Abstract

Asymmetry in gymnastics underpins successful performance and may also have implications as an injury mechanism; therefore, understanding of this concept could be useful for coaches and clinicians. The aim of this study was to examine kinematic and external kinetic asymmetry of the arm segments during the contact phase of a fundamental skill, the forward handspring on floor. Using a repeated single subject design six female National elite gymnasts (age: 19±1.5 years, mass: 58.64±3.72 kg, height: 1.62±0.41 m) each performed 15 forward handsprings whilst synchronised 3D kinematic and kinetic data were collected. Asymmetry between the lead and non-lead side arms was quantified during each trial. Significant kinetic asymmetry was observed for all gymnasts ($p<0.005$) with the direction of the asymmetry being related to the lead leg. All gymnasts displayed kinetic asymmetry for ground reaction force. Kinematic asymmetry was present for more gymnasts at the shoulder than the distal joints. These findings provide useful information for coaching gymnastics skills, which may subjectively appear to be symmetrical. The observed asymmetry has both performance and injury implications.

INTRODUCTION

In the sport of artistic gymnastics the forward handspring on floor is a fundamental skill (Arkaev & Suchilin, 2009; Readhead, 1997), which represents a foundation for developing gymnasts and an acceleration skill for more established performers who wish to generate the correct take off conditions to perform more complex movements (e.g. multiple somersaults). The assessment of this skill is based on criteria outlined by the International governing body (FIG, 2013). According to these recommendations one would expect the movement patterns undertaken by the gymnast to have little or no asymmetry. Furthermore, excessive amounts of asymmetry are penalised by points deductions in competition (FIG, 2013). The coaching recommendations concur with the belief that the handspring is a symmetrical movement and consequently this forms the guidance for the development of this skill via preparatory activities (Arkaev & Suchilin, 2009; Readhead, 1997).

Research on upper extremity asymmetry is underdeveloped, particularly within the sporting context. However, research into lower-limb asymmetry during running gait (Vagenas & Hoshizaki, 1992; Exell, Irwin, Gittoes & Kerwin, 2012) has suggested that asymmetry may lead to a predisposition for injury in one limb. From a clinical framework research has examined asymmetry of the arms during wheelchair propulsion (Boninger et al., 2002; Hurd, Morrow, Kaufman & An, 2008). Boninger et al. (2002) reported upper limb asymmetries in propulsion patterns which was suggested to have clinical consequences contributing to the development of upper limb injury. Furthermore, Hurd et al. (2008) also reported upper-limb asymmetry but with no consistent pattern in the direction of asymmetry, which is a limiting factor in the prediction of injury and may also have implications for skill development. The presence of asymmetry in joint movements patterns without consistent direction (i.e. a dominant side) may suggest that asymmetry can be viewed as a joint-specific compensatory mechanism that is used to minimise injury risk for the different sides.

Much of the research in asymmetry has been concentrated upon the lower extremity during impact forces incurred whilst jumping or landing (Fuchs, Bauer & Snow, 2001; Fuchs, Cusimano & Snow, 2002) and during activities such as submaximal running (Hamill, Bates & Knutzen, 1984; Vagenas & Hoshizaki, 1992; Zifchock, Davis, & Hamill, 2006), the triple jump (Wilson, Simpson, van Emmerick & Hamill, 2008) and sprint running (Exell, Irwin et al., 2012; Exell, Gittoes, Irwin & Kerwin 2012). Čuk and Marinšek (2013) looked specifically at landing quality in a variety of somersaulting movements in men's gymnastics. The authors found that, in order to avoid asymmetry in landing, gymnasts need to develop enough height, produce high angular momentum around the transverse and longitudinal axes and better control angular velocity in the longitudinal axis. It has been reported that if the frequency of jumping and landing is very high in sporting activities, there is an increased risk of over load injury (Bressel & Cronin, 2005). It has been suggested that a smaller peak of vertical ground reaction force (GRF) exists when landing from movements unilaterally due to the absorption of injury inducing force and this may be an argument for the production of asymmetrical movement in landing (Ortega, Rodriguez Bies, & Berral, 2010). However, the utilisation of functional asymmetry in landing is limited in gymnastic events due to the associated scoring penalty. Asymmetry has been assessed, for the most part, in clinical settings to attempt to quantify inter limb discrepancies and to assess the injury potential of limb imbalances (Exell, Irwin et al., 2012; Schache, Wrigley, Baker & Pandy, 2009).

