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Biomechanical responses to landing strategies of female artistic gymnasts

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ABSTRACT

Inconsistencies between sexes in the landing criteria provided by the international gymnastics governing body (FIG) may predispose female gymnasts to lower extremity injury. This study aimed to investigate lower extremity biomechanics when performing the male and female landing strategy. Seven collegiate, female gymnasts (age: 20.5 ± 1.2 years, height: 1.64 ± 0.06 m, mass: 60.4 ± 10.2 kg) performed drop landings using the prescribed women's and men's landing strategy. Kinematic and kinetic data from 10 trials of each landing strategy were collected. Differences between landing strategy at individual and group level for key injury risk variables of the lower limb were explored. Group differences ($p \leq .05$) were reported in the sagittal range of motion (ROM) at the knees and hips, with the men's landing strategy eliciting a larger ROM decelerating the body upon impact. Large inter and intra-individual variation was apparent with different movement responses shown across individuals and demonstrating degeneracy as gymnasts satisfied the overall landing objective. These results indicate an individually favoured landing strategy to fulfil the informational constraints and hence supporting the use of a single-subject design. The current study emphasises the potential injury risk associated with the different informational constraints placed on females' landing strategy by the FIG, whilst recognising the individual gymnasts' task response.

Highlights:

- An increase in the range of motion at the knee and hip may support the recommendation of the men's landing style.
- Gymnasts appear to utilise individual landing strategies to complete the landing objective, supporting the use of a single-subject design.

KEYWORDS
Injury prevention; impact biomechanics; instructional constraints; single-subject design

Introduction

Female, artistic gymnasts have been reported to sustain the greatest number of injuries per year compared to any other women's intercollegiate sport in the USA (Hootman, Dick, & Agel, 2007). The lower extremity has been regularly reported as the most common anatomical site for injury (Kerr, Hayden, Barr, Klossner, & Dompier, 2015; Kirialanis, Malliou, Beneka, & Giannakopoulos, 2003; Marshall, Covassin, Dick, Nassar, & Agel, 2007; O'Kane, Levy, Pietila, Caine, & Schiff, 2011). Previous studies have reported 36–70% of total injuries affecting the lower limb (Kolt & Caine, 2010; O'Kane et al., 2011), predominantly resulting in ankle and knee sprains (Kerr et al., 2015; Marshall et al., 2007). Further evidence suggests 49–52% of these lower extremity injuries occur during the landing phase during dismounts (Kirialanis et al., 2003; O'Kane et al., 2011) with a higher proportion of lower extremity injuries (70.7%) reported to occur during the competition (Marshall et al., 2007). The frequency of landings performed has been suggested to be a significant contributor to the high incidence rates of lower extremity injury in women's artistic gymnastics (Kirialanis et al., 2003). The frequency of landings may not explain the causative mechanisms of injuries and the nature of the landing needs consideration. Successful landing technique in female artistic gymnastics is constrained by the rules (code of points) stipulated by the international governing body (FIG) (Fédération Internationale de Gymnastique, 2020a, 2020b) in terms of the movement patterns and body positions allowed.

The code of points provides information regarding the difficulty value (D-score) and the execution (E-score) of skills. Universal regulations governing the E-

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score for landings are common across all apparatus (Fédération Internationale de Gymnastique, 2020a, 2020b). However, the rules governing the nature of landing within artistic gymnastics differ between the men's and women's competition, with such a discrepancy appearing to lack a clear rationale. Whilst both codes penalise gymnasts for excessive arm swings, lack of balance and additional steps upon landing, there are clear disparities in penalties awarded for leg separation (Fédération Internationale de Gymnastique, 2020a, 2020b). In the women's code of points, any amount of leg separation is considered a fault following the landing of an acrobatic element, with 0.1 deducted from the final execution score on every occasion (Fédération Internationale de Gymnastique, 2020a). The men's code of points dictates a different regulation whereby male gymnasts are able to land with their legs apart and receive no penalty, providing they can join their heels together upon the termination of movement without moving the front of the feet (Fédération Internationale de Gymnastique, 2020b). The potential accumulative effect of these deductions for females landing without legs together can amount to 0.8 during the floor exercise, which separated second and eighth place during the women's floor final at the 2016 Rio Olympic Games. The disparities in landing strategy in artistic gymnastics may have important implications regarding the high incidence of traumatic ankle and knee injuries particularly within the female competition (Kerr et al., 2015; Marshall et al., 2007). The recommended landing strategy in other sporting contexts is one which encourages the feet to be positioned shoulder width apart (Tillman, Hass, Brunt, & Bennett, 2004), with any deviation from this stance to be associated with a poor landing performance and increased potential of lower extremity soft tissue injury when assessed against the Landing Error Scoring System (Padua et al., 2009). The allowance of a larger degree of leg separation in the men's competition may allow for a less impactful, less constrained and more stable landing strategy, thereby reducing injury potential in comparison to the women's competition.

