THE BIOMECHANICAL ANALYSIS OF STANDING FALL[*]

MIRCEA BARBUCEANU, DANIELA BĂRBUCEANU,
DANIELA GIOSANU, ION IORGA-SIMĂN

University of Pitesti, Faculty of Science, Targul din Vale Street, No. 1, Pitesti, Romania

The actual development and evolution of training, imposes a large approach to the risk to meet with an accident accepting besides the main purpose of the sporting performance, the aspects of its prevention and recovery. This work is supposed to elaborate a bio-mechanical study, in view of a risk valuation of the accidents affecting the bones and the joints, in the case of young sportsmen, as a consequence to a particular, but quite frequent motion, that is the falling down.

Key words: sports, risk, biomechanics, modeling, standing fall.

1. RISKY SPORTING MOTIONS

1.1. SPORTING FIELDS OF STUDY WITH RISKY FALL ONTO THE GROUND

As part of the tendencies often met with in nowadays competitions and sporting trainings, the wish to achieve high sporting performances, leads to a permanent growing of the number of injured or sportsmen who suffer traumas. The high level sports is an activity typically to the physical and mental condition limits of these individual, which implies a certain acceptance of the fact that the reaching and the transcending of these limits, may determine the occurrence of accidents which have as a consequence serious traumas.

This investigation has as a starting point the fact that the traumas provoked by those sport activities, cannot be excluded, but the comprehension of their objectives may have an important role in the settlement of some landmarks of sporting training and conduct, which will succeed in diminishing these traumas in what concerns their number and seriousness, besides the general improvement of training.

The Olympic sports which are in the centre of attention of the majority of discussions, offer various situations which present certain risk degrees in what concerns the accident of sportsmen. Out of all this, many are those who suppose detachment and subsequent falling onto the ground, and they can be classified in two categories:

– with obligatory, without fail and scored fall:
  – all types of gymnastics;
  – springing board jumps (skiing);
  – swinging rings;
  – figure skating, etc.
– with involuntary, unforeseeable, non-scored fall:
  – basketball;
  – football;
  – volleyball;
  – handball;
  – steeple chases etc.

In what concerns the first category, there is a great danger, especially as a consequence of the increased speed of fall, a good score obtained by the sportsman, imposing flight amplitudes previously to the relatively great fall onto the ground. However, this danger is diminished to a certain extent, by the fact that these falls are experienced and estimated by the sportsman as a result of an adequate training, based on scientifically, up-to-date methods. However, in terms of a competition, the stress that the sportsmen have to undergo, leads to some little inaccuracies in self-control and performance which are frequently deadly, or they bring about accidents.

As for the second category of sports which imply fall onto the ground, the impact conditions with the ground are quite harmless; however in such a case the risk of an accident is increased by the fact that the typical jumps are unforeseeable (in basket "at the head", for throwing, etc.) in all their aspects: speed, falling angle, the moment of the fall, disturbances during the flight itself etc. As a consequence to this, the sportsman is in many cases, "caught on the wrong foot", such a thing doesn't allow him to have a proper control of the fall, which triggers the same consequences.

1.2. TYPES OF TRAUMAS; AFFECTED ANATOMICAL STRUCTURES

Out of the majority of investigations, it results that serious injuries in the case of Olympic sports, generally affect the bones and the joints, also implying cartilages, tendons, ligaments.

The most often met traumas which affect the bones, are the clefts and the fractures, and in what concerns the joints, the traumas can be: sprains and luxations. The condition which makes one's bones and other joints stiff and painful

is called osteoarthritis. Traumas represent a functional and sometimes morphological alteration of the typical tissues, and are generally accompanied by pains. Such a trauma takes place when one or more structures of the muscles and of the bones are put to mechanical actions (mechanical forces, moments, pressures etc.) which surpass the respective endurance limits of these structures (to stretching, torsion, compression, etc.).