The aim of this study was to examine the kinematic and external kinetic asymmetry of the arm segments during the contact phase of the forward handspring on floor. The hypothesis of this research was that there would be gymnast-specific asymmetry profiles influenced by the technique employed. This research contributes to the applied area of gymnastics and the understanding of biological asymmetry, helping coaches, clinicians and biomechanists

2. METHODS

2.1. Participants

Ethical approval was gained from the University's Research Ethics Committee prior to commencement of the study. Six female national level gymnasts gave voluntary written informed consent to participate in the study. Gymnasts mean [±SD] age, mass and stature were 19 [±1.5] years, 58.64 [±3.72] kg and 1.62 [±0.41] m, respectively. Participants were all free from injury at the time of data collection.

2.1. Equipment

Three-dimensional kinematic data were collected using an automated motion analysis system (CODAmotion, Charnwood Dynamics, Ltd., UK) operating at 200 Hz. Two cx1 scanners were used to provide a field of view of approximately 2.00 m, which covered the ground contact phase of the action. Synchronised ground reaction force data were collected using two force plates operating at 1000 Hz

(Kistler 9287BA), mounted end-to-end, perpendicular to the direction of the action and separated by a distance of 0.006 m. Kinematic and kinetic data were collected simultaneously using the CODA software so that they were time synchronised. Force plates were mounted in recessed customised housings and covered with a Mondo running track surface (Mondo, USA) and thin gymnastic mat (0.02 m thickness, Baenfer, Germany) similar to the set up reported by Farana, Irwin, Jandacka, Uchytil and Mullineaux, 2015. The experimental set up is illustrated in Figure 1.

2.3. Experimental procedure

Twelve active cx1 CODA markers were connected in pairs to “twin-marker drive boxes” and attached to gymnasts using adhesive tape prior to commencement of data collection. Markers were attached to the proximal inter phalangeal joint, and joint centres of the wrists, elbows, shoulders and hips on both sides of the body. Following a warm up, participants each performed 15 forward handsprings from a two- step approach. Participants were allowed sufficient recovery, lasting approximately 10 min between trials, to avoid the effects of fatigue. Kinematic and kinetic data were collected simultaneously during the performance of each forward handspring.

****** FIGURE 1 NEAR HERE ******

2.4. Data analysis

Data were processed using custom code (MATLAB R2010a, The Mathworks, USA). Sagittal plane coordinates were extracted from the three dimensional marker coordinates and used for all calculations. Kinematic data were filtered using a 12 Hz Butterworth filter, which was customised through Winter's residual analysis (Winter, 2009).

Data were analysed using a repeated single subject design. All analyses focused on the ground contact phase of the hands during the handspring. Touch down and take off were defined as the times when the vertical ground reaction force rose above and fell below the mean plus two standard deviation value of the unloaded plate, respectively. The four kinetic variables comprised peak vertical and anteroposterior GRFs and times to these peaks. The six kinematic variables comprised sagittal plane wrist, elbow and shoulder angles at touchdown and take off. Asymmetry (percentage difference) was quantified for kinetic variables (timing and magnitude) using the symmetry angle equations presented by Zifchock, Davis, Higginson and Royer (2008). This method provides a percentage score to quantify the magnitude of asymmetry present for a given variable, with 0% indicating perfect symmetry. Asymmetry was calculated with the incorporation of intra-limb variability proposed by Exell, Gittoes et al. (2012):

$$\theta_{SYM} = \frac{\left(45° - arctan(X_{lead}/X_{non-lead})\right)}{90°} \times 100\% \qquad [1]$$

Where θ_{SYM} is the symmetry angle, X_{lead} is the value for lead side and $X_{non-lead}$ is the value for non-lead side. However, if:

$$\left(45° - arctan(X_{lead}/X_{non-lead})\right) > 90°$$

then [2] was substituted:

$$\theta_{SYM} = \frac{(45° - arctan(X_{lead}/X_{non-lead}) - 180°)}{90°} \times 100\% \qquad [2]$$

