EFFECTS OF DIFFERENT LEG LOADINGS AT TAKE-OFF ON LANDING CHARACTERISTICS IN TWISTING SOMERSAULTS

Miha Marinšek[1], **Ivan Čuk**[2]

[1] Faculty of Education, University of Maribor, Maribor, Slovenia
[2] Faculty of Sport, Univerity of Ljubljana, Ljubljana, Slovenia

Original article

Abstract

The purpose of the study was to determine whether take-off asymmetry affects landing asymmetry. Eleven male gymnasts performed forward and backward somersaults with 1/2, 1/1, and 3/2 twists. The leading leg for each participant was defined according to the twisting direction. Ground reaction forces under each foot were measured with Parotec insoles. Absolute and relative measures of lateral asymmetry were used as dependent variables. Three-way ANOVA and a series of one-way ANOVAs were used to determine the main effects between take-off and landing. A series of paired t-tests with Bonferroni corrections were used to find differences between the leading and non-leading legs. Maximal ground reaction forces showed that the leading leg was set out to a higher load at take-off than the non-leading leg for twisting somersaults. There were no statistically significant differences found in the maximal ground reaction force between the legs at landings. Index of bilateral asymmetry indicated landings with negligible asymmetry. However, the maximal force differences between the legs in somersault 3/2 were higher when compared to other somersault variations. No evidence was found to affirm that the asymmetry at take-off affects asymmetry at landing in a twisting somersault. Presumably, gymnasts can take corrective measures during the aerial phase of the twisting somersault that effectively diminish the tilt of the body and enable gymnasts to prepare for the landing with small proportional asymmetry. Prudence is required as these proportions rise in the quantity of load with the height of the somersault.

Keywords: *Acrobatics, floor, asymmetry, twisting technique.*

INTRODUCTION

In gymnastics, most injuries on the floor occur during landing (Pettrone & Ricciardelli, 1987; Hudash & Albright, 1993; Gervais, 1997; Kirialanis, et al., 2002). The greatest dynamic loads on the lower extremities occur for asymmetrical landings rather than for unsuccessful landings, as typically assumed. The asymmetrical, yet reasonably successful landings appear to represent the greatest injury potential for the Achilles tendon, knee joint, and spine (Panzer, 1987). Additionally, landing asymmetry decreases landing quality and the possibility of landing without deductions (Marinšek, 2010; Čuk & Marinšek, 2013; Pajek Bučar, Hedbávný, Kalichová, & Čuk, 2016). Landings with different dynamic loading on legs (which we refer to in this article as asymmetrical landings) occur in non-twisting and in twisting (rotations around longitudinal axis) somersaults. The different loading on legs in the non-twisting somersault can be explained by the fact that a small rotational motion exists even in the non-twisting somersault. During the wobbling motion in the non-twisting somersault, the body tilts first in one way and then the other way (Yeadon, 2000). These small sideway tilts of the body can result in sideway landing and thus produce different loading to the legs. In the twisting somersaults, landing characteristics are associated with the twisting technique. In the somersault, any technique that tilts the body away from the somersault plane will result in twisting in order to maintain constant angular momentum (Frolich, 1980). When the tilt of the body is introduced while the feet are in contact with the take-off surface, this can be defined as a contact twisting technique; when the tilt of the body is introduced in the aerial phase of the somersault, this can be defined as an aerial twisting technique (Yeadon, 1993a; Yeadon, 1993b). To stop twisting, gymnasts must eliminate the tilt of the body. If the tilt is not eliminated, asymmetrical landing occurs. In the aerial twisting technique, asymmetrical movements of the arms, chest, or hips about the sagittal plane can eliminate the tilt; while piking, the body can remove it in the contact twisting technique (Yeadon, 1993a; Yeadon, 1993b). Modification of the shoulder joint moment is believed to be the most effective mechanism for controlling the body in the aerial phase in preparation for landing without inducing a modification in mechanical loading after foot contact (Requejo, McNitt-Gray, & Flashner, 2002). In contrast, modifications in neck, knee, and hip joint cause less advantageous joint angles at touchdown.

There is evidence that the somersaults that are performed in competition with a lower aerial phase and with more twists are more likely to end in asymmetrical landings (Marinšek & Čuk, 2010). However, to our knowledge no study has explicitly focused on the association between take-off and landing characteristics in twisting somersaults. Does the asymmetrical take-off with different leg loadings mean a potentially greater chance for an asymmetrical landing? Is there a leg that is constantly more loaded at take-off and landing than the other is?

