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Standard tests ability to measure impact forces reduction on mats

Pedro Pérez [1], Salvador Llana [1], Enrique Alcántara [2]

[1] Department of Physical education and Sports (University of Valencia, Spain).

[2] Institute Biomechanics of Valencia (Polytechnic University of Valencia, Spain)

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Abstract. Landing is one of the most important and dangerous actions that a gymnast takes. Although landing mats are supposed to meet standard criteria, the number of injuries in this action continues being high, which has raised questions as to the validity of the standard. In this study was analysed the effect of the mat on different kinematical and kinetic variables during gymnast landing, and it was examined the validity of normative tests to predict such variables. 5 elite gymnasts performed several landings on a sample of 6 mats previously selected on the basis of their mechanical behaviour. Maximum vertical reaction forces and peak tibial and forehead acceleration were analysed, with average maximum reaction force of 4450 ± 195.34 N, and 15.57 ± 0.54 g and 4.72 ± 0.55 g on tibial and forehead acceleration respectively. Gymnasts modulate execution based on mat properties, and not all the biomechanical variables studied are faithfully reproduced in the mechanical tests of the standard, which could have some influence on the occurrence of certain injuries.

Keywords: impact forces, acceleration, mechanical test, gymnastic.

1. Introduction

In gymnastics, the main mechanical loads gymnasts face in their training [1] and competition take place during the landing [2,3,4]. Landing is not only relevant for the final competition score but also because it is an action that entails a high risk of injury, mainly due to the high impact magnitudes and to instability on the mat [3,5,6].

Between 55-65% of injuries in gymnastics occur on the lower extremities; they are related with high repetition frequencies [7], 50-70 % of lower limb injuries occurring on the tibiotalar and knee joints [8,5]. Several authors [6,8,9] argue that poor sporting materials and equipment can be linked to an increased injury rate. In this regard, in gymnastics, mats are one of the most important protective elements and a major extrinsic injury factor [10]. If we also consider that high heights can be reached during the flight of almost 4 m [11,12], then mats play an important shock absorption role: the higher the flight, the greater the impact forces at landing: between 10-14 times the gymnast's weight [1,3,13,14].

In comparison with other sports [15,16,17], gymnasts do not use shoes that can protect them from high impact magnitudes or improve stability. Mats are for them the only element between their feet and the floor and therefore a possible injury factor [2,18]. Hence, mat properties play a very important role, and standards like the Fédération Internationale de Gymnastique (FIG) or the European Regulation (E.N. 12503 -1) try to lay down strict and specific criteria for the properties and features of the mats.

But, despite such rules, the incidence of injuries on mats has important effects [2,9,19]. This could be due to several reasons: 1) the mats used may not conform to the standards, in which case their use should be banned [this is not likely to be the case, at least in important competitions), 2) normative mechanical tests may not correctly simulate body/mat interaction or the strategies used by gymnasts during landing [9,19,20], and 3) normative mechanical tests may not record all the relevant properties and features of the mat such as recovery speed or areaelastic and homogeneous behaviour [4].

Based on the above, the main goals of the study were: (a) to analyse the effect during landing on several mat types on kinetic (reaction forces) and kinematic variables (tibial and forehead acceleration) related to landing impacts, and (b) to examine the validity of normative tests to predict these biomechanical variables.

2. Methodology

Prior to conducting the biomechanical tests, mats were selected on the basis of their mechanical features according to EN 12503. To that end, 23 mat prototypes were produced, their structures and materials being similar to those of gymnastics mats. 1 x 1 x 0.2 m test tubes were extracted from the prototypes in order to test them against standard *"EN 12503-4:2001 Determination of shock absorption test"* (Figure 1). Using a uniaxial accelerometer (ISO 6487) and a 500 Hz sampling frequency, the decelerations of a 20 kg mass was recorded when it impacted the mat after falling from a 0.8 m height. This operation was repeated 10 times on each mat.

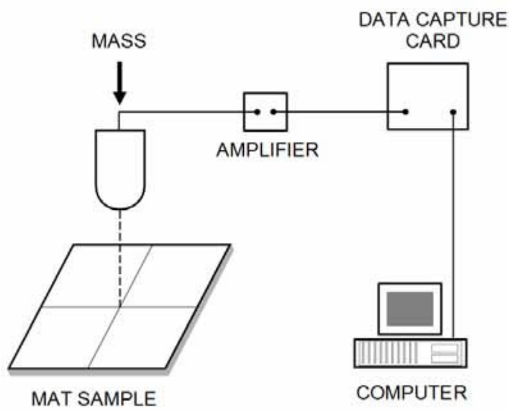

Figure 1.- EN 12503-4:2001 "Determination of shock absorption test".