Due to the potential influence of angle definitions on asymmetry magnitude, joint kinematic asymmetry was calculated as the difference in joint angles between lead and non-lead sides. All statistical tests were performed using SPSS v.17.0 (Chicago, IL.) Using the criteria of Peat and Barton (2005), all variables were accepted as displaying a normal distribution; therefore, parametric statistical tests were subsequently employed. To determine the magnitude of intra limb variability relative to the amount of asymmetry for each gymnast, independent t-tests were used to test for significant differences (Bonferroni adjusted $p < 0.005$) between values for lead and non-lead sides for each variable. Variables that displayed a significant difference between sides were described as displaying ‘‘significant asymmetry’’ (Exell, Gittoes et al., 2012) meaning that the magnitude of the difference that occurred between limbs was significantly greater than the magnitude of intra limb variability.

3. RESULTS

Individual gymnast kinetic results for lead and non-lead sides are included in Table 1. Furthermore, asymmetry values relating to these variables are presented in Table 2. All gymnasts except Gymnast 1 demonstrated significant kinetic asymmetry with the largest symmetry angle value being 10.70% for maximum horizontal ground reaction force (Fz) of Gymnast 4. Four gymnasts also exhibited significant asymmetry for timing of maximum force (greatest symmetry angle value Gymnast 4 = 25.11%).

****** TABLES 1 & 2 NEAR HERE ******

Table 3 contains bilateral joint angle values at instants of touch down and take off for all gymnasts. Kinematic asymmetry values relating to these variables are presented in Table 4. The number of kinematic variables displaying significant asymmetry ranged from 2/6 (Gymnasts 2 & 6) to 6/6 (Gymnast 4). Significant asymmetrical kinematic variables were reported for touchdown and take off at the wrist, shoulder and elbow. Kinematic asymmetry did not appear to be related to the lead leg side for wrist and elbow results. For the shoulder, five out of six gymnasts demonstrated significant asymmetry at touchdown and take off, with touchdown values being larger for the non-lead side and take off values being larger for the lead leg side for all of these five gymnasts.

****** TABLES 3 & 4 NEAR HERE ******

Figure 2 includes mean [±SD] vertical and antero-posterior ground reaction force profiles for all gymnasts. The profiles highlight the individual nature of kinetic asymmetry, in particular for Fz. For Gymnast 4 the Fz profile was the most asymmetrical, this finding was reflected by the discrete results, where both timing and magnitude were significantly asymmetrical and asymmetry values were larger than the other gymnasts for most variables.

****** FIGURE 2 NEAR HERE ******

4. DISCUSSION

Asymmetry is a fundamental characteristic of gymnastic performance and assessment and may have implications as an injury mechanism. The aim of the current investigation was to examine the kinematic and external kinetic asymmetry, of the arm segments during the contact phase of the forward handspring on floor. It was also proposed that there would be gymnast-specific asymmetry profiles influenced by the individual techniques employed. Asymmetry for kinetic variables was calculated using the symmetry angle approach as presented by Zifchock et al. (2008) and recently adopted by Exell, Gittoes et al. (2012).

Three gymnasts (2, 4 & 6) demonstrated significant asymmetry in peak vertical GRF values, with no gymnasts demonstrating significant asymmetry in the horizontal direction. However, asymmetry in the time of maximum force was reported in both horizontal (Gymnasts 3, 4 & 6) and vertical (Gymnasts 4 & 5) directions. The magnitude of asymmetry for significant maximum Fz values was larger for all gymnasts compared to values reported during sprint running (Exell, Gittoes et al., 2012). With gymnasts performing high volumes of these skills within a session and across a season the implications for micro traumas become apparent, the load will affect the nature and severity of injury (Irwin, 2011) particularly at vulnerable joints such as the wrist. Biomechanical asymmetry has been a prominent research area in walking and running gait research and has provided important information relating to injury potential, coaching, and data collection (Exell, Gittoes et al., 2012; Hamill et al., 1984; Schache et al., 2009). To the authors' knowledge, symmetry in the upper extremities has not been investigated during sporting activity; however, results of the current investigation can be associated with those of Hurd et al. (2008), who investigated upper extremity symmetry during wheelchair propulsion. Hurd et al. (2008) found significant asymmetry in propulsion timing, effort and force, however, due to the variability produced by this action it proved difficult for the authors to prescribe specific training and conditioning regimes that could aid in injury prevention. An in-depth knowledge of asymmetry can facilitate the development of a sound understanding of the mechanisms of specific techniques, which in turn can inform strength and conditioning regimes (Arkaev & Suchilin, 2009). The data presented in this study demonstrate the potential importance of considering asymmetry in external loading experienced by gymnasts. Robust methods of quantifying asymmetry, such as the symmetry angle used in this study allow asymmetry to be measured and compared across different skills; however, it is important to consider the magnitude of asymmetry in relation to other factors that may influence injury such as magnitude of force. This is exemplified in the current study by the larger asymmetry magnitude in peak vertical force for Gymnast 4 (10.70 %) than Gymnast 6 (-8.18 %), however the peak force applied to one side by Gymnast 6 (2.09 BW) was almost three times larger than the largest mean value recorded for Gymnast 4 (0.70 BW).

