Aspects regarding the traumatology of the foot in the body jumping

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Abstract. The aim of this paper is to make the connection between the forces in the lateral ligaments of the ankle joint and in the Achilles tendon, with the forces of ground reaction, for the vertical jump with landing on one foot or both. The fall is experimental analyzed, on a platform of force, when the contact of the foot on the platform is on the whole sole of the foot or on an edge, outer or inner. The ligaments of the ankle joint for which the forces are determined are the deltoid ligament and the calcaneo-fibular ligament. These ligaments are subjected to high forces when the fall on one leg, from a jump, takes place on one edge of the sole of the foot. In this case there is the possibility of ligament rupture, so an analysis and a mathematical simulation can highlight situations that could cause trauma. The paper is a continuation of previous research by the authors in which the forces in the mentioned lateral ligaments and in the Achilles tendon were determined, based on a biomechanical model.

1. Introduction

The jump from the place can be dominantly horizontal or dominantly vertical and the landing, respectively the contact of the foot on the ground, can be on the whole sole, on the toes or on the heels. The biomechanics of jumping start from the muscular kinetic energy that is converted into the body's potential energy. During the vertical jump, the propulsive force must exceed the force of the body weight [1]. The balancing of the arms has the effect of increasing the acceleration of detachment from the ground and, implicitly, of increasing the vertical propulsive force [2]. Landing from the vertical or horizontal jump can be analyzed in biomechanics from a traumatological perspective, respectively in terms of joint, ligament or muscle injuries that may occur. The cause of an incorrect landing, which leads to trauma, is the inability of the individual to maintain proper body balance or postural control [3, 4, 5, 6]. Regarding the ankle joint, its functional instability is associated with reduced muscle strength, muscle imbalance, ligament relaxation and postural imbalance [7]. Functional instability can also occur due to delayed reflex responses to stress of the ankle ligaments, due to damage to the receptors of the joint at the time of the initial injury [8].

There is also research [9] that shows that a dynamic control of joint stability is influenced to a much greater extent by the mechanisms of advance or anticipation of the central nervous system, rather than by feedback through periodic reflexes.

The determination of the analytical expressions of the forces that appear in the calcaneo-fibular and deltoid ligaments, as well as in the Achilles tendon, during the dominant horizontal jump, from running, with landing on toe, were determined by the authors in a previous paper [10]. The numerical results used the vertical component of the ground reaction force, determined experimentally and the
other two horizontal components were approximated as a certain percentage of the vertical force. With the help of that theoretical model, the cases when the traumas of the studied ligaments or of the Achilles tendon appeared could be highlighted.

The current paper aims to highlight the forces and moments of reaction forces with the ground at the dominant vertical jump, from the spot, with landing on the inner and outer side of the sole of the foot.

A force platform was used to experimentally determine the components of the torsor of the ground reaction force.

2. Theoretical considerations

A physical simplified model of the ankle joint is presented in [10]. In this model are highlighted the lateral ligaments of the ankle joint, the Achile's tendon and the calculus relations for ligament force $R_1$ and Achile's tendon force $R_A$. Figure 1 shows the two ligaments for which the forces were determined when the reaction force with the ground is assumed to be concentrated in a point on the inner or outer side of the sole of the foot, point towards the tip of the foot.

![Figure 1. Lateral ligaments of the ankle joint](image1)

In a state of contact on one side of the sole of the foot, as seen in Figure 2, only one of the two ligaments considered is strained at maximum, the other not being strained.

![Figure 2. Lateral contact of the sole of the foot with the ground](image2)

Based on the dynamic balance and taking into account the anthropometric dimensions of the foot, the calculation relations for the ligament force and from the Achilles tendon, were determined as follows [10]:
where: \( a, b, c, d, e \) – are anthropometric dimensions of the foot;
\( F_z \) – is the vertical reaction of the foot on the ground;
\( F_x, F_y \) – reactions with the ground in the horizontal plane;
\( R_l, R_A \) – ligament and tendon forces, respectively.

The + or - signs are used for either the deltoid ligament or the calcaneo-fibular ligament, depending on the contact between the edge of the sole of the foot and the ground.

3. Numerical results

For the numerical evaluations, experimental measurements were done regarding the force reaction between foot and soil. There were measured the force components \( F_x, F_y \) and \( F_z \), using the system AMTI AccuGait. This is a portable system for analysis and quantification of human gait. It has sensors of type Hall and together with the software NetForce/BioAnalysis, it allows to measure the forces \( F_x, F_y \) and \( F_z \) and the torques \( T_x, T_y, T_z \), function of the individual parameters of the patient. This system is connected to the platform AccuGait Walkay. This platform is made from aluminum-based composite material, in length of 2.9 meter, at the middle of which it is placed the force plate AccuGait (Figure 3, Figure 4).