Through the Matlab.6® application, maximum values were obtained for the shock absorption, deflection and resilience curves of each mat. Later, using the SPSS.10® statistical package, a dispersion and variance analysis (ANOVA) was conducted, with multiple post hoc comparisons (Bonferroni) for differences with a $p < 0.05$ significance level.

Five top male gymnasts participated in the biomechanical tests voluntarily (weight: 68 ± 5.9 kg, height: 1.7 ± 0.07 m). All subjects were informed verbally and in writing about the nature of the study, including all potential risks. Written informed consent was obtained prior to participation and the ethics committee of the University of Valencia granted ethical approval. Each gymnast jumped 5 times from a platform at 0.8 m from the ground (a similar height to the one specified by the standard for a 20Kg mass) on each of the mats selected.

As in other studies [2,5,14], the type of jump used was a *"Drop landing"*, modified as follows : (a) gymnasts let themselves fall in such a way that the height did not surpass 0.8 m [21], (b) their hands were to remain on the hip during execution, (c) the centre of gravity had to remain as vertical as possible, minimising horizontal displacement [21], and (d) the gymnast had to become stable as soon as possible after contacting the mat, without jumping. To get familiar with the type of jump, before the test, the gymnasts warmed up, performing 5 of the jumps previously described. During the tests, to avoid possible fatigue, 30 seconds were allowed for between jumps on the same mat and 3 minutes between different mats. Variables and instruments are listed next:

- Reaction forces were obtained by means of a dynamometric platform, Dinascan/IBV® 8.1 (500 Hz), fitted under the mat.
- Tibial and forehead acceleration were measured by two uniaxial low-mass accelerometers, 3031 ICSENSORS® (500 Hz) and Giles® (750 Hz).

Data were analysed by MATLAB 6®, signal curves being obtained according to time; the following parameters were selected:

- Maximum vertical reaction forces (Fmax),
- Peak tibial (TD) and forehead acceleration (HD).

The statistical processing of the parameters using SPSS.10® consisted of:

(a) Outliers analysis: exploratory analysis of the parameters obtained in the curves of the signals obtained (using simple box diagrams, summarised by case groups). This allowed us to eliminate data points considered to be outliers.

(b) A variance test: ANOVA using mat and gymnast with fix variable, and mechanical and biomechanical factors as dependent variables analysis. The factorial model used was completed with type III squares addition. Significant differences were assessed via multiple post hoc comparisons (Bonferroni) for the means per gymnast and mat, with descriptive statistics that used a $p<0.05$ significance level (95% confidence interval).

(c) A correlation analysis (Pearson), between biomechanical and standard mechanical variables, a $p<0.05$ significance level being established (95% confidence interval).

3. RESULTS.

3.1. Results of mechanical tests conducted on the mats:

The ANOVA of each variable analysed in the E.N 12503-4:2001 tests on a sample of 23 mats showed significant differences between mats ($p < 0.05$) and a wide range of results in shock absorption (10.1m/s^2 / 20.8 m/s^2), deflection (106.1mm / 190.2 mm) and resilience (17.4% / 41.4%). These findings allowed us to select a sample of 6 mats with significant mechanical behaviour differences (Figure 2).