Čuk and Marinšek (2013) suggested that the landing quality in artistic gymnastics is related to landing symmetry. Furthermore, they found that limb angles at the moment of touch down can influence the ability of the muscles to absorb energy, thus reducing injury potential for the corresponding joints. Therefore, asymmetry at the moment of touchdown can lead to one limb being at a greater risk of injury. Indeed, much of this research has concentrated upon the lower extremities of the body during landing and the purpose of the current investigation was to assess the upper extremities. However, comparisons may be drawn between the discrepancies found in the limbs.

The initial phase of the movement that requires weight bearing at the upper extremities is in fact used for propulsion and does not represent the landing stage of this movement. Thus, the asymmetry found at the upper extremity of the movement in the forward handspring may represent an absorbing and stabilising function (Riccio, 1993; Wilson et al., 2008) to ensure a symmetrical landing is achieved in the lower extremities at landing. This is an interesting concept and although the answer is beyond the scope of this study, it would certainly be interesting to observe the kinetics and kinematics of the landing of these gymnasts from the forward handspring. Despite this, these findings certainly have implications in terms of coaches attempting to replicate the spatio-temporal characteristics of the target skill by developing certain preparatory activities (Irwin & Kerwin, 2007; Wilson et al., 2008).

In the current investigation, the direction of asymmetry for maximum Fz appears to be related to the gymnasts' lead leg, with larger values observed for the side of the lead leg. This finding suggests an absorbing function of the upper extremity on this side of the body. In their study, Čuk and Marinšek (2013) discovered that the main predictor for asymmetry was the difference in vertical hip velocities in the lowest position, reporting that while the velocity of the leading hip stopped at the lowest position, the velocity of the non- leading hip was still decreasing (difference = 0.1 m.s^{-1}). This finding may suggest that asymmetries result from the force absorbing properties of the dominant side. Hurd et al. (2008) investigated wheelchair propulsion using the dominant and non-dominant arm, reporting no large differences between the two limbs. As previously noted, the function of the upper extremities in the front handspring is one of weight bearing and force production prior to the final landing stage of the motion. Therefore, the asymmetries represented may suggest that the coordinating limbs are adapting to movement requirements in a force absorbing capacity, thus representing an initial stage of an overall movement system that is privy to change to ensure overall symmetry is established (Turvey & Beek, 1990; Sternard, Turvey & Schmidt, 1992; Wilson et al., 2008). Again, without obtaining results for these gymnasts for the kinetics of the lower extremity at landing, it is impossible to suggest whether the asymmetries exhibited at the upper extremity are compensating for overall symmetry at landing. However, if this were the case it could be suggested that the kinetic asymmetries play an important role in the movement from a dynamical systems perspective (Hamill, Haddad & McDermott, 2000; Kurz & Stergiou, 2004). The dynamical systems theory suggests that variations in movement patterns are attributable to the neuromuscular junction's response to global (changes in the environment of task) and local perturbations (joint flexion and proprioception) (Kurz & Stergiou, 2004) and proposes that when the neuromuscular system is globally or locally perturbed, it will spontaneously return to a stable state of equilibrium after the perturbation subsides (Kurz & Stergiou, 2004; Wilson et al., 2008).

