Technique selection in young female gymnasts: elbow and wrist joint loading during the cartwheel and round-off

Roman Farana, Timothy Exell, Gerda Strutzenberger & Gareth Irwin

Abstract

Biophysical loading of the elbow and wrist are a potential reason for chronic lesions in gymnastics, and present a real concern for coaches, scientist and clinicians. Previous research has identified injury risk factors during round-off (RO) skills in elite female gymnasts. The aim of this study was to investigate key elbow and wrist joint injury risk factors during different techniques of fundamental cartwheel (CW) and RO skills performed by young female artistic gymnasts. Seventeen active young female gymnasts performed 30 successful trials of both CW and RO from a hurdle step with three different hand positions (parallel (10), T-shape (10) and reverse (10)). Synchronized kinematic (240 Hz) and kinetic (1200 Hz) data were collected for each trial. One-way repeated measures ANOVA and effect-size (ES) statistics determined differences between each hand position. The results showed statistically significant differences ($p<0.05$) and large ES (>0.8) among hand positions for peak VGRF, peak elbow compression force, peak wrist compression force, elbow internal adduction moment and wrist dorsiflexion angle. In conclusion, the parallel and reverse techniques increase peak VGRF, elbow and wrist compression forces and elbow internal adduction moment. These differences indicate that the parallel and reverse techniques may increase the potential of elbow and wrist injuries in young gymnasts compared with the T-shape technique; this is of particular importance with the high frequency of the performance of these fundamental skills.

Keywords: biomechanics, 3D analysis, injury & prevention, youth, coaching.

Introduction

Gymnastics is a sport in which the musculoskeletal system is exposed to extensive loads, which must be distributed through the elbow and wrist joints when the body is supported by the upper-extremities (Farana, Jandacka, Uchytil, Zahradnik, & Irwin, 2014; Farana, Jandacka, Uchytil, Zahradnik, & Irwin, 2017). Injury can have adverse effects on gymnasts given the potential risk of long-term or permanent disability (including reduced quality of life), the risk of early degenerative musculoskeletal disorders, the cost of injury treatment, loss of gymnastics participation time, and a reduction in the gymnast's well-being (Bradshaw & Hume, 2012). A specific characteristic of gymnastic training is the alternation of support between upper and lower limbs, with the upper extremities often used for weight-bearing (DiFiori, Caine, & Malina, 2006). Weight-bearing by upper extremities generates large impact loads that are distributed through the elbow and wrist joints (Webb & Rettig, 2008). The major challenge for the coaches and athletes is the selection of technique, due to the fact that the same skill can be performed with a number of different techniques. Technique selection may have an impact on injury and the evolution of the skill and is an important area for research (Farana et al., 2014; Farana et al., 2017; Manning, Irwin, Gittoes, & Kerwin, 2011).

In gymnastics the cartwheel (CW) and the round-off (RO) are two of the most fundamental skills and are defined as the primary way for gymnasts to change from forward to backward-rotating movements. Previous research by Lindner and Caine (1990) shows that most injuries happened with skills that are of basic or moderate difficulty. This finding is supported by the epidemiological study of Singh, Smith, Fields, and McKenzie (2008) who investigated gymnastics-related injuries and highlighted that the CW and RO make up 30 % of the skills in which injury occurred. The prevalence of injury occurrence during these skills may be due to the fact that the more fundamental skills are perform at a higher frequency, increasing the chance of injury potential (Daly, Rich, Klein, & Bass, 1999). Previous gymnastics research showed that serious chronic injuries, such as osteochondritis of the humeral capitellum (Aronen, 1985; Jackson, Silvino, & Reiman, 1989) and distal radius physeal stress fracture (DiFiori et al., 2006; Webb & Rettig, 2008) may affect the elbow and wrist joints of young gymnasts aged 10 – 14 years (Gabel, 1998; Jackson et al., 1989). These injuries are primarily a disorder of young adolescent athletes, typically involved in a highly repetitive activity such as gymnastics (Baker, Romeo, & Baker, 2010). Moreover, an epidemiological study of gymnastics related injuries (Singh et al., 2008) highlighted that upper-extremity injuries were the most common (42 %) in gymnasts aged 9 – 11 years.