Traumas can be of two types:

– <u>acute</u> (luxations, stretching of muscles, etc.) - anomalies of the muscles and bones' structures caused by mechanical actions, superior to the endurance limits of the healthy tissues. These mechanical actions crop up, either when the sportsman is relaxing, or as a consequence of some wrong movements that he has performed.

– <u>chronically</u> (fractures, affections of the tendons, etc.) - anomalies of the muscles and bones' structures, caused by mechanical stresses, inferior to the endurance limits of the structure's tissues, but in the circumstances in which the respective tissues, for some reason or another, do not have the normal strength capacity. These ones diminish on the one hand the endurance limits of the implied structures, and on the other hand, the sportsman's capacity of concentration (he can't perform properly the respective movements).

1.3. BIOMECHANICAL SOLUTIONS

As we have seen so far, the risk of accidents in what concerns the fall onto the ground in sports, is a real, considerable one, and it leads to great personal or collective damages.

As a consequence to this, the problem of the stressed diminution of this risk seems more and more acute. The natural question is obviously: HOW?

Until a few years ago, the answer to this question was ambiguous to a certain extent. At that time, one used to resort to empirical training methods, based on the experience or on the intuition of some trainers which ended in dissatisfactory results in most of the cases. As the biomechanical sporting developed, as an independent science, it became more and more clear that this was the only capable one to offer the scientifically bases - and consequently the only correct ones of improving the sportsmen trainings in order to get the performance and the diminution of any risk of accidents.

As we said in the previous discussions, the big problem concerns the finding of some solutions in order to obtain performance in maximum security conditions in what concerns the sportsman's integrity.

A series of investigations from the last years, confirms the efficiency of the directions and of the sportsmen's training education, in terms of the pedagogical process, within which one has taken into consideration their typological qualities, corroborated with the best movements, typical to this typology and to the respective sporting field of study.

It is precisely this optimum which is given by biomechanics. By analyzing the typological characteristics of different classes of sportsmen, and the final purposes of any sporting activity (typical performances and risks), this applied branch of the biophysics, biomechanical models the phenomenon, and, in terms of it, in a theoretical way, it establishes one or a few variants of the ideal sportsmen and of the best states or movements of achieving these purposes.

The applied part is continued afterwards by the trainers. These ones, selecting hundreds of sportsmen, are looking for the best gifted, that is those who by their sporting qualities are the most close to the theoretical ideal. Once selected, these ones are trained, so that, after a while, their exercises could aim at the biomechanical optimum, and could be performed in the most proper and natural way (in order to become conditioned reflexes). This fact is pursued by the selection and training of sportsmen.

2. GENERAL CONSIDERATIONS

For the purpose of a simplification which could make possible the writing of some mathematical equations, but who mustn't lose anything of the mechanical significance of the real pattern in what concerns us, we will consider from the beginning the following hypothesis:

– the superior part of the human body (from the hips upwards) is a stiff solid, of negligible size, similar to a heavily material point (we are interested in the possible accidents of the inferior part of the body);

– the inferior part of the human body is reduced to only one leg ("double") made up of three stiff sections;

– the stiff system, considered in this way, is set in motion by a complex of nine muscles, coupled by the agency of tendons which we would consider as being laid ropes; this complex of muscles will represent the main muscular properties within the biosystem of one's legs.

3. THE BIOMECHANICAL MODEL

The human body implied in the already studied biomechanical phenomenon, can be modeled as a system of articulated rigid bodies, leant on the ground and put to some external functions. More precisely, we can tell that we have to do with a biomechanism. In the first figure, it is sketchily represented the skeleton of the inferior part of the system responsible for the locomotion and its mechanical characteristics, whilst in the second figure, it is sketchily represented the biomechanism studied.