Kinematic asymmetry in the current investigation did not appear to be related to the lead leg side for wrist and elbow angles. For the shoulder, five gymnasts demonstrated significant ($p < 0.005$) asymmetry at touchdown and take off. This result is similar to that of Čuk and Marinšek (2013) who found that the more distal joints of the lower extremity (ankle and knee) were less affected than the hip for landing kinematics. They found that the uneven load of the legs (whole leg chain) was mostly expressed in the hips due to their weight bearing capacity. This fact is also true for the shoulder joint, at this joint the gymnast has the ability to adjust their movement profile and as such, kinematics at this joint provide the greatest asymmetry. Furthermore, the greater asymmetry at the shoulders may represent a compensatory mechanism to allow the increased symmetry at the more distal segments. The kinematic values obtained at touchdown were larger for the opposite side to the lead leg and take off values were larger for the lead leg side. This may represent the unbalanced distribution of force absorption at initial contact and the force required to propel the athlete to a landing position (Čuk & Marinšek, 2013)

It was hypothesised in the current investigation that gymnast-specific asymmetry profiles would exist, influenced by the individual technique employed. Indeed, the individual nature of asymmetry was highlighted by the fact that no two participants displayed identical asymmetric profiles for the same kinematic or kinetic variables. This led to the hypothesis being accepted. Three gymnasts exhibited significant asymmetry for timing of maximum force (greatest symmetry angle value 25.11%). Furthermore, four gymnasts (1, 3, 4 & 5) displayed significant asymmetry for four or more of the eight kinematic variables. The profiles displayed in Figure 2 highlight the individual nature of the kinetic asymmetry, in particular for Fz. The Fz profile produced by Gymnast 4 was the most asymmetrical, this finding was also reflected by the discrete results, where both timing and magnitude were significantly asymmetrical and asymmetry values were larger than for the other gymnasts. Exell, Irwin et al. (2012) also discovered diverse variability between athletes during sprint running. The individual nature of variables displaying significant asymmetry makes profiling of such movements very difficult. This reinforces the recommendation of a single participant design (Dufek, Bates, Stergiou, & James, 1995) when analysing asymmetry data.

5. CONCLUSIONS

This study aimed to increase understanding of the kinematic and kinetic asymmetry of the arm segments during the contact phase of the forward handspring on floor. The main findings include significant external kinetic asymmetries during the hand contact from touch down to take off and a possible compensatory mechanisms with decreased asymmetry from proximal to distal segments. Future research in this area could investigate the complex interaction of joint kinetic asymmetries to identify any potential within-limb compensatory mechanisms that may be employed. The results of this study provide new information regarding the understanding of gymnastics skills, which may subjectively appear to be symmetrical but that display significant asymmetry. These findings and their implications could provide useful information to coaches, biomechanists and clinicians.

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TABLES

Table 1

Individual gymnast results for maximum vertical (Fz) and antero-posterior (Fy) ground reaction forces.

Gymnast: side	Time of maximum Fz (% of ground contact)	Maximum Fz (BW)	Time of maximum Fy (% of ground contact)	Maximum Fy (BW)
1: Lead	20.9 (5.1)	0.93 (0.16)	13.8 (8.3)	-0.26 (0.09)
Non-lead	20.7 (4.4)	0.96 (0.22)	16.7 (8.6)	-0.23 (0.10)
2: Lead	16.1 (2.6)	1.22 (0.17)	16.5 (2.4)	-0.36 (0.09)
Non-lead	16.7 (2.4)	0.95 (0.19)	16.9 (2.5)	-0.32 (0.09)
3: Lead	15.9 (2.1)	0.82 (0.14)	16.1 (2.1)	-0.28 (0.05)
Non-lead	20.4 (6.2)	0.66 (0.19)	12.5 (3.2)	-0.25 (0.05)
4: Lead	34.7 (10.3)	0.70 (0.10)	11.0 (3.9)	-0.27 (0.04)
Non-lead	23.3 (11.3)	0.50 (0.07)	4.5 (1.3)	-0.29 (0.03)
5: Lead	13.7 (1.5)	1.30 (0.13)	13.4 (1.6)	-0.44 (0.07)
Non-lead	22.5 (5.6)	1.19 (0.07)	12.4 (2.3)	-0.41 (0.04)
6: Lead	14.6 (2.1)	1.61 (0.23)	15.2 (2.0)	-0.57 (0.14)
Non-lead	13.7 (2.8)	2.09 (0.16)	14.2 (2.6)	-0.70 (0.15)

Table 2

Individual gymnast symmetry angle (θ_{SYM}) values (%) and p values for magnitude and timing of maximum vertical (Fz) and antero-posterior (Fy) ground reaction forces.