Previous studies by Farana et al. (2014 and 2017) examined injury risk and technique selection associated with the choice of hand placement in RO skills performed by elite female gymnasts, and highlighted that hand placement selection during the fundamental RO skill has a direct influence on the bio-physical demand placed on the performer. These authors found that the T-shape hand position reduced peak ground reaction forces (GRF), decreased elbow joint moments and axial compression force applied on the wrist joint compared to a parallel hand position, indicating the T-shape as a safer technique for the RO skill. Targeted injury prevention strategies, based on biomechanical analyses, have the potential to help reduce the incidence and severity of injuries (Bradshaw & Hume, 2012). However, there is a lack of research that has focused on the injury risk associated with different hand placements during fundamental skills (i.e. CW and RO) of young female gymnasts. The CW and RO are key skills in the safe and effective motor development of gymnasts. Due to the fact that these skills are precursors to developing more complex skills and are often performed by general, recreational, and competitive gymnasts and also as part of the school curriculum. Previous research by

Farana et al. (2014 and 2017) has demonstrated the load exposed to gymnasts performing the RO, the current study aims to examine another key skill that is often learnt as the precursor to the RO. The CW is an essential skill, and its inclusion in the current study is based on the fact that this skill is frequently performed by young gymnasts and technique selection of this skill is a key point for coaches, gymnasts, non-gymnasts and also physical education teachers. The CW also underpins the development of the RO as a fundamental skill. Increasing knowledge of CW technique may help in decreasing mechanical load by selecting techniques that are less risky and provide an effective transfer for the RO skill. Within gymnastics training and competitions three different hand positions during CW and RO skills have emerged (parallel, T-shape and reverse) (Figure 1). The frequency that these skills are performed means that the exposure to low and medium loads can accumulate across a session and training year. Moreover, the injury risk to the gymnasts is based on micro trauma from high repetitions that occurs mostly in training compared to competition as previously highlighted by the epidemiological research (e.g. Caine et al., 2003; Marshall, Covassin, Dick, Nassar, & Agel, 2007; Kerr, Hayden, Barr, Klossner, & Dompier, 2015). These loads along with high risk hand placement may create an environment for the development of mircotrauma and hence injury especially in young gymnasts during growth. Previous research shows that young gymnasts between the age of 10 – 14 are at highest risk of overuse injuries of the elbow and wrist (Gabel, 1998; Jackson et al., 1989), and these injuries may occur from weight-bearing activities such as CW and RO (Daly et al., 1999; Singh et al., 2008).

Insert Figure 1 Above Here

The need for this research is supported theoretically to develop understanding of the stochastic nature of injury incidence in young gymnasts, who typically perform a high number of repetitions of these fundamental skills when training. Therefore, the aim of the current study was to investigate key elbow and wrist joint injury risk factors during different CW and RO techniques performed by young female artistic gymnastics. It was hypothesized that different hand positions would affect external forces and elbow and wrist joint kinematics and kinetics. Specifically, the parallel and reverse techniques would increase upper limb injury risk factors including external forces, elbow and wrist kinematics and kinetics compared with the T-shape technique. The overall purpose of this research is to increase the understanding of upper-limb injury potential of young female gymnasts, which would be useful for gymnasts, coaches, clinicians and scientists.

Material and Methods

Participants

Seventeen young active female gymnasts with more than 5 years' experience with systematic training and competitive gymnastics participated in the current study (age: 10.3 ± 1.4 years, height: 140.2 ± 7.9 cm and mass: 31.9 ± 4.8 kg). All gymnasts had no previous history of upper extremities injury and at the time of testing were injury-free. Informed assent and parental consent were obtained from each gymnast and her parents, respectively, in accordance with the guidelines of the Institute's Ethics and Research Committee.