The aim of any gymnastics landing is to safely reduce all body momenta to zero with a simultaneous placement of both feet whilst adhering to the expectations stated in the code of points (Gittoes & Irwin, 2012). Adhering to these objectives requires the gymnast to be stable and is highlighted as an important performance characteristic of successful landings (Bradshaw & Hume, 2012). Stability and its association with the base of support have been observed to be key to successful landing performance (Meyer & Ayalon, 2006) particularly in landings from rotations about a single axis. However, the code of points dictates the nature of the landing movement patterns regardless of the complexity of the preceding skill.

In order to assess injury potential during impacts, external forces have been measured and associated with force attenuation mechanisms such as joint loading (Dufek & Bates, 1991). Biomechanical risk factors suggested to contribute to the frequency and severity of lower extremity injuries during landing are well documented in general (Dufek & Bates, 1991) and specific to gymnastics landings (Gittoes & Irwin, 2012; Gittoes, Irwin, & Kerwin, 2013; McNitt-Gray, 1991). The injury causation process has been identified as a multifaceted interaction of both external and internal risk factors leading towards an inciting event and the increased potential for injury (Bahr & Krosshaug, 2005). In addition, seminal studies, such as that of Nigg (1985), highlighted the need to examine the forces, loading rates and the geometry of the task. This multifactorial characteristic of injury causation together with the complex, interactive nature of the human system creates unique, individual response patterns when performing motor tasks (Bates, 1996). In order to suggest recommendations for load accommodation strategies or introduce preventative measures to reduce the potential of injury, an in-depth examination of the individual movement characteristics is required together with the group aggregate (Bates, James, & Dufek, 2004). Inter-individual variation during the same task has been observed in gymnastics vaulting (Irwin & Kerwin, 2009) and longswing development (Williams, Irwin, Kerwin, & Newell, 2012). These observations support the idea of self-organisation as the performer seeks out the most effective movement strategy for their current biological and environmental situation, and as such degeneration is observed (Edelman & Gally, 2001). Newell (1985), based on the earlier work of Bernstein (1967), recognised that self-organisation and, as such degeneration, occurs as the individual seeks to achieve the performance goal through an interaction of the task, organism and environment (Edelman & Gally, 2001; Newell, 1985). An important point to note is that in gymnastics informational constraints based on the FIG code of points places a restriction on the permitted movement strategies.

Therefore, the aim of this study was to quantify the differences in the lower limb biomechanical demands on female gymnasts, when utilising the two landing strategies dictated by the FIG. We hypothesised that the women's landing strategy (W_{LS}) during a drop landing task would exhibit loads and kinematics that were associated with increased injury potential compared with the men's landing strategy (M_{LS}). With the welfare of performers central to the focus of gymnastics, the purpose of this study was to examine the injury potential due to different landing strategies. This study provides new insights for the FIG, in terms of governance and injury risk, coaches, when informing the safest techniques and biomechanists in the study of injury.

Materials and methods

Participants: Purposeful sampling was employed and seven female, competitive, collegiate, artistic gymnasts (age: 20.5 ± 1.2 years, height: 1.64 ± 0.06 m, mass: 60.4 ± 10.2 kg) were recruited to participate in the study. To overcome the inherent issues of a small sample size, statistical power was kept above 0.8 and effect size statistics were used to assess the biological relevance of the differences between mean values. All participants were free from any lower extremity injury and were actively training at least three times per week at a University gymnastics club. Exclusion criteria included any lower extremity injury that had previously required surgery and any neurological or medical condition that would impair the performance of the landing movement. All participants provided voluntary informed consent and ethical approval was granted by the University's research ethics committee.