The modeled muscular groups are those represented in the key of Figure 2. These act over the stiff linear sections which model the skeleton's bones in points, whose position must be established with a certain precision, so that, once estimated the muscular brawn, the couples of forces from the joints could be estimated. The stiff sections are jointed to one another, respectively they are jointed to the body through ideal joints (spherical couplings without friction).
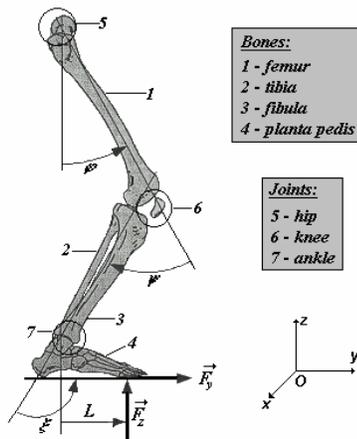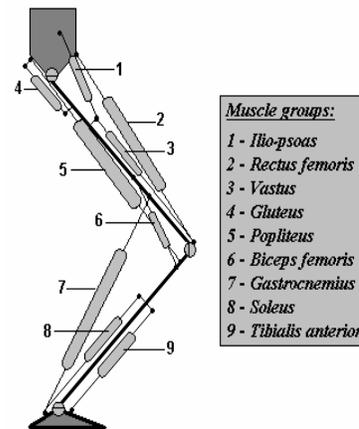

Fig. 1   Fig. 2

For the reasons of this study, it will be enough to consider the analyzed motion as being plane (it takes place in the plan *Oyz* - the sagittal plan) that is the equivalent biomechanism is plane.

4. THE MATHEMATICAL MODEL OF THE MOTION

The mathematical simulation of the considered biomechanism will be given by a corresponding matrix equation. Its general form is that of kinetic equilibrium, resulted from d'Alembert's principle (in the Lagrangean formalism):

$$[M(q)]\ddot{q} + g^c(q,\dot{q},t) = g^e(q,\dot{q},t) \qquad (1)$$

where the terms and the notations used have the following physical significances:

q - the generalized position vector, $q = (q_1,...,q_l)^T$;

l - the number of the system's degrees of freedom;

$[M(q)]$ - the inertia matrix; the general form:

$$[M(q)] = \sum_{i=1}^{n} \left(m_i R_{T_i}^T R_{T_i} + J_{S_i}^z R_{R_i}^T R_{R_i} \right) \tag{2}$$

$\vec{g}^{\,c}(q,\dot{q},t)$ - the force of inertia's resultant; the general form:

$$\vec{g}^{\,c}(q,\dot{q},t) = \sum_{i=1}^{n} \left(m_i R_{T_i}^T \vec{a}_{S_i} + R_{R_i}^T \vec{\varepsilon}_i \right) \tag{3}$$

$\vec{g}^{\,e}(q,\dot{q},t)$ - the resultant of the applied forces; the general form:

$$\vec{g}^{\,e}(q,\dot{q},t) = \sum_{i=1}^{n} \left(R_{T_i}^T \vec{f}_i^{\,e} + R_{R_i}^T \vec{M}_{S_i}^{\,e,z} \right) \tag{4}$$

$\vec{f}_i^{\,e}$ - the external applied forces;

$\vec{M}_{S_i}^{\,e,z}$ - the external applied moments, reduced in comparison with the centroids.

(the other unexplained quantities have the usual significance).

In the following analytical considerations, we will create a set of notations whose material is rendered in Figure 3.
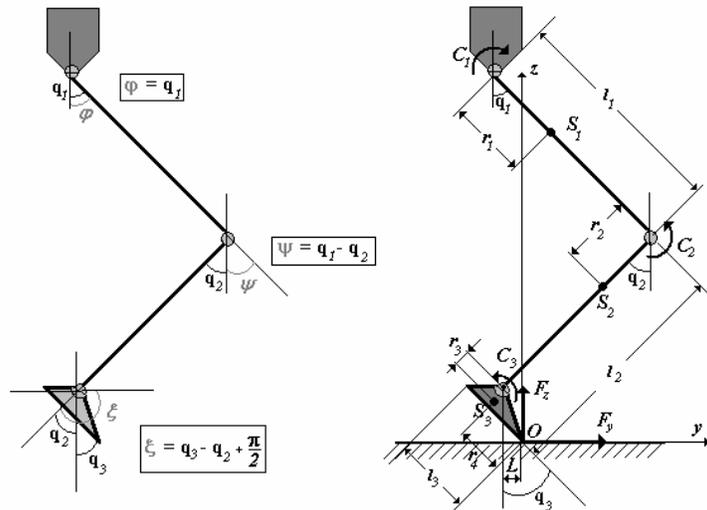

Fig. 3.