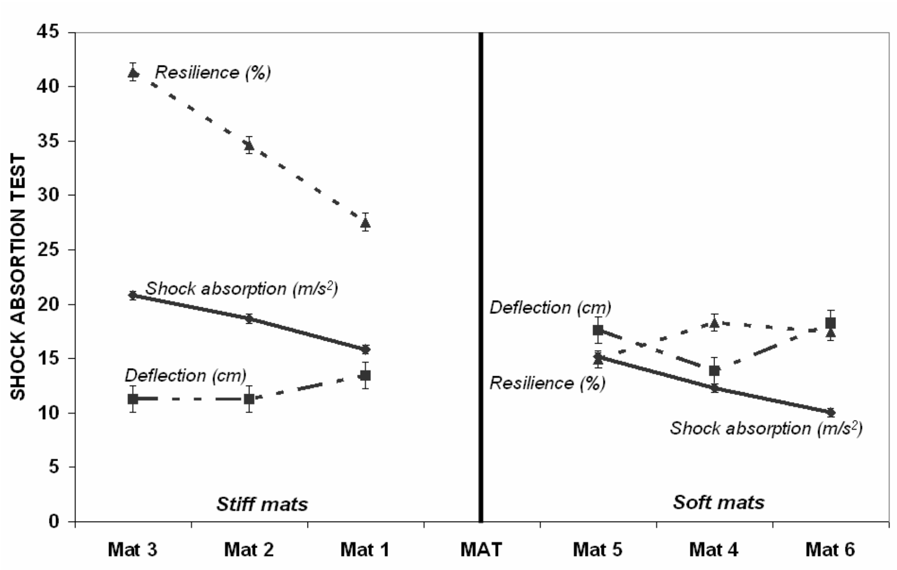

Figure 2. Selection of mats with significant differences in EN 12503-4:2001 tests**.**

3.2. Results of gymnast tests:

Three phases were identified in the landing: (1) phase 1 included the gymnast's take off and flight towards the mat, (2) phase 2 covered impact and subsequent stabilisation on the mat, and (3) phase 3 constitutes the end of the landing, when the gymnast goes back to a standing position. As per the goals set by the study, these are the most relevant results of phase 2.

Deceleration values clearly showed a typical curve (Figure 3) with 2 peaks on tibia (DT1 and DT2) and forehead (HD1 and HD2). Mean tibia values were 4 times higher than those recorded for the forehead: DT1 = 15.57 ± 0.54 g and DT2 = 11.62 ± 0.69 g for tibia accelerations, and HD1 = 4.72 ± 0.55 g and HD2 = 3.05 ± 0.27 g for forehead accelerations. Vertical ground reaction force values drew a typical curve with a clearly identifiable peak (Fmax) whose mean value was 4450 ± 195.34 N. Mean impact magnitude (times body weight) was different for each mat: 6.9 BW (M1), 7.4 BW (M2), 7.4 BW (M3), 6.3 BW (M4), 6.1 BW (M5) and 5.9 BW (M6).

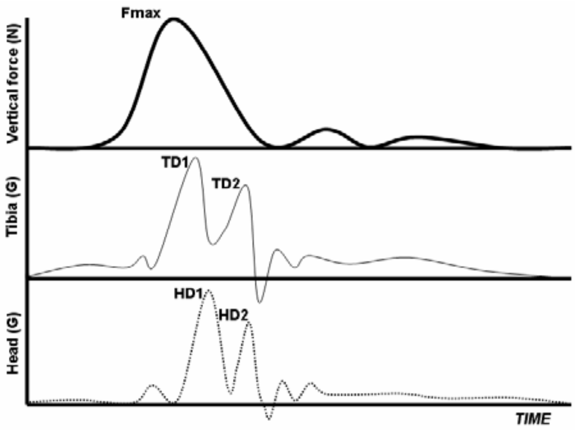

Figure 3.- Time chart of vertical reaction force and tibia/forehead acceleration.

The ANOVA between the analysed variables showed that they were dependent on the type of mat, some of them having significant differences ($p<0.05$) (Table 1).

Table 1: ANOVA results for the studied variables (mean ± SD, *N*=5).

	Mats					
Variables	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**
Fmax	[2,3,4,5,6] 4605.67 (215.24)	[1,4,5,6] 4918.77 (176.24)	[1,4,5,6] 4903. 94 (247.93)	[1,2,3,6] 4201. 83 (149.81)	[1,2,3] 4105.31 (186.22)	[1,2,3,4] 3966.78 (196.58)
TD1	[5,6] 14.81 (0.91)	[4,5,6] 15.36 (0.89)	[4,5,6] 15.57 (1.54)	[2,3] 14.07 (0,80)	[1,2,3] 13.56 (0.94)	[1,2,3] 11.62 (0.89)
HD1	[4,5,6] 4.5 (0.85)	[4 ,5,6] 4.72 (0.55)	[4,5,6] 4.55 (0.53)	[1,2,3] 3.46 (0.39)	[1,2,3,6] 4 (0.3)	[1,2,3,5] 3.05 (0.27)

[1] Statistically significant differences ($p < 0.05$) with respect to M1.

[2] Statistically significant differences ($p < 0.05$) with respect to M2.

[3] Statistically significant differences ($p < 0.05$) with respect to M3.