Landing protocol: All data collections occurred in the biomechanics laboratory at the University. Prior to the formal data collection, each gymnast was given time to perform a self-prescribed warm-up to prepare for subsequent movement trials. Following the practice trials, each gymnast executed 20 randomised drop landings performing either the women's landing strategy (W_{LS}) or the men's landing strategy (M_{LS}) (Figure 1).

Participants were instructed to perform a competition landing style, only changing their foot positioning when requested. The drop landings were performed stepping off of a 0.72 m high box to replicate typical landing velocities experienced by gymnasts on apparatus such as the floor (McNitt-Gray, 1991) onto two force plates covered with two individual gymnastics mats. A trial was deemed successful if participants performed a landing in accordance with the code of points and if they were able to land bilaterally with one foot on either force plate.

Instrumentation: Three-dimensional kinematic data were collected using 13 infrared cameras (250 Hz, Vicon; Oxford Metrics, Oxford, UK). Simultaneous external kinetic data were collected using two forces plates (Kistler 9287BA, Winterhur, Switzerland) sampling at 1000 Hz. Each force plate was covered with its own custom gymnastics landing mat (900 × 600 × 100 mm) to allow for a decoupling of the force plates so two independent measures could be taken. Although the mats will have reduced the magnitude of force data, not only do they provide ecological validity to the research, the dampening effect of mats (<12 cm thick) has been reported to be minimal (McNitt-Gray, Hester, Mathiyakom, & Munkasy, 2001). Forty-two retroreflective markers (14 mm) were affixed to the skin according to a custom, full-body 6DOF model based on ISB recommendations (Wu et al., 2002). The markers were placed as follows: bilaterally on the first, third and fifth metatarsals, calcaneus, lateral and medial malleoli, lateral and medial epicondyles of the knee, posterior superior iliac spine, anterior superior iliac spine, iliac crest, second metacarpal, lateral and medial epicondyle of elbow, medial and lateral wrist, acromioclavicular joint, xyphoid process, jugular notch, 10th thoracic vertebra, 7th cervical vertebra, and four on a headband. Eight marker clusters were placed on the shank, thigh, upper and lower arms to aid with tracking. The medial markers at the ankle, knee and elbow were used for calibration of the static trial but removed for the movement trials.

Data processing: Kinematic data were processed using Vicon Nexus (v2.9.2, Nexus, Oxford Metric Inc., UK) to interpolate any gaps (no bigger than 100 frames) within marker trajectories using either a pattern or rigid body fill. The gap-filled data were further processed and filtered in Visual 3D (C-motion, Rockville, MD, USA), where marker trajectories and external ground reaction force data were filtered using a fourth-order Butterworth filter with cut-off frequencies of 11 and 50 Hz, respectively, customised through Winter's residual analysis (Winter, 2009).

All analyses were focused on the landing phase of the drop landing movement. This phase was defined from initial contact (IC), where the vertical ground reaction force exceeded a 10 N threshold. The three kinetic variables chosen for analysis were peak vertical ground reaction force (F_{ZPEAK}), loading rate (both normalised to bodyweight) and the timing of F_{ZPEAK} (T_{FZPEAK}). The peak loading rate was calculated by dividing F_{ZPEAK} by T_{FZPEAK}.

A neutral anatomical position was used for the static, calibration trial where neutral ankle dorsiflexion, full knee extension and hip extension were reported as zero degrees. Knee and hip flexion and further ankle dorsiflexion were reported as positive values. Sagittal joint range of motion (ROM) was calculated as the difference between the initial contact (IC) joint angle and maximum flexion of the joint during the landing cycle. A Newton-Euler inverse dynamics approach was used