![Figure 3. Systems of measuring the reaction force with the soil: a) AccuGait ; b) AccuGait Walkay](image)

![Figure 4. The axes systems attached to AccuGait platform](image)

For two human subjects, data were acquired, for the following types of motions:
- normal speed gait – stepping forward with the right foot (denoted with mn);
- jumping in one leg (denoted with sp)
- jump on both feet, with equal landing on the surface of the sole (denoted with ap);
- jumping on both legs with external contact (denoted with sext);
- jumping on both legs with internal contact (denoted with sint).
Each motion was repeated 5 times. The values were registered with the software NetForce/BioAnalysis. The average of these values was represented graphically, versus time, making a comparison between the two subjects, both for forces and for torques (Figure 5, a...j).
Figure 5. Forces and moments for two subjects, depending on the activity performed: going at normal speed: forces (a), torques (b); jumping on one leg: forces (c), torques (d); jumping on both legs: forces (e), torques (f); jumping on both legs with external contact: forces (g), torques (h); jumping on both legs with internal contact: forces (i), torques (j).

Table 1 shows the calculated values of the ligament forces and from the Achilles tendon, for the five cases: normal gait (mn), jump on one leg (sp), jump on both legs (ap), jump on both legs with external contact (sext); bounce on both legs with internal contact (sint).

The results presented in the previous table correspond to both the first case of extreme support of the foot, respectively point A, and the second case of support of the extreme foot of the foot (point B, on the inside).

Table 1. Calculated values of ligament and Achilles tendon forces for both subjects.

| Motion [abr.] | Subject | G [N] | H [m] | Fx [N] | Fy [N] | Fz [N] | Rl [N] | RA [N] |
|---------------|---------|-------|-------|--------|--------|--------|--------|--------|
| mn            | 1       | 740   | 1.71  | 41.48  | -35.2585 | 773.4953 | 823.4982 | 418.1533 |
|               | 2       | 686   | 1.65  | 46.8554 | -37.9476 | 775.9512 | 829.7678 | 391.8671 |
| sp            | 1       | 740   | 1.71  | 1.84075 | 6.4135  | 704.6863 | 713.7818 | 1142.91 |
|               | 2       | 686   | 1.65  | 2.3808  | 6.2248 | 557.5968 | 566.4247 | 905.1114 |
| ap            | 1       | 740   | 1.71  | 4.295  | 3.80925 | 742.5988 | 734.0008 | 1206.34 |
|               | 2       | 686   | 1.65  | 2.1842  | 0.521 | 736.3386 | 737.1075 | 1194.461 |
| sext          | 1       | 740   | 1.71  | -0.2702 | 4.8964 | 704.6052 | 711.5492 | 1141.485 |
|               | 2       | 686   | 1.65  | 0.0248  | 4.2712 | 737.2022 | 743.2595 | 1194.08  |
| sint          | 1       | 740   | 1.71  | 0.908   | 4.74  | 704.4974 | 1141.835 | 711.2196 |
|               | 2       | 686   | 1.65  | -0.9818 | 4.8442 | 738.0654 | 1196.267 | 744.9354 |
In Table 1, H is the height of the subject and G is the force of weight of the subject. The forces determined in Table 1 have relatively small values due to the fact that the height at which the jump was performed did not exceed 10 centimeters.

4. Discussions
As can be seen from the calculated data, the highest values result for the forces in the Achilles tendon in most cases, as expected. It is also observed that all the values of the forces of the calcaneo-fibular ligament are comparable with the weight force of the subjects, for the case of jumping on both legs with internal contact being clearly superior to it. These values therefore constitute the critical limits of the ligament and Achilles tendon forces, from which injuries can occur.

Theoretical calculations, which must be confirmed by experimental measurements, but possible, electromyographically, only for the Achilles tendon, can contribute to determining the critical threshold, individualized to each athlete, starting from which accidents can be caused. Comparisons with the experimental values of the forces that cause rupture in a ligament contribute to the definition of the "tolerance" of stress on the joint, specific to each person. Knowing such a tolerance allows the coach, but also the sports doctor, to recommend to some athletes, more than others, the necessary caution in performing jumps, as well as, possibly, taking precautions.

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