We will also work in an unitary matrix form (the method of the homogeneous operators). We will successively obtain:

- the inertia matrix of the biomechanism:

$$[M] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & M_{11} & M_{12} & M_{13} \\ 0 & M_{21} & M_{22} & M_{23} \\ 0 & M_{31} & M_{32} & M_{33} \end{bmatrix} \quad \begin{cases} M_{11} = J_{S_1} + m_1 r_1^2 + (m_2 + m_3) l_1^2 \\ M_{12} = (m_2 r_2 + m_3 l_2) l_1 \cos(q_1 - q_2) \\ M_{13} = m_3 l_1 [r_3 \cos(q_1 - q_3) + r_4 \sin(q_1 - q_3)] \\ M_{21} = M_{12} \\ M_{22} = J_{S_2} + m_2 r_2^2 + m_3 l_2^2 \\ M_{23} = m_3 l_2 [r_3 \cos(q_2 - q_3) + r_4 \sin(q_2 - q_3)] \\ M_{31} = M_{13} \\ M_{32} = M_{23} \\ M_{33} = J_{S_3} + m_3 (r_3^2 + r_4^2) \end{cases} \quad (5)$$

- the resultant of the inertia forces:

$$\vec{g}^c = \begin{bmatrix} (m_2 r_2 + m_3 l_2) l_1 \sin(q_1 - q_2) \dot{q}_2^2 + m_3 l_1 (r_3 \sin(q_1 - q_3) - \\ -r_4 \cos(q_1 - q_3)) \dot{q}_3^2 + [m_1 r_1 + (m_2 + m_3) l_1] \cos q_1 a_y(t) - \sin q_1 a_z(t) \\ \\ (m_2 r_2 + m_3 l_2) l_1 \sin(q_2 - q_1) \dot{q}_1^2 + m_3 l_2 [r_3 \sin(q_2 - q_3) - \\ -r_4 \cos(q_2 - q_3)] \dot{q}_3^2 + (m_2 r_2 + m_3 l_2) \cos q_2 a_y(t) - \sin q_2 a_z(t) \\ \\ m_3 l_1 [r_3 \sin(q_3 - q_1) + r_4 \cos(q_3 - q_1)] \dot{q}_1^2 + m_3 l_2 (r_3 \sin(q_3 - q_2) + \\ + r_4 \cos(q_3 - q_2)) \dot{q}_2^2 + m_3 [(r_3 \cos q_3 - r_4 \sin q_3) a_y(t) + (r_3 \sin q_3 + r_4 \cos q_3) a_z(t)] \end{bmatrix} \quad (6)$$

- the resultant of the applied forces:

$$\vec{g}^e = \begin{bmatrix} F_y(t) l_1 \cos q_1 + ((F_z(t) - (m_2 + m_3) g) l_1 - m_1 g r_1) \sin q_1 + C_1 - C_2 \\ \\ F_y(t) l_2 \cos q_2 + ((F_z(t) - m_3 g) l_2 - m_2 g r_2) \sin q_2 - C_2 - C_3 \\ \\ F_y(t)(l_3 \cos q_3 - L(t) \sin q_3) + F_z(t)(l_3 \sin q_3 + L(t) \cos q_3) - \\ - m_3 g (r_3 \sin q_3 + r_4 \cos q_3) + C_3 \end{bmatrix} \quad (7)$$

The quantities which have never before been met with, have the following significance:

$a_y(t)$ - the horizontal acceleration of the hip-coupling (coupling 1);

a_z *(t)* - the vertical acceleration of this coupling;

l_1 - the length of the section *i;*

L(t) - the distance measured from the ankle's joint up to the contact point with the ground (the point of application of the ground's reactions);

t - the time;

C_i - the couple forces which take action in the joint *i*.