Protocol

Each gymnast completed her self-selected warm up and completed a number of practice CW and RO trials with different hand positions. To maintain ecological validity, a thin gymnastics floor mat (thickness 20 mm, Baenfer, Germany) was taped down onto the force plates to replicate the feel of a typical gymnastics floor. Since the dimension of the mat covering force plates could affect kinetic calculations, depth of the transducer was set as the sum of the manufacturer depth for the specific force plate and the depth of the mat. This corrected the centre of pressure location (Farana et al., 2017). Additionally, Arampatzis, Brüggemann, and

Klapsing (2002) showed that stiffness properties of a gymnastics mat have no effect on the peak magnitude of ground reaction forces transmitted to the gymnast. Using this mat is more valid given that the gymnasts work on a floor with this type of mat (Farana et al., 2014). Landing mats were used to provide safety for the gymnasts' landings. After their warm up and practice, the gymnasts performed 10 trials for each condition of the CW and RO skills from a hurdle step with parallel, T-shape and reverse hand positions. All trials were performed in a random order and separated by a one-minute rest period. Based on previous research by Farana et al. (2014, 2017), two time gates were used to measure and control hurdle step velocity. However, due to the nature of CW and simple RO skills we used different approach velocities for this study. These velocities were chosen based on natural velocities which young gymnasts used during training of these fundamental skills. This approach maintained a higher level of ecological validity and also did not alter the intra subject variability. Preceding the main data collection, a series of pilot studies were carried out to investigate this velocity and based on these studies we used a range of 2.0 – 2.5 m/s for CW and from 2.5 – 3.0 m/s for RO skills.

Experimental set-up

Two force plates (Kistler, 9286 AA, Switzerland) embedded into the floor were used to determine ground reaction force data at a sampling rate of 1200 Hz. A motion-capture system (Qualisys Oqus, Sweden) consisting of nine infrared cameras was employed to collect the kinematic data at a sampling rate of 240 Hz and synchronized with the force plate data. A right handed global coordinate system was employed and defined using an L-frame with four markers of known location. A two-marker wand of known length was used to calibrate the global coordinate system so that the z-axis was vertical, the y-axis was anterior–posterior, and the x-axis was medio-lateral. Data from the force plates and the cameras were collected simultaneously. Based on C-motion (Rockville, MD, USA) recommendations, retroreflective markers (diameter of 12 mm) and clusters were attached to the gymnasts' upper limbs and trunk. Markers were bilaterally placed on each participant at the following anatomical locations: the acromio-clavicular joint, centre of shoulder deltoid muscle, lateral epicondyle of the humerus, medial epicondyle of the humerus, radial-styloid, ulnar-styloid, head of the second metacarpal. Two clusters containing four markers each were also placed bilaterally on the upper arm (Figure 2).

Insert Figure 2 Above Here

Data analysis

Raw data were processed using Visual 3D software (C-motion, Rockville, MD, USA). The coordinate data were low-pass filtered using a fourth-order Butterworth filter with a 12 Hz cut off frequency. All force plate data were low-pass filtered using a fourth-order Butterworth filter with a 50 Hz cut off frequency. The local coordinate systems (LCS) were defined using a standing calibration trial in the handstand position (Farana et al., 2014). LCS for the elbow and wrist were oriented such that the y-axis points anteriorly, z-axis points vertically, and x-axis is perpendicular to the plane of the other two axes with its direction defined by the right-hand rule (Hamill, Selbie, & Kepple, 2014). Three-dimensional joint angles for the wrist were calculated using an XYZ Cardan rotation sequence. In addition, the net three-dimensional elbow joint moments and elbow and wrist joint reaction forces were quantified using the Newton–Euler inverse dynamics technique (Selbie, Hamill, & Kepple, 2014) and are expressed in the LCS of the upper arm and forearm respectively. All analyses focused on the contact phase of the second hand during the three different CW and RO techniques. Key injury risk variables included peak vertical GRF, elbow joint internal adduction moment (+ adduction / – abduction), elbow and wrist joint axial compression forces, and wrist joint dorsiflexion (+ plantarflexion / – dorsiflexion). Wrist joint dorsiflexion angle was determined as angle between LCS of the hand

and forearm (0° indicates full extension). The GRF data, moment of force data and joint reaction force data were normalized to each gymnasts' body mass.