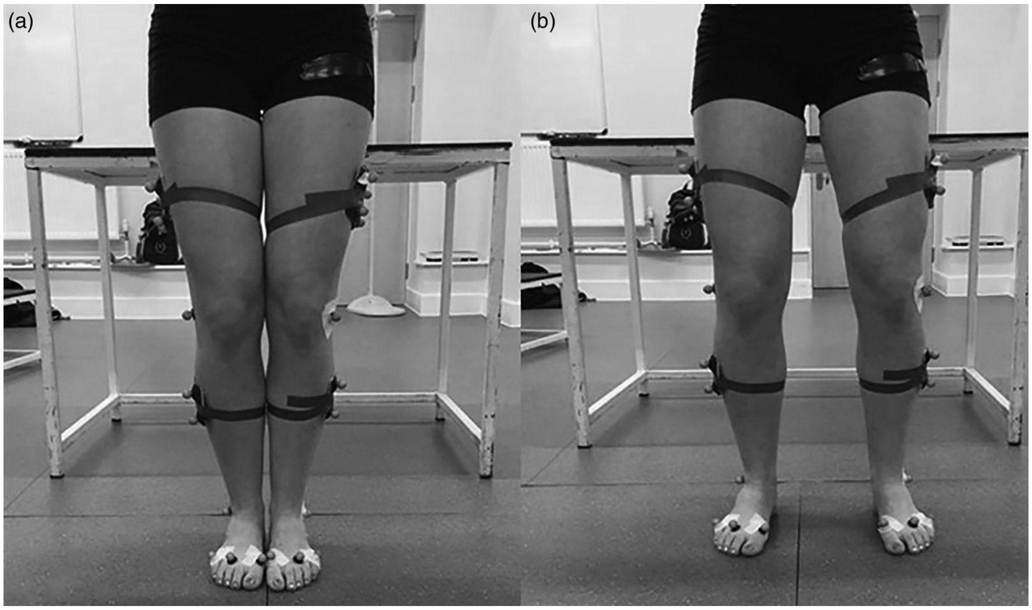

Figure 1. Two different landing styles (a) women's landing style (W_{LS}) and (b) men's landing style (M_{LS}).

to calculate joint moments (τ). By convention, ankle plantarflexion, knee and hip extension moments were all reported as positive values. Joint power was calculated ($JP = M \times \omega$), with negative joint power indicating energy absorption. Joint moments and powers were all normalised to the participant's body weight to reduce the effect of anthropometric differences.

Statistical analysis: Statistical analyses were performed using Microsoft Excel (2007, Microsoft Inc., New Mexico, USA). The mean and standard deviation (SD) of 10 trials were calculated for the right leg of each landing style and grouped together to assess differences between the two groups. The data were tested for normality using the criteria of Peat and Barton (2005). Normality was assumed if the difference between the mean and median values for each group were ≤10%. If the data did not satisfy the first test then it must violate two of four additional tests to be deemed as having a non-normal distribution. Variables satisfying the above criteria were compared using a paired *t*-test to assess differences between group responses, variables that violated the test of normality were tested using the Wilcoxon signed rank test. To evaluate single subject differences between conditions, a model statistic procedure was used according to Dufek and Bates (1991). All statistical tests were conducted at $\alpha = 0.05$ level of significance. Due to a small sample size Hedges g was used to determine the measure of these associations, with the effect size (ES) interpreted as small ($g = 0.2–0.5$), medium ($g = 0.51–0.8$) and large ($g > 0.8$) (Hedges, 1981).

Results

Table 1 displays the group and individual external and kinetic responses when performing the women's (W_{LS}) or the men's (M_{LS}) style of landing. No significant differences were reported in the group response for normalised F_{ZPEAK} ($p = .319$), T_{FZPEAK} ($p = .458$) or peak vertical

Table 1. Mean (SD) group and individual F_{ZPEAK}, T_{FZPEAK} and LR of the right leg when performing the W_{LS} and M_{LS}.