5. APPLICATION: REAL ANALYSIS

Next we will take into consideration a concrete, numerical case, based on data collected from a real experiment, realized within this work. In the limits of a physical study, we will confine ourselves to describe the realized experiment in view of a complete system of figures.

As it can be observed from the previous written relations, the calculation of these three groups imposes first of all that one be familiar with the number of the anthropometrical data of the respective sportsman (l_i, r_i, m_i, J_{si}). Generally, this problem is not solved for a special sportsman. One has in view independent categories of sportsmen, function of sex, age and typology, for which the respective mediate data, are listed.

We have registered figures concerning a sportswoman, which could be placed in the following category:

– sex: female;

– age: 10–12 years old;

– typology: Caucasian (European);

– mass = 26 *kg* (the total medium weight of the sportswoman);

– length = 1,30 *m* (the medium height of the sportswoman);

For this, the listed data (Hannavan Tables) are the following:

– l_1 = 0,3 *m* (the medium length of the thigh);

– l_2 = 0,3 *m* (the medium length of the shank);

– l_3 = 0,15 *m* (the medium length of the sole)

In terms of the anthropometrical formulas internationally acknowledged, we have obtained the following values of the quantities implied in the previous established expressions:

r_1 = 0,1116 *m*;	m_1 = 2,6702 *kg*;	J_1 = 0,0290 *kg m²*;
r_2 = 0,1112 *m*;	m_2 = 1,1310 *kg*;	J_2 = 0,0130 *kg m²*;
r_3 = 0,0300 *m*;	m_3 = 0,3822 *kg*;	J_3 = 0,0019 *kg m²*.
r_4 = 0,0693 *m*;		

The analysis of the final formulas from the previous paragraph, shows us that, for a numerical evaluation, besides the formerly established data, there are still necessarily direct measurements concerning the variations during the fall-from the stated contact with the ground, until the final stopping - of the following quantities:

$$F_y,\ F_z,\ q_1,\ q_2,\ q_3,\ a_y,\ a_z,\ L$$

In this experiment, these ones have been determined by using a video-computing analysis as follows:

➢ For the respective age category, one has recorded with high-speed camera (250 *frames/second*) a fall onto the ground of a sportswoman in a competition, having the anthropometrical parameters very close to those in the chart. Consequently, the image has been digitized, by using an PC and an adequate soft (card of digital capture). Finally, the digitized film was processed into, frame by frame, with the help of a specialized soft, namely "*World in motion*". This soft has offered us data under the form of the following graphical temporal variations (accompanied by experimental values, with a time basis corresponding to the filming speed, $t = 0.05\ s$):
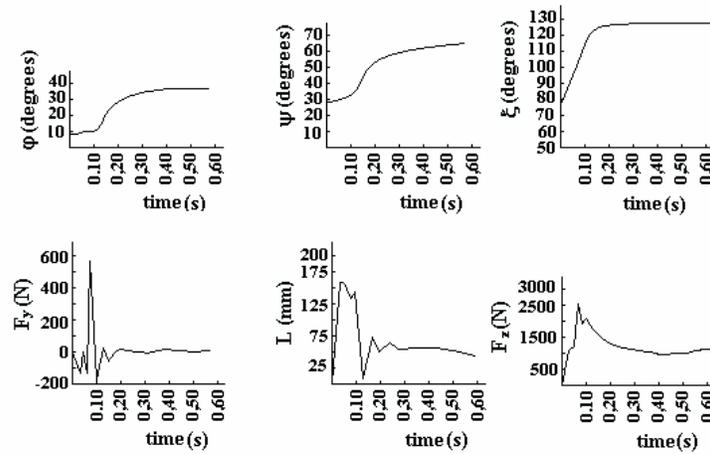