[4] Statistically significant differences ($p < 0.05$) with respect to M4.

[5] Statistically significant differences ($p < 0.05$) with respect to M5.

[6] Statistically significant differences ($p < 0.05$) with respect to M6.

Finally, the analysis of correlations for parametric tests (Pearson) between the different biomechanical variables (Fmax, TD1 and HD1) analysed in the gymnasts, and also between them and the mechanical variables produced some significant correlations ($p<0.01$) (Table 2).

Table 2: Correlation results (Pearson) between biomechanical and mechanical variables.

CORRELATIONS BETWEEN MECHANICAL AND BIOMECHANICAL VARIABLES (p < 0.01)			
	Shock absorption	***Deflection***	***Resilience***
Fmax	r = 0.588	r = -0.615	
TD1 and TD2	r = 0.386	r = -0.298	

4. DISCUSSION

The analysis of gymnasts' kinetic and kinematic variables during landing has been approached in different ways. Some authors [21,22] have studied landing taking into account the range of motion of the lower extremities. Others [2,5,8,18], however, like in our study, have analysed landing using different mat types and considering the effects of the mat on the gymnast's execution.

In this regard, as far as reaction forces during landing are concerned, peak forces reached around 7 BW (4450 ± 195.34 N), which are in fact rather high. These results are similar to those reported in the literature[3,7,11,23]. Thus, the force/time chart presents a curve characterised by a first peak on the vertical component in the first 30-50 ms after the impact[21,22], with values ranging from 5.9 BW to 7.4 BW. These values are higher than those described for other sport actions such as racing; 2.3 BW[24], 1.6-3.0 BW[25], or landing after jumping in basketball: 2,5 -2,8 BW[16]. However, when landing takes place from greater heights than those in our study, gymnasts can surpass 10 BW[11,14,25], which could damage the gymnast's internal structures if the impact's magnitude is too large[26].

This impact magnitude during landing can be modified by the technique used[9,11,22,25], and by the properties of the mat[6,8,21], as shown by the results of our study, with a 10% reduction on times body weight between mat M6 and mat M1.

As for the acceleration variables studied, there are no published studies for gymnastics analysing impact on the forehead. However, Nigg[27] obtained maximum tibia decelerations of 28 - 35 g on mats. These magnitudes are higher if compared with the acceleration values obtained for other actions like walking: 1-5 g[28], running: 12 g[29], or after jumping: over 25 g[28].

The results of our study showed an acceleration/time curve with two peaks, the first one being higher than the second one (Figure 3). The values obtained for the tibia were 4 times greater than for the forehead (15.57 ± 0.54 g vs 4.72 ± 0.55 g for the first peak and 11.62 ± 0.69 g vs 3.05 ± 0.27 g for the second one), which points to the great shock absorption effect of the lower limb joints, as shown by kinematics studies [2,5,8,11]. Statistically significant differences were found (Table 1) ($p<0.05$) in the maximum tibia and forehead values depending on the type of mat, values being higher for those mats with greater shock absorption values in the mechanical tests: M1, M2 and M3 (Figure 2].

Regarding standard tests, not all the selected samples accomplished with established criteria, but as for the mat, despite complying with the standard in the shock absorption results, it does not seem to be sufficient for reducing the impact and so the gymnast is forced to use other mechanisms like, for instance, a foot-supinating movement on harder mats, with a pronating action when mat deformation is greater[18], and a supinating one when it is smaller. This could be useful for better understanding the mechanics used by the gymnast to stabilise and for the analysis of certain injury factors, as is the case with epidemiological studies on sports footwear[15].

The correlation analysis (Pearson) conducted on the variables analysed in the gymnasts allowed us to demonstrate some interesting links in the kinetics and kinematics of landing. The results cause us to think that landing has a high potential for injuries if impact forces are high[25,30], as the misalignment of the extremities in respect of the mat could lead to injuries[27]. Besides, if we take mat deformation into account, the mat could really endanger the joints involved, as poor shock absorption could lead to an increased load on the lower extremities, particularly on biological tissues like ligaments, muscular tendons, bones, and joint cartilages[9]; if their tolerance were surpassed, the metatarsal bones and the navicular bone could be fractured, for instance[31].