For somersaults with more twists, a greater twisting rate is required. According to Yeadon (1993a, 1993b), gymnasts can achieve a greater twisting rate with appropriate movements at the take-off and/or aerial phase. The movements initiated at take-off are more effective in obtaining the greater twisting rate but boost the initial value of the tilt angle. The tilt of the body at take-off increases the difference in leg loading. Therefore, if gymnasts need to augment the tilt of their body to perform more twists, the asymmetry of leg loading at take-off would be expected to increase with number of twists. In order to initiate the twist at take-off, the body must tilt to the side of the twisting direction (tilt to the left side if the twist is performed to the left direction). The tilt is supposed to be produced with reduced muscle activity of the twisting leg in backward take-offs and with the increased muscle activation of the twisting leg in forward take-offs (McNeal, Sands, & Shultz, 2007). Despite the take-off asymmetry, gymnasts can detect errors and take corrective measures that change the position of the body prior to landing in the aerial phase of twisting somersaults with flight times of 1.4s (Yeadon & Hiley, 2014). The corrections in the body position allow gymnasts to land with negligible quantities of asymmetry. Although the flight times of twisting somersaults on the floor are shorter (Karacsony & Čuk, 2005) than the ones on trampolines reported from Yeadon and Hiley (2014), it is believed that participants in our study will have enough time to take eventual corrective measures and prepare for landing. Therefore, it is expected that the number of twists and the increase in asymmetry of leg loading at take-off will not increase the asymmetry of leg loading at landing.

The purpose of this study was to use empirical data to examine the effects of absolute and relative measures of take-off characteristics on landings in twisting somersaults in training- and competition-specific situations. For the purpose of this study, the following questions were asked: (a) Does the asymmetry in dynamic loading on legs at take-off and landing change with the number of twists? (b) Does the asymmetry in dynamic loading on legs at take-off affect landing asymmetry? (c) Which leg is more loaded during take-off and landing in twisting somersaults?

METHODS

Eleven male gymnasts took part in the research, who were all competing as national team members on international competitions or higher. Informed consent was obtained from each gymnast and/or parents for minors according to the Helsinki Declaration. The local ethics committee approved the conduct of the study. On the day of the measurements, the average participants' age was 18.83 ± 2.74 years; their average height was 169.63 ± 6.21 cm; and the average weight 67.79 ± 10.64 kg.

Every gymnast had to demonstrate proficiency in performing the acrobatic skills of interest: stretched forward and backward somersault, stretched forward and backward somersault with 1/2 twist, stretched forward and backward somersault with 1/1 twist, stretched forward and backward somersault with 3/2 twist. Because the gymnasts did not twist in the same direction, the leading and non-leading leg was defined according to the direction of the twist. The leg corresponding to the direction of the gymnast's twist was assigned as the leading leg. In that sense, the gymnast who twisted to the left had his left leg as his leading leg and his right leg as his non-leading leg.

Participants performed two familiarisation sessions with all testing procedures. After the familiarisation sessions gymnasts attended a testing session that was considered for the analysis. All the somersaults were performed on a Spieth competition floor after a warm-up. The difficulty of the somersault was increased in half-twist intervals.

Reaction forces under each foot were sampled at 300 Hz using an insole pressure measurement system (Parotec, Paromed GmbH). The Parotec system was found to be an effective tool for assessing pressure under each foot in dynamic situations. Parotec insoles are equipped with 24 discrete hydro cell pressure sensors for each foot; both insoles are triggered at the same time. Hydro cell technology enables measurement of compressive force and shear force but does not discriminate between them. Sensors have shown less than 2% measurement error in the range of 0-400 kPa and provided highly consistent data (Zequera, Stephan, & Paul, 2006), which was deemed acceptable for the current study. A study by Chesnin, Selby-Silverstein, and Besser (2000) assessed the concurrent validity comparing the Parotec System to a force plate. The Parotec System showed good correlation and small root mean square errors when compared to the force plate; force calculated from the two systems showed excellent correlation (>0.90) for 20/20 trials. Additionally, a study by Koch, Lunde, Ernst, Knardahl, and Veiersted (2016) showed that the use of insoles may be an acceptable method for measuring vertical ground reaction forces in field studies.