Fig. 4. The relative angles, the components of the ground's impact and the length L variation during the fall

These are the dates accessible to the respective soft. However, they are sufficiently, because according to them we can calculate the temporal variation of the other necessary parameters. Therefore, we have:

– the absolute angles (the generalized coordinates):

From the relations in Figure 5 it results:

$$
\begin{aligned}
q_1 &= \varphi \\
q_2 &= \varphi - \psi \\
q_3 &= \xi - \psi + \tfrac{\pi}{2}
\end{aligned}
\tag{8}
$$

- the components of the hip's acceleration:

In Fig. 3, considering the notations for the couplings from the same joints as those of the couplings, one can notice the following vectorial relation:

$$\overrightarrow{OC_1} = \overrightarrow{C_1C_2} + \overrightarrow{C_2C_3} + \overrightarrow{C_3O} \tag{9}$$

which, studied by each component, gives exactly the abscissa of the point C_1, that is of the hip:

$$Y = l_1 \cos q_1 + l_2 \cos q_2 + \frac{L}{tg q_3}$$
$$Z = l_1 sin q_1 + l_2 \sin q_2 + L \tag{10}$$

hence, the quantities from the right side of the equal marks, being already known, we can determine:

$$a_y = \ddot{Y}$$
$$a_z = \ddot{Z} \tag{11}$$

Next, we will describe the algorithm of the numerical resolution, according to which we have estimated the value of the three couples from the joints of the inferior part of the sportswoman's body, responsible for the greater part of accidents, that is for the acute traumas. There are the following stages which must be pursued:

1. One calculates the values of the generalized coordinates − q_1, q_2, q_3 − at the respective time moments, on the basis of the previous established formulas and of the charts containing numerical data obtained by a video-computing analysis.
2. One calculates by adequate numerical methods their first and second order derivates.
3. One calculates the values of the functions Y and Z at the moments t_j.
4. One calculates numerically the second order derivates of these functions.
5. One calculates the hip's vertical and horizontal accelerations, a_y, a_z, at the moments t_j.
6. One calculates the elements of the inertia matrix (unique-they don't depend on time).
7. One calculates the elements of the matrix g^c, at the moment t_j.
8. One calculates the elements of the matrix g^e, in terms of the formula (3) at any time moment t_j.
9. One calculates the couples from the joints, C_1, C_2, C_3, in terms of knowing the values of the matrix elements and of their expressions, at any time moment t_j.

10. One interpolates the resultant values, in the end getting the approximate variation of the couples from the leg's joints during the fall, for the respective sportswomen.

11. One determines numerically the extreme absolute and local values registered by these couples during the motion.

12. The extreme values are compared to the extreme physiological values (those over which appear affections of the respective joints), estimating the danger of producing some affections at the level of the system's components, responsible for the locomotion.

The maximum numerical values of these three couples resulted within the described numerical application, were:

$$C_1 = 0{,}27 \; Nm \qquad\qquad C_2 = 0{,}39 \; Nm \qquad\qquad C_3 = 0{,}31 \; Nm \qquad (12)$$

The limiting physiological value - over which can occur traumas - for a joint similar to the three joints of the inferior part of the human body (the hand's joints affections and the arthritis) are considered to be of the order:

$$C_r = 0{,}1...0{,}3 \; Nm \qquad\qquad\qquad (13)$$

One can notice the similarity of the quantity order. In the implied approximations of the biomechanical simulation comprised in the study, this fact leads, at this first phase, to the conclusion of the existence of a real danger, which generates acute traumas at the level of the respective joints. Next, in terms of the existent pattern, we can make clear the best avoiding methods of the extreme situations - we refer to the typical biomechanical improvements, which presuppose the calculation of the so-called functional-cost, to whom are consequently imposed extreme conditions modeled in accordance with the reality of the individual physical exercises.

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