Apart from execution, a protection element like the mat could reduce the number of injuries provided it has the best properties for rapid shock absorption and gymnast stabilisation. However, several authors[7,9] have stated that the criteria for evaluating the properties of mats are based on the need to establish some uniformity in the equipment during competition permits and not on the distribution of impacts through the musculoskeletal system. Other important factors are also overlooked, i.e. height from which landing starts [14], the different participation of the legs[32], individual strategies[29], type of landing[11,22], etc.

Some of the results obtained in this study allow us to take the hypothesis further that normative trials based on mechanical tests do not really show what actually happens[2,9,10,19] and therefore do not adequately predict some biomechanical variables that affect major injury mechanisms in gymnastics[4]. In this regard, the correlations analysis (Pearson) (Table 2) between the mechanical variables of the mat and the biomechanical variables of the gymnast shows that:

a) The standard's criteria for shock absorption are related with kinetic and kinematic variables analysed in gymnasts (for similar height). It is related positively with first maximum tibial and forehead acceleration.

That is the increase acceleration in standard test involved increase in maximum tibial and forehead acceleration, therefore it involved a great absorption by gymnast.

b) The criteria laid down by the standard for deflection are related with the acceleration peaks on tibia/forehead and time landing, in such a way that increased deflection reduces the magnitude of the impact but the gymnast takes longer to stabilise and to stop on the mat.

Also, to understand others kinematics adaptations, different studies have focused on landing [2,3,8,11,18,21,22] modifying the range of motion on the lower extremities as well as the jump height or the type of mat. These studies show that, depending on the landing technique used, significant differences can be found in the different kinematics variables, such as an increase joint flexion degree on the lower extremities when surface stiffness rises [7]. In this way, the impact is largely absorbed by the musculotendinous system, preventing bone and joint tissues from suffering potentially damaging stress; once the lowest point is reached, extension is started until stabilisation on the mat is reached.

5. CONCLUSIONS:

Results show that mat properties influence both the kinetics and kinematics of the gymnast. In this respect, gymnasts modulate their performance to adapt to the features of the mat but, with some high impact magnitudes that occur in gymnast, the shock absorption ability of the locomotor system seems to be conditioned. By considering all these aspects, although the normative trial helps predict the magnitudes of the impact and its transmission for a 0.8 m height, magnitudes obtained in vertical reaction forces, and peak tibial and forehead acceleration were different that literature shows in competition. This aspect should be further studied and with landing heights similar to those used in competition; if necessary, the normative trial should be modified to try to simulate landings more in line with reality.

6. REFERENCES

[1] W. A. Sands, D.Caine ,J. Borms. Scientific aspects of women´s Gymnastics. In J. Borms, M. Hebbelinck & A.P. Hills (eds), *Medicine and Sport Science*, Basel: Karger, 2003, 33-35.

[2] J. L. cNitt-Gray, T. Yokoi, C. Millward, Landing strategies used by gymnasts on different surfaces. *Journal Applied biomechanics*. 1994, **10**: 237-252.

[3] A. Arampatzis, G. M. Klapsing ,G. P. Brüggemann. The effect of falling height on muscle activity and foot motion during landings. *Journal of electromyography and kinesiology*. 2003, **13**: 533-544.

[4] P. Pérez, S. Llana and E. Alcantara .Partial implementation of the Q.F.D. methodology for the identification of the most important characteristics and features of gymnastics mats design. *International Journal of Applied Sports Science*. 2006, **18**: 65-77.

[5] A. Arampatzis, G. P. Brüggemann, G. M. Klapsing and M. Wiehn. A three dimensional lower leg-foot model to determine the influence of various gymnastic mats on foot during landings. *Medicine & Science in Sports & Exercise*. 2002, **34**:130-138.

[6] C. Mills, M. T. G. Pain and R. Yeadon. Modelling a viscoelastic gymnastics landing mat during impact. *Journal Applied Biomechanics.* 2006, **22**: 103-111.

[7] J. L. McNitt-Gray. Musculo-skeletal loading during landing. In V. Zatsiorky (Eds), *Biomechanics in Sport*. London: Blackwell Science. 2000, 523-549.

[8] J. L. McNitt-Gray, T. Yokoi and C. Millward .Landing strategy adjustments made by female gymnasts in response to drop height and mat composition. *Journal Applied Biomechanics*. 1993, **9**: 173-190.

[9] B. M. Nigg .The validity and relevance of the test used for the assessment of sports surfaces. *Medicine & Science in Sports & Exercice*. 1990, **22**: 131-139.