	F_{ZPEAK} (BW)		T_{FZPEAK} (s)		LR (BW/s)	
	W_{LS}	M_{LS}	W_{LS}	M_{LS}	W_{LS}	M_{LS}
Group	3.2 (0.7)	3.1 (0.5)	0.048 (0.010)	0.049 (0.010)	66.7 (20.1)	66.5 (18.4)
P1	3.1 (0.5)	2.7 (0.3)	0.056 (0.005)	0.064 (0.005)*	52.0 (3.7)	43.0 (5.6)*
P2	2.3 (0.5)	2.9 (0.5)*	0.053 (0.009)	0.047 (0.010)	42.7 (9.9)	67.5 (20.7)*
P3	3.2 (0.3)	3.5 (0.4)	0.046 (0.005)	0.040 (0.005)*	72.3 (13.5)	88.3 (18.0)*
P4	3.3 (0.5)	3.0 (0.4)	0.048 (0.004)	0.048 (0.004)	69.6 (15.8)	64.0 (10.8)
P5	3.8 (0.9)	2.9 (0.6)*	0.032 (0.004)	0.041 (0.006)*	105.5 (22.0)	64.2 (28.0)*
P6	3.6 (0.5)	3.5 (0.3)	0.049 (0.006)	0.051 (0.003)	75.4 (14.4)	68.4 (4.5)
P7	3.2 (0.5)	3.1 (0.3)	0.049 (0.006)	0.054 (0.005)	64.6 (6.6)	58.5 (8.5)

Notes: P, participant; $W_{LS,}$ women's landing strategy; $M_{LS,}$ men's landing strategy; $F_{ZPEAK,}$ peak vertical ground reaction force; $T_{FZPEAK,}$ relative time of F_{ZPEAK}; LR, loading rate; BW, bodyweights; BW/s, bodyweights per second. Significant differences in strategy are denoted by *.

Table 2. Mean (SD) group and individual ankle kinematics and kinetics of the right leg when performing the W_{LS} and M_{LS}.

	θA_{IC}		θA_{FZPEAK}		$\Delta\theta A_{ROM}$		ωA_{IC}		$J\tau A_{EXT}$		JPA_{PEAK}	
	W_{LS}	M_{LS}	W_{LS}	M_{LS}	W_{LS}	M_{LS}	W_{LS}	M_{LS}	W_{LS}	M_{LS}	W_{LS}	M_{LS}
Group	−49.7 (5.2)	−50.4 (5.5)	−4.7 (9.4)	−1.7 (6.0)*	56.2 (5.4)	57.8 (7.3)	7.3 (2.6)	6.8 (3.0)	1.5 (0.4)	1.4 (0.5)	28.6 (7.0)	28.0 (5.9)
P1	−50.4 (1.0)	−52.0 (0.9)*	−0.8 (3.7)	0.7 (2.1)	61.5 (3.3)	63.5 (3.1)	4.1 (1.3)	3.3 (1.1)	2.0 (0.2)	2.0 (0.2)	33.2 (6.4)	33.7 (3.3)
P2	−52.5 (1.9)	−52.5 (1.3)	−10.4 (5.3)	−7.9 (4.4)	53.3 (2.8)	50.1 (2.0)*	8.5 (1.7)	8.5 (2.2)	1.9 (0.2)	2.0 (0.2)	29.7 (5.2)	31.1 (4.8)
P3	−53.5 (9.3)	−48.2 (3.0)	−10.6 (9.6)	−4.2 (2.3)	50.5 (1.9)	49.2 (2.3)	8.8 (1.8)	8.7 (1.7)	1.1 (0.2)	1.1 (0.1)	28.6 (4.4)	27.1 (2.8)*
P4	−49.2 (2.9)	−49.6 (2.3)	5.0 (2.0)	5.1 (1.8)	63.5 (2.9)	65.1 (2.7)*	8.0 (2.2)	7.9 (2.3)	0.9 (0.2)	0.7 (0.1)*	22.1 (2.7)	20.2 (4.9)
P5	−44.1 (3.9)	−45.2 (2.4)	−7.6 (4.6)	−3.3 (3.3)*	54.6 (6.8)	56.2 (8.3)	9.5 (1.2)	8.9 (1.1)	1.6 (0.2)	1.2 (0.2)*	26.7 (11.3)	22.4 (4.0)
P6	−46.2 (2.9)	−45.0 (3.3)	5.2 (3.6)	6.0 (2.9)	57.6 (3.2)	58.2 (4.6)	6.7 (1.9)	5.1 (2.8)	1.4 (0.2)	1.6 (0.2)	33.4 (4.0)	33.9 (2.9)
P7	−51.5 (1.4)	−61.1 (0.9)*	−6.7 (3.7)	−6.5 (1.9)	54.1 (2.3)	64.7 (2.8)*	5.0 (1.5)	4.7 (3.0)	1.2 (0.2)	1.1 (0.1)	21.7 (3.3)	25.8 (2.2)*