The dependent variables were categorized into two groups: absolute measures of lateral asymmetry and relative (proportional) measures of lateral asymmetry. The absolute measures were represented by the following set of variables: (a) maximal ground reaction force for leading (*maxFll*) and non-leading leg (*maxFnl*), and (b) maximal ground reaction force difference between legs (*mFdiff*). The proportional measure was represented by the absolute index of lateral asymmetry (*aIndex*).

Maximal ground reaction force was measured with Parotec insoles within the contact time and normalized on the gymnast's body weight (BW) [times BW]. The contact time was defined as the period from the point of ground contact to the point at which the total ground reaction force reached the magnitude of BW after the maximal ground reaction force. Maximal ground reaction force difference was calculated as a maximal difference between legs during the contact time at take-off and landing. It was normalized on the gymnast's BW [times BW].

The index of lateral asymmetry (Teixeira, 2008; Teixeira, Silva, & Carvalho, 2003) was calculated to measure proportional asymmetry between legs at take-off and landing. An index of lateral asymmetry was proposed by Teixeira, Silva, & Carvalho (2003) as proportional difference between the legs, in relation to summation of the values obtained with each leg:

$$[|(maxFll-maxFnl)|/(maxFll+maxFnl)] /2*100$$

where *maxFll* corresponds to maximal force for the leading leg, *maxFnl* corresponds to maximal force for the non-leading leg. The absolute values of the proportional difference between leading and non-leading leg were used in our study, thus making magnitude of asymmetry independent of any specific direction.

All statistical analyses were performed using Microsoft Excel software and IBM SPSS Statistics version 21.0. Intra-class coefficient correlations (ICC) were utilised to verify the reliability of forward somersaults (somersault ICC = 0.930; somersault 1/2: ICC = 0.785; somersault 1/1: ICC = 0.875; somersault 3/2: ICC = 0.830) and backward somersaults (somersault ICC = 0.945; somersault 1/2: ICC = 0.810; somersault 1/1: ICC = 0.910; somersault 3/2: ICC = 0.855). Additionally, differences between two familiarisation sessions were tested with paired t-test and no differences were observed (p > .05).

For the analysis of maximal ground reaction force three-way ANOVA ($p \leq .05$) with one between-subject factor (*rotation*: no twist, 1/2 twist, 1/1 twist, 3/2 twist) and two within-subjects factors (*contact*: take-off, landing; *laterality*: leading, non-leading) was used with repeated measures on the last factors and Bonferroni post hoc adjustments. Preliminary analyses were also conducted, including *direction of the somersault, direction of the take-off* and *direction of the landing* as between-subject factors, but no statistically significant effect was found. For this reason, these factors were not considered in the final analysis. A series of paired t-tests with Bonferroni corrections was used to evaluate differences between take-off and landing for each leg (leading and non-leading). Additionally, the averaged maximal ground reaction forces for leading and non-leading legs were compared for take-off and landing separately across twist modalities (no twist, 1/2 twist, 1/1 twist, 3/2 twist).

For the analysis of maximal force difference at take-off and at landing one-way ANOVA (*rotation*: no twist, 1/2 twist, 1/1 twist, 3/2 twist) was employed ($p \leq .05$) independently with Bonferroni post hoc adjustments. A series of paired t-tests was used to evaluate differences ($p \leq .05$) in maximal force difference between take-off and landing for each twist modality.

A one-way ANOVA ($p \leq .05$) for the proportional measure of lateral asymmetry at take-off and landing with one between-subject factor (*rotation*: no twist, 1/2 twist, 1/1 twist, 3/2 twist) and Bonferroni post hoc adjustments was used. Preliminary analyses on the *direction of the somersault, direction of the take-off* and *direction of the landing* as between-subject factors did not reveal a statistically significant effect. Therefore, the latter factors were not considered in the final analysis. A series of paired t-tests with Bonferroni corrections was used to evaluate differences between take-off and landing in relation to proportional lateral asymmetry. The averaged absolute indices of lateral asymmetry were compared for take-off and landing separately for each twist modality.