Statistical analysis

Statistical tests were used to examine the effects caused by the independent variable "hand position" (parallel, T-shape, reverse) on the dependent variables (i.e., ground reaction forces, elbow and wrist joint kinematics and kinetics). Mean values of the 10 trials for each gymnast in each technique were calculated for all measured variables and used in statistical analysis. A Shapiro–Wilk test confirmed the normality assumption for the data and a one-way repeated measure ANOVA determined significant differences between each hand position. If Mauchly's test result was significant, Greenhouse–Geisser corrections were used. This was followed by carrying out Bonferroni pairwise comparisons. Effect size (ES) statistics were used to assess the biological relevance of the differences between hand positions. According to Cohen (1992) ESs were interpreted as trivial (<0.2), small (0.21–0.5), medium (0.51–0.8), or large (>0.8) and statistical power (SP) was kept above 0.8. Statistical tests were processed using the IBM SPSS Statistics 20 Software (IBM SPSS Inc., Chicago, IL, USA). The significance level was set to P <0.05.

Results

Means, standard deviations and effect size values for VGRFs, elbow and wrist joint kinematics and kinetics for all techniques of CW and RO skills are displayed in Table I.

For CW skills the results of the ANOVA indicated statistically significant main effects among hand positions for elbow internal adduction moment (F =40.82, P =0.000, partial η^2 =0.71 and SP =1.00) and wrist dorsiflexion angle (F =21.10, P =0.000, partial η^2 =0.57 and SP =0.99). Subsequent pairwise comparisons using Bonferroni corrections and effect sizes between hand positions for all variables are presented in Table I. Significant differences and large effect sizes were observed for elbow joint internal adduction moment between parallel and T-shape techniques (*P* =0.000, *ES* =1.9), and between T-shape and reverse techniques (*P* =0.000, *ES* =1.4). As for wrist dorsiflexion angle, significant differences and medium to large effect sizes were observed between parallel and T-shape techniques (*P* =0.04, *ES* =0.6), between T-shape and reverse techniques (*p* = .000, ES = 1.6) and between parallel and reverse techniques (*P* =0.001, *ES* =1.1).

For RO skills the results of the ANOVA showed statistically significant main effects among hand positions for peak VGRF (*F* =46.39, *p* =0.000, partial η^2 =0.74, *SP* =1.00), peak elbow compression force (*F* =24.17, *P* =0.000, partial η^2 =0.60, *SP* =1.00), peak wrist compression force (*F* =32.98, *P* =0.000, partial η^2 =0.67, SP = 1.00), elbow internal adduction moment (*F* =61.98, *P* =0.000, partial η^2 =0.79 *SP* =1.00) and wrist dorsiflexion angle (*F* =29.97, *P* =0.000, partial η^2 =0.65, *SP* =1.00). Subsequent pairwise comparisons using Bonferroni corrections and effect sizes between hand positions for all variables are presented in Table I. Significant differences and large effect sizes in peak VGRF were found between parallel and T-shape techniques (*P* =0.000, *ES*= 1.2) and between reverse and T-shape techniques (*P* =0.000, *ES* =1.2). As for elbow joint internal adduction moment, significant differences and large effect sizes were observed between parallel and T-shape techniques (*p* = .000, ES = 1.9), and between T-shape and reverse techniques (*P* =0.000, *ES* =2.0). Elbow joint vertical reaction forces displayed significant differences and large effect sizes between parallel and T-shape techniques (*P* =0.000, *ES* =0.9), and between reverse and T-shape techniques (*P* =0.000, *ES* =1.0). As for wrist joint vertical reaction force, significant differences and large effect sizes were found between parallel and T-shape techniques (*P* =0.000, *ES* =1.0) and between T-shape and reverse techniques (*P* =0.000, *ES* =1.1). Significant differences and large effect sizes in peak wrist joint dorsiflexion were found between parallel and T-shape techniques (*P* =0.003, *ES* =0.9), between T-shape and reverse techniques (*P* =0.000, *ES* =1.9) and between parallel and reverse techniques (*P* =0.000, *ES* =1.1).

