solve this problem are at present under way.

Having determined all functions appearing in (2), the synthesis (simulation) part of the ANSYN approach may now be carried out. However, the analysis part yielded the control moments $Q^M(t)$ only for the take-off phase of the long jump, so that for the flight and landing phase these functions had to be estimated by trial and error. This was done in a rather laborious procedure taking about 110 hours. In this process, functions $Q^M_4(t)$, $Q^M_5(t)$, ..., $Q^M_{21}(t)$ were estimated for $t \in [t_1, t_2]$, the simulation was then performed on a digital mainframe computer, the result displayed on an electronic screen in the form of successive configurations of a human figure, and corrective actions were then taken on the grounds of this visual information. In this way, the complete long jump was simulated. A super-8 mm film was made by recording, frame by frame, the video displays of the successive long jump configurations. While the simulation outputs were available at time intervals of 0.002 s corresponding to 500 frames per second, the frame rates for the production of the movie were chosen to be 25 (normal speed), 125 (moderate slow motion), and 250 (slow motion). The film permits a detailed visual analysis of the simulated motion.

Simulation (synthesis) of motions is, of course, not a purpose in itself. Rather, it serves to convey insight into the dynamic behaviour of the simulated system, allowing the application of sensitivity analysis techniques, the determination of dependencies on parameter inaccuracies, etc. In the present example of the long jump simulation, it could be observed that the performance criterion, i.e., the distance jumped exhibited a high sensitivity to

(1) changes in the initial state variables $q_{16}(0)$ and $q_{17}(0)$ which denote respectively the initial hip and knee joint angle of the (left) stance leg, and
(2) to variations in the timing of the functions $Q^M_{16}(t)$, Q^M_{17} and $Q^M_{18}(t)$, i.e. to variations in the coordination of muscular actions across the

hip, knee and ankle joint of the stance leg during the take-off phase. More detailed investigations are at present being conducted that will permit quantitative statements as to the optimal initial states and control patterns during the take-off (details in Hatze, 1981a), flight and landing phases of the long jump.

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