RESULTS

Nine participants twisted to the left side, which is why their left leg was assigned as the leading leg. Two participants twisted to the right side and had their right leg assigned as the leading leg. Take-off and landing loadings were measured for somersaults with different numbers of twists for each leg separately. The maximal ground reaction forces for leading leg (mFle) and non-leading leg (mFnl) are provided in Table 1. Similar values with ground reaction take-off force below 3.3 times BW have been reported in other research for backward tucked somersault on a force plate (Krol et al. 2016, Mkaouer et al. 2014) and for backward tucked somersault on balance beam (Kim, Ryu & Jeon, 2012). Other authors (Panzer, 1987) reported much higher ground reaction forces (8.8–14.4 times BW), however their research analysed double backward tucked somersault with take-off directly from force plate, without use of elastic floor.

The three-way ANOVA revealed a significant main effect for the interaction between contact and laterality, $F(1,84) = 26.03$, $p < .001$, $\eta p^2 = .24$. The statistically significant main effects for the interaction were due to the higher maximal ground reaction force of the leading leg at take-off (leading leg 2.14 vs. non-leading leg 1.94 times BW) in comparison to landing (leading leg 1.94 vs. non-leading leg 2.02 times BW). Bonferroni correction was applied for analysis of individual twist modalities, resulting in a significance level set at $p < .008$. Analysis of individual twist modalities revealed no statistically significant difference between leading and non-leading leg at take-off (all $p \geq .031$) or landing (all $p \geq .061$).

Although the results (Table 1) suggest an increase of take-off and landing asymmetry with rising number of twists, a three way Contact x Laterality x Rotation interaction failed to reach significance, $F(3,84) = 0.22$; $p = .885$, $\eta p^2 = .01$. Following the aforementioned interaction, a series of paired t-test for each leg and somersault modality was conducted with Bonferroni correction with a significance level set at $p < .013$. Tests revealed no statistically significant differences between take-off and landing loading for leading (all $p \geq .022$) or non-leading leg (all $p \geq .242$) (Table 1).

The analysis of maximal force differences between legs at take-off indicated a significant main effect for rotation, $F(3) = 5.96$; $p = .001$, $\eta p^2 = .18$, due to the lower maximal force difference for the non-twisting somersault (0.59 ± 0.19 times BW) in comparison to other somersault modalities (1/2 twist 0.82 ± 0.35 times BW, 1/1 twist 0.73 ± 0.35 times BW, 3/2 twist 0.95 ± 0.30 times BW), as seen in Figure 1. A significant main effect was also found for the maximal force differences at landing for rotation, $F(3) = 8.18$; $p < .001$, $\eta p^2 = .23$. Post hoc comparison indicated a significantly higher maximal force difference for the 3/2 twist (1.2 ± 0.52 times BW) in comparison to other somersault variations (no twist 0.66 ± 0.18 times BW, 1/2 twist 0.81 ± 0.39 times

BW, 1/1 twist 1.01 ± 0.48 times BW). Further analysis with series of paired t-test and Bonferroni correction ($p < .008$) indicated no significant differences between take-off and landing in maximal force difference for individual twist modalities.

Table 1.
Mean maximal forces scaled to BW and standard deviations (in brackets) at take-off and landing, differences in mean maximal forces between take-off and landing, p-values for paired t-test, and Cohen's d for leading and non-leading leg of somersaults with various rotations around longitudinal axis.

	Take-off		**Landing**		**Diff**		***p*(t)**	***d***
Leading leg								
no twist	2.10	(0.46)	1.95	(0.47)	0.14	(0.28)	0.163	-0.31
1/2 twist	2.13	(0.47)	1.93	(0.48)	0.20	(0.47)	0.072	-0.42
1/1 twist	2.14	(0.43)	1.92	(0.36)	0.22	(0.31)	0.022	-0.56
3/2 twist	2.17	(0.39)	1.94	(0.43)	0.23	(0.37)	0.048	-0.55
Non-leading leg								
no twist	1.96	(0.56)	2.06	(0.51)	-0.10	(0.23)	0.242	0.18
1/2 twist	1.90	(0.46)	1.99	(0.45)	-0.09	(0.25)	0.327	0.19
1/1 twist	1.94	(0.55)	2.06	(0.53)	-0.11	(0.34)	0.267	0.21
3/2 twist	1.96	(0.62)	1.96	(0.51)	0.00	(0.39)	0.991	0.00
Sum								
no twist	4.06	(0.97)	4.01	(0.94)	0.05	(0.74)	0.764	-0.05
1/2 twist	4.04	(0.79)	3.92	(0.84)	0.12	(0.70)	0.442	-0.14
1/1 twist	4.08	(0.91)	3.98	(0.84)	0.11	(0.76)	0.516	-0.12
3/2 twist	4.13	(0.89)	3.90	(0.88)	0.23	(0.86)	0.233	-0.26