Discussion

The purpose of this research was to increase understanding of injury potential of young female gymnasts during the performance of fundamental skills and builds on previous research (Farana et al., 2014 and 2017) which focused on elite female gymnastics. The aim was to investigate key elbow and wrist joint injury risk factors during different CW and RO techniques in young female artistic gymnastics. The current study provides new insights into how impact forces and elbow and wrist joint kinetics and kinematics are associated with different hand positions during ground contact of the second hand during CW and RO skills performed by young female gymnasts. Based on the presented findings, the hypothesis that the parallel and reverse technique would increase upper limb injury risk factors compared to T-shape technique was accepted.

A previous study (Farana et al., 2014) highlighted that T-shape hand positions reduced peak VGRF of the second contact hand compared to the parallel technique in the RO. In the current study, no significant differences between techniques were found for peak VGRF of the second contact hand when gymnasts performed CW skills. However, during RO skills, peak VGRF of the second hand increased compared to the CW and was highest in the reverse technique followed by the parallel and then T-shape technique with the lowest peak VGRF (Table I). These findings concur with a previous case study by Farana, Janeczkova, Uchytil, and Irwin (2015), who investigated three different hand positions during RO skills performed by an elite male gymnast. Comparing magnitudes of VGRFs with previous findings (Farana et al., 2014), elite gymnasts demonstrated an increase in peak VGRF in the parallel technique by 0.48 BW and by 0.51 BW in the T-shape technique. From an injury perspective, these observations can be contextualised against the comments of Davidson, Mahar, Chalmers, and Wilson (2005), who stated that peak impact forces are among the central injury risk factors associated with the upper limb in gymnastics. However, from a technical perspective, higher VGRF may be important for successful performance of CW and RO skills due to the need for vertical and angular velocity. In addition, coaching literature (Cuk & Karacsony, 2004) shows that the reverse position is an effective technique for the RO family vaults. An explosive take-off from the vaulting table is required to increase post-flight time, which provides gymnasts with the opportunity to complete more complex skills, increase the vault difficulty and the potential for a higher resultant score (Bradshaw, Hume, Calton, & Aisbett, 2010).

Previous studies have highlighted an important role of forearm rotation on the elbow and wrist joint loading during the RO in female elite gymnasts (Farana et al., 2014; Farana et al., 2017). Current findings found significant differences and large effect sizes for peak internal adduction moments in the CW and RO with parallel and reverse hand positions compared with the T-shape hand position (Table I). These findings are in accordance with previous research by (Farana et al., 2014), identifying significantly lower magnitudes of internal adduction moment in the T-shape technique compared with parallel hand position during the RO performed by elite female gymnasts. As for elbow joint compression force, no significant differences between techniques were found for CW skills. However, during the RO, significantly higher magnitudes of elbow joint vertical reaction force were observed in the parallel and reverse techniques compared with the T-shape technique (Table I). Combinations of these factors has significant influence on injury potential and are in accordance with previous findings by Koh, Grabiner, and Weiker (1992) who indicated that these compression forces and sizeable adduction moments placed on the elbow joint may be responsible for chronic injuries. When comparing the magnitudes of elbow internal adduction moment reported by Farana et al. (2014) for the RO, there is a decrease in the parallel and T-shape technique by 0.33 Nm/kg and