[10] D. Caine, B. Cochrane, C. Caine and E. Zemper. An epidemiologic investigation of injuries affecting young competitive female gymnasts. *American Journal of Sports Medicine*. 1989, **17**: 811-820.

[11] S. N. Zhang, B. T. Bates and J. S. Dufek. Contributions o lower extremity joints to energy dissipation during landings. *Medicine & science in Sports & Exercise*. 2000, **32**: 812-819.

[12] D. G. Kerwin, M. R. Yeadon and S. C. Lee. Body configuration in multiple somersault high bar dismounts. *International Journal of Sport Biomechanics*. 2000, **6**: 147-156.

[13] B. M. Nigg and M. Boobert. On the potential of various approaches in load analysis to reduce the frequency of sport injuries. *Journal of biomechanics*. 1990, **23**: 3-12.

[14] J. L. McNitt-Gray. Kinematics and impulse characteristics of drop landing from three heights. *International Journal of Sports Biomechanics*. 1991, **7**: 201-204.

[15] E. M. Hennig and T. L. Milani .In-shoe pressure distribution for running in various types of footwear. *Journal of Applied Biomechanics*. 1995, **11**: 299-310.

[16] G. Brizuela, S. Llana, R. Ferrandis and A. C. García .The influence of ankle support basketball shoes on shock absorption and performance in running and jumping. *Journal of Sports Sciences*. 1997, **15**: 505-515.

[17] B. M. Nigg, A. Khan, V. Fisher and D. Stefanyshyn. Effect of shoe insert construction on foot and leg movement. *Medicine & Science in Sports & Exercise*. 1998, **3**: 550-555.

[18] A. Arampatzis, G. M. Klapsing and G. P. Brüggemann. Orthotic effect of a stabilising mechanism in the surface of gymnast mats on foot motion during landings. *Journal of electromyography and kinesiology*. 2005, **15**: 507-515.

[19] F. Gatto, P. Swannell and R. Neal. A force indentation relationship for gymnastic mats. *Journal of Biomechanics Engineering.* 1991, **114**: 338 -345.

[20] M. J. Gittoes, M. A. Brewin, & D. G. Kerwin . Soft tissue contributions to impact forces simulated using a four-segment wobbling mass model of forefoot-heel landings. *Human Movement Science*. 2006, **25**: 775-87

[21] A. Devita and W. A. Skelly. Effect of landing stiffness on joint kinetics and energetic in the lower extremity. *Medicine & Science in Sports & Exercise*. 1992, **24**: 108-115.

[22] A. Lees. Methods of impact absorption when landing from a jump. Engineering in Medicine, 1981, **10**: 207-211.

[23] H. N. Özgümen and N. Berme. An experimental and analytical study of impact forces during human jumping. *Journal of Biomechanics*. 1988, **21**: 1061-1066.

[24] A. Arampatzis, G. P. Brüggemann and V. Metzler. The effect of the speed on leg stiffness and joint kinetics in human running. *Journal of biomechanics*. 1999, **32**: 1349 - 1353.

[25] J. S. Dufek .and B. T. Bates .The evaluation and prediction of impact forces during landing. *Medicine & Science in Sports & Exercise*. 1990, **22**: 370-377.

[26] R. Butler, H. Crowell and I. Davis. Lower extremity stiffness: Implications for performance and injury. *Clinical Biomechanics*. 2003, **18**: 551-517.

[27] B. M. Nigg. Biomechanics load analysis and sport injuries in the lower extremities. *Sports Medicine*. 1985, **2**: 367-379.

[28] D. J. Loy and A. S. Voloshin. Biomechanics of stair walking and jumping. *Journal of Sports Sciences*. 1991, 9: 137-49.

[29] B. M. Nigg and M. R. Yeadon. Biomechanical aspects of playing surfaces. *Journal of Sports Sciences*. 1987, **5**: 117-145.

[30] W. A. Sands. Injury prevention in women´s gymnastics. *Sports medicine*. 2000, **30**: 359-373.

[31] G. G. Weiker. Injuries in club gymnastics. *Physical Sports Medicine*. 1984, **13**: 63-66.

[32] V. P. Panzer, G. A. Wood, B. T. Bates and B. R. Mason. Lower extremity loads in landing of elite gymnasts. In G. de Groot, P. Hollander, P. Huijing & G. van Ingen Schenau (Eds), *Proceedings of the Biomechanics XI-B, International Series On Biomechanics*. Amsterdam: Free University Press, 1988, 721-735.