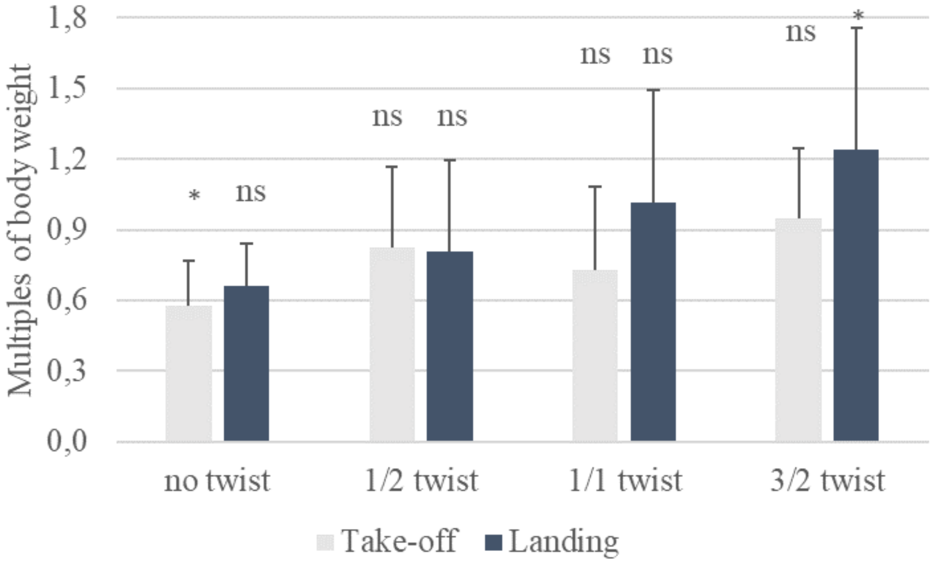

Figure 1. Mean maximal force differences (standard deviations represented by vertical bars) for take-off and landing across somersaults with various rotations around longitudinal axis. * p < .05, ns – no significant differences.

Analysis of variance for mean absolute index of lateral asymmetry indicated no significant twist-related effect in take-off, F(3) = 2.17, $p = .097$, $\eta p^2 = .07$, nor landing, F(3) = 0.78; $p = .510$, $\eta p^2 = .03$ situations, as depicted in Figure 2. The variation of lateral asymmetries (index of lateral asymmetry) as a function of the number of twists was compared through t-tests for repeated measures, comparing the results of take-off and landing. Bonferroni correction was applied, resulting in a significance level set at $p < .008$. T-tests did not reveal significant differences (all $p > .131$). These results indicate that performance with negligible quantities of asymmetry was consistent across twisting modalities.

DISCUSION

Twisting somersaults on the floor were initiated during the take-off, which indicates that the contact technique of twisting was used. This was seen as a significant rise in maximal load difference between legs in comparison to non-twisting somersaults; gymnasts probably tilted their body at take-off to the side of the twisting direction to boost the twist (Yeadon, 1993a, 1993b). Leading leg was set out to a higher load at take-off than the non-leading leg. However, the load on the leading leg decreased at landings, which enabled gymnasts to land with negligible asymmetry.

Our results suggest that lateral asymmetry at take-off increased significantly with the initiation of twist but it remained stable following the adding of more twists to the somersault. It seems that for the purpose of up to 3/2 twist executions longitudinal rotational velocity initiated at contact does not need to rise significantly, as probably, the majority of longitudinal rotational velocity needed for the completion of the twist is initiated in aerial phase. Possibly, higher longitudinal rotational velocity is initiated at contact, as circumstances require when more twists are performed. Therefore, it would be useful to measure the asymmetry at take-off in somersaults with multiple twists. The magnitude of force difference at take-off would be expected to increase because of the need to initiate higher rotational velocity around longitudinal axis.

The index of lateral asymmetry showed that lateral asymmetry at landings was stable. Although the index of lateral asymmetry did not change significantly with the addition of twists to the somersaults, the maximal force difference between legs at landing 3/2 twists was significantly different to other somersaults performed. The reason might be in the magnification of total ground reaction force at landing due to the higher aerial phase. Although the proportions of asymmetry at landing suggest that landings are performed with low outcome variability, caution is needed as these proportions rise in the quantity of load with the height of the somersault. The latter can influence the safety and quality of the landings. This effect is probably even more evident in somersaults with multiple twists that are performed higher.