0.38 Nm/kg respectively. These differences may be due to the fact that elite gymnasts in the previous study (Farana et al., 2014) performed the RO followed by an accelerated back handspring and thus greater approach velocity was needed. Moreover, in the current study, significantly higher magnitudes of wrist joint axial compression force were found in the reverse and parallel techniques compared with the T-shape technique during the RO, with the highest magnitude of wrist joint reaction force reported in the reverse technique (Table I). These findings are in accordance with the previous study (Farana et al., 2017) highlighted that in the T-shape technique the second contact hand wrist joint is exposed to lower mechanical loads demonstrated by decreased axial compression forces. It has been highlighted that these compressive loads are transmitted through the carpals to the radius and ulna, with the radius accepting approximately 80% of the load (DiFiori, Puffer, Aish, & Dorey, 2002). Moreover, evidence from previous research has identified that repetitive loads placed on the wrist joint can lead to distal radius stress injury (DiFiori et al, 2002; DiFiori et al, 2006). However, when comparing magnitudes between elite and young gymnasts there is a decrease of 3.85 N/kg and 5.38 N/kg in young gymnasts for the parallel and T-shape techniques, respectively. These differences can be explained by the suggestion that mechanical loading of the wrist and elbow joints increased as a function of skill difficulty. As such we speculate that the increase in skill difficulty level, i.e. CW to RO then to accelerated RO (Farana et al., 2014; Farana et al., 2017), may influence the mechanical demands placed on the performer and consequently the mechanical load placed on the wrist and elbow joint. Other factors such as skill level in pommel horse circles (Fujihara & Gervais, 2012) and stage of learning for the long swing on high bar (Williams, Irwin, Kerwin, & Newell, 2015) have also been shown to influence joint loading.

Finally, higher wrist joint dorsiflexion was found in the T-shape technique compared with the parallel and reverse techniques for both CW and RO skills. Previous research demonstrated that >95° of hyperdorsiflexion of the wrist places the scaphoid waist at the highest risk for fracture (Weber & Chao, 1978). Interestingly, these results demonstrated wrist dorsiflexion for all CW and RO techniques to be lower than this critical value. However, from an injury perspective, the use of very soft mats may exaggerate the amount of dorsiflexion and thus increase the risk of chronic distal radial injury (DiFiori et al., 2006; Farana et al., 2017).

Protecting young athletes from exposure to injury risk is a key aim of sports medicine and coaching. Gymnastics training requires the high frequency performance of fundamental skills and as previous gymnastics research has shown this can result in serious chronic injuries (Baker et al., 2010; Daly et al., 1999; Jackson et al., 1989; Singh et al., 2008). In the current study the elbow and wrist, joint loading during fundamental gymnastics skills are examined with the aim to gain insights gained into the risk factors associated with these sporting techniques. The specific clinical application and as such relevance to sports medicine falls into three areas. Firstly, diagnosis of specific lesions for example explaining identifying risk factors associated with the occurrence of injuries such as osteochondritis of the humeral capitellum (Aronen, 1985; Jackson et al., 1989) and distal radius physeal stress fracture (DiFiori et al., 2006; Webb & Rettig, 2008). Secondly, athlete screening in terms of identification of the development of potential hazardous movement patterns and bio-physical loading, in combination with knowledge of epidemiology of gymnastics related injuries (Singh et al., 2008). Finally, clinical education in terms of demonstrating the need for an interdisciplinary approach to understanding and explaining the potential of elbow and wrist injuries in young gymnasts developing fundamental skills. Long-term prospective studies on large samples of young gymnasts that include descriptive and analytical components would be useful to clarify the distribution and determinants of elbow and wrist pain and injury potential. As already highlighted the injury risk comes to the gymnasts is based on micro trauma from high repetitions that occurs mostly in training compared to competition as previously highlighted by the epidemiological research (e.g. Caine et al., 2003; Marshall, Covassin, Dick, Nassar, & Agel, 2007; Kerr, Hayden, Barr, Klossner, & Dompier, 2015). Coaches, sports scientist and clinicians can better inform practitioners regarding the risk factors of these gymnastics techniques. The identification of potential risk factors within certain techniques should make the process of technique selection more objective and safe.

Conclusions

The parallel and reverse techniques increased peak VGRF, elbow and wrist compression forces and elbow internal adduction moments. These differences indicated that the parallel and reverse techniques of CW and RO may increase the potential of elbow and wrist injuries in young gymnasts. This is of particular importance with the high frequency of the performance of these fundamental skills. Findings from the current study further reinforce and support the use of the T-shape technique for the CW and RO skills; this is of particular importance with the high frequency of performance of these fundamental skills. These results should inform the clinical application from a sports medicine perspective and also applied coaching and development of fundamental gymnastics skills.

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Figure 1. *Round-off hand positions (A) Parallel, (B) T-shape and (C) Reverse.*

Figure 2. *Marker placement on the gymnasts' body*.