Gymnast		Time of maximum Fz	Maximum Fz	Time of maximum Fy	Maximum Fy
1:	θ_{SYM}	0.35	-1.05	-5.98	4.43
	p	0.886	0.432	0.008	0.007
2:	θ_{SYM}	-1.29	7.90	-0.64	3.43
	p	0.146	0.000*	0.714	0.103
3:	θ_{SYM}	-7.79	6.61	7.83	3.53
	p	0.017	0.008	0.001*	0.068
4:	θ_{SYM}	12.34	10.70	25.11	-2.18
	p	0.004*	0.000*	0.000*	0.085
5:	θ_{SYM}	-15.29	2.84	2.47	1.65
	p	0.000*	0.011	0.181	0.177
6:	θ_{SYM}	1.95	-8.18	-6.31	2.16
	p	0.176	0.000*	0.000*	0.078

Positive θ_{SYM} values = lead > non-lead, negative values = non-lead > lead

* = significant asymmetry

Table 3

Individual gymnast wrist, elbow and shoulder joint angles at instants of touchdown (TD) and take off (TO) for lead and non-lead sides.

Gymnast		Wrist		Elbow		Shoulder	
		TD	TO	TD	TO	TD	TO
1:	Lead	144 (3)	138 (6)	158 (7)	171 (2)	130 (7)	149 (2)
	Non-lead	134 (3)	140 (4)	155 (7)	165 (4)	139 (9)	142 (3)
2:	Lead	141(4)	130 (3)	157 (2)	156 (3)	123 (4)	143 (2)
	Non-lead	142(3)	132 (5)	161 (3)	155 (3)	136 (4)	133 (5)
3:	Lead	129 (2)	124 (1)	151 (3)	149 (3)	123 (4)	154 (2)
	Non-lead	128 (2)	120 (2)	147 (7)	140 (5)	135 (7)	129 (2)
4:	Lead	118 (2)	119 (2)	154 (2)	154 (2)	139 (2)	140 (2)
	Non-lead	125 (2)	125 (2)	146 (1)	146 (1)	130 (2)	130 (2)
5:	Lead	159 (2)	162 (2)	157 (2)	163 (3)	122 (3)	139 (4)
	Non-lead	142 (3)	149 (3)	155 (6)	158 (4)	143 (10)	132 (3)
6:	Lead	162 (3)	170 (5)	165 (5)	173 (7)	154 (6)	149 (5)
	Non-lead	152 (3)	160 (2)	165 (6)	171 (2)	150 (8)	141 (5)

Table 4

Individual gymnast asymmetry magnitude (θ) and p values for wrist, elbow and shoulder joint angles at instants of touchdown (TD) and take off (TO).

Gymnast		Wrist		Elbow		Shoulder	
		TD	TO	TD	TO	TD	TO
1:	θ (°)	10.3	-1.5	3.5	6.2	-9.0	7.0
	p	0.000*	0.127	0.143	0.000*	0.000*	0.000*
2:	θ (°)	-1.1	-1.8	-4.1	0.8	-13.6	10.2
	p	0.083	0.214	0.011	0.539	0.000*	0.000*
3:	θ (°)	1.2	4.1	3.4	9.17	-11.8	25.0
	p	0.068	0.000*	0.029	0.000*	0.000*	0.000*
4:	θ (°)	-7.2	-6.7	8.5	8.4	-9.3	9.5
	p	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*
5:	θ (°)	17.8	13.3	2.4	4.6	-21.5	6.8
	p	0.000*	0.000*	0.171	0.002*	0.000*	0.000*
6:	θ (°)	9.9	10.2	0.1	2.0	4.1	7.9
	p	0.000*	0.000*	0.976	0.256	0.490	0.000*

Positive θ values = lead > non-lead, negative values = non-lead > lead

* = significant asymmetry

FIGURES

Figure 1. Diagram showing the experimental set up.

Figure 2. Mean [±SD] vertical and antero-posterior ground reaction force profiles for all gymnasts. Black = lead side, grey = non-lead side.