The current findings show that augmented lateral asymmetry at take-off did not result in augmented lateral asymmetry in landing. One explanation for this effect can be that gymnasts used body movements in the aerial phase of the somersault as correctional movements to adjust their body for the appropriate landing. Gymnasts can initiate and reduce twist in the aerial phase of the somersault with asymmetrical body movements, and twisting somersaults are of sufficient duration to permit the detection of errors in the performed movement; corrective discrete or continuous measures can be taken (Yeadon & Hiley, 2014). The balance mechanisms of the inner ear are the ones that provide information on linear and angular accelerations (Wendt, 1951), which can be used by athletes to help control aerial movements (Yeadon &

Mikulcik, 1996). However, the application of correctional movements is probably highly associated with experience acquired through practice. Voyer and Jansen (2017) found that motor expertise in gymnastics positively influences performance in spatial tasks that require spatial visualization, mental rotation, and spatial perception, which are all the visual-spatial abilities required for execution of twisting somersaults. Although variability is never eliminated, Cohen and Sternad (2009) demonstrated that with practice the cost of movement variability to the performance outcome can be reduced. In the opinion of authors of this paper, only enough experienced gymnasts that were exposed to appropriate twisting somersault progressions when learning how to twist can adequately use correctional movements for a safe and effective landing. Additionally, it is vital that coaches devote enough time to teaching twisting techniques and allow gymnasts to acquire the necessary experience. It should be emphasized that in this study gymnasts executed all somersault attempts without major errors. We can assume that the executions in which the magnitude of lateral asymmetry at take-off leads to major technical errors (and consequently make correctional movements in the aerial phase impossible) can also amplify the asymmetry at landing.

The data in the present study was collected in a real-life environment. Consequently, it could be argued that data are less objective in comparison to laboratory studies. When designing the study we were aware of the bias because of the different twisting techniques or other factors. One of the main goals of the present study was to analyse the data in training- and competition-specific situations. Take-off and landing loadings were tested for up to the 3/2 twist somersaults. Nowadays multiple twists are commonly seen in elite modern gymnastics; thus, it would be interesting to see how multiple twists affect take-off and landing loadings. The possibility of further studies in the analysis of take-off and landing dynamic characteristics of multiple twists are seen.

CONCLUSIONS

Asymmetry of leg loading at take-off in twisting somersaults does not directly influence landing asymmetry, probably because potential errors that can affect landing symmetry can be adjusted in the aerial phase. However, even small proportional asymmetries, which gymnasts cannot avoid due to the wobbling and tilting motion of their bodies during somersaults, rise in magnitude with higher aerial phases of the somersaults. Gymnasts have to be mindful when including twisting somersaults in their competition routines as other factors (anxiety, fatigue, etc.) can influence twisting performance and consequently landings.

REFERENCES

Chesnin, K. J., Selby-Silverstein, L., & Besser, M. P. (2000). Comparison of an in-shoe pressure measurement device to a force plate: concurrent validity of center of pressure measurements. *Gait & posture*, *12*(2), 128-133.

Cohen, R. G., & Sternad, D. (2009). Variability in motor learning: relocating, channeling and reducing noise. *Experimental Brain Research*, *193*(1), 69–83.

Čuk, I., & Marinšek, M. (2013). Landing quality in artistic gymnastics is related to landing symmetry. *Biology of sport*, *30*(1), 29.

Frolich, C. (1980). The physics of somersaulting and twisting. *Scientific American*, *242*, 112 – 120.

Gervais, P. L. (1997). Movement changes in landings from a jump as a result of instruction in children. *Coaching and Sport Science Journal, 2*, 11–16.

Hudash, G. W., & Albright, J. P. (1993). Women's intercollegiate gymnastics injury patterns and permanent medical disability. *American Journal of Sports Medicine*, *21*, 314–320.

Karacsony, I. & Čuk, I. (2005). *Floor exercises – Methods, Ideas, Curiosities, History.* Ljubljana: STD Sangvinčki.

Kim, K-W., Ryu, Y., & Jeon, K-K. (2012). A kinetics Analysis of Tucked Backward Salto on the Balance Beam. *Korean Journal of Sport Biomechanics*, *22*(4), 395-404.

Kirialanis, P., Malliou, P., Beneka, A., Gourgoulis, V., Giofstidou, A., & Godolias, G. (2002). Injuries in artistic gymnastic elite adolescent male and female athletes. *Journal of Back and Musculoskeletal Rehabilitation*, *16*, 145–151.

Krol, H., Klyczcz-Morciniec, M., Sobota, G., & Nowak, K. (2016). The Complex Analysis of Movement in the Evaluation of the Backward Somersoult Performance. *Physical Activity Review*, *4*, 28-39.

Koch, M., Lunde, L. K., Ernst, M., Knardahl, S., & Veiersted, K. B. (2016). Validity and reliability of pressure-measurement insoles for vertical ground reaction force assessment in field situations. *Applied ergonomics*, *53*, 44-51.

Marinšek, M. (2010). Basic landing characteristics and their application in artistic gymnastics. *Science of Gymnastics Journal*, *2*(2), 59–67.

Marinšek, M., & Čuk, I. (2010). Landing errors in the men's floor exercise are caused by flight characteristics. *Biology of Sport*, *27*(2), 123–128.

McNeal, J. R., Sands, W. A., & Shultz, B. B. (2007). Muscle activation characteristics of tumbling take-offs. *Sports Biomechanics*, *6*(3), 375-390.

Mkaouer, B., Jemni, M., Amara, S., Chaabene, H., Padulo, J., & Tabka, Z. (2014). Effect of three Technical Arms Swings on the elevation of the Center of Mass During a Standing Back Somersault. *Journal of Human Kinetics, 40,* 37-48.

Pajek Bučar, M., Hedbávný, P, Kalichová, M., & Čuk, I. (2016). The asymmetry of lower limb load in balance beam routines. *Science of Gymnastics Journal*, *8*(1), 5–13.

Panzer, V. P. (1987). *Lower Extremity Loads in Landings of Elite Gymnasts*. Phd. thesis, Oregon, University of Oregon.

Pettrone, F., & Ricciardelli, E. (1987). Gymnastic injuries: The Virginia experience 1982–1983. *American Journal of Sports Medicine, 15*, 59–62.

Requejo, P. S., McNitt-Gray, J. L., & Flashner, H. (2002). Flight phase joint control required for successful gymnastics landings. *Medicine & Science in Sports & Exercise*, *34*(5), 99.

Teixeira, L. A. (2008). Categories of manual asymmetry and their variation with advancing age. *Cortex*, *44*(6), 707–716.

Teixeira, L. A., Silva, M. V., & Carvalho, M. (2003). Reduction of lateral asymmetries in dribbling: The role of bilateral practice. *Laterality: Asymmetries of Body, Brain and Cognition*, *8*(1), 53–65.

Voyer, D., & Jansen, P. (2017). Motor expertise and performance in spatial tasks: A meta-analysis. *Human Movement Science*, *54*, 110–124.

Wendt, G. R. (1951) Vestibular functions. In S. S. Stevens (Ed.), *Handbook of Experimental Psychology* (pp. 1191–1223). New York: Wiley.

Yeadon, F. (1993a). The biomechanics of twisting somersaults Part III: Aerial twist. *Journal of Sports Sciences*, *11*(3), 209–218.

Yeadon, F. (1993b). The biomechanics of twisting somersaults Part II: Contact twist. *Journal of Sports Sciences*, *11*(3), 199–208.

Yeadon, M. R. (2000). Aerial movement. In: Zatsiorsky, V. M. (Ed.). *Biomechanics in Sport: Performance Enhancement and Injury Prevention. Olympic Encyclopaedia of Sports Medicine* (pp. 273–283). Oxford: Blackwell Science.

Yeadon, M. R., & Hiley, M. J. (2014). The control of twisting somersaults.

Journal of biomechanics, *47*(6), 1340–1347.

Yeadon, M. R., & Mikulcik, E. C. (1996). The control of non-twisting somersaults using configuration changes. *Journal of biomechanics*, *29*(10), 1341–1348.

Zequera M, Stephan S, & Paul J (2006). The "parotec" foot pressure measurement system and its calibration procedures. In *28th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (pp. 5212-16). New York.

Corresponding author:
Miha Marinšek
Faculty of Education
University of Maribor
Maribor
Slovenia
E mail: miha.marinsek@um.si