Notes: P, participant; $W_{LS,}$ women's landing strategy; $M_{LS,}$ men's landing strategy; $\theta A_{IC,}$ Ankle angle at initial contact; $\theta A_{FZPEAK,}$ Ankle angle at peak vertical ground reaction force; $\Delta\theta A_{ROM,}$ Ankle range of motion; $\omega A_{IC,}$ Ankle angular velocity at initial contact; $J\tau A_{EXT,}$ Peak ankle extensor moment; $JPA_{PEAK,}$ Peak ankle joint power.
Significant differences in technique are denoted by * ($p \leq .05$).

loading rate ($p = .969$), however, significant differences were identified at an individual level. P1 demonstrated a significant decrease in T_{FZPEAK} during W_{LS} ($p \leq .05$) and a subsequent significant increase in loading rate. Whereas both P2 and P3 presented opposing results with significant decreases in loading rate when performing the W_{LS} ($p \leq .05$).

The difference in ankle biomechanics (Table 2) between the two landing strategies demonstrated an increased ankle plantarflexion angle at the instance of peak vertical ground reaction force (θA_{FZPEAK}) during the W_{LS} ($p = .001$, $g = 0.3$). Two participants (P1 and P7) demonstrated a significantly more plantarflexed ankle angle at initial contact θA_{IC} with P7 also utilising significantly more $\Delta\theta A_{ROM}$ ($p \leq .05$) and exhibiting greater JPA_{PEAK} during the $M_{LS.}$ P2 demonstrated a significantly increased ($p \leq .05$) $\Delta\theta A_{ROM}$ during the $W_{LS.}$

The difference in knee biomechanics (Table 3) between the two landing strategies showed a larger $\Delta\theta K_{ROM}$ when utilising the M_{LS} ($p = .001$, $g = 0.2$). P4 exhibited a more extended knee position at initial contact (θK_{IC}) using the M_{LS} ($p \leq .05$) whilst P7 demonstrated a significantly more extended θK_{IC} using the W_{LS} ($p \leq .05$).

A significant increase in knee flexion at the instance of F_{ZPEAK} was identified for P1 during the M_{LS} ($p \leq .05$). Other individual differences are displayed in Table 3, for example, P1 and P3 demonstrated opposing biomechanical responses ($p \leq .05$) in both $J\tau K_{EXT}$ and JPK_{PEAK} with higher and lower magnitudes during the M_{LS}, respectively.

Significant group differences at JPH_{PEAK} ($p < .001$, $g = 0.4$) and $\Delta\theta H_{ROM}$ ($p < .001$, $g = 0.3$) were reported in the hip biomechanics when performing either of the two landing strategies (Table 4); however, individual differences were also apparent. Greater hip flexion was observed during the M_{LS} for P4 and P5 ($p \leq .05$) at the key instances of initial contact and $F_{ZPEAK.}$ In addition, hip mechanics played an important role with participants (1 and 6) demonstrating larger $\Delta\theta H_{ROM}$ when performing the M_{LS} ($p \leq .05$).

Table 3. Mean (SD) group and individual knee kinematics and kinetics of the right leg when performing the W_{LS} and M_{LS}.

	θK_{IC}		θK_{FZPEAK}		$\Delta\theta K_{ROM}$		ωK_{IC}		$J\tau K_{EXT}$		JPK_{PEAK}	
	W_{LS}	M_{LS}	W_{LS}	M_{LS}	W_{LS}	M_{LS}	W_{LS}	M_{LS}	W_{LS}	M_{LS}	W_{LS}	M_{LS}
Group	13.3 (6.1)	14.9 (4.6)	41.5 (9.4)	43.3 (6.5)	69.5 (9.3)	71.9 (11.9)*	5.3 (1.6)	5.2 (1.8)	2.4 (0.6)	2.4 (0.5)	32.6 (9.1)	31.8 (8.4)
P1	10.4 (3.1)	12.2 (2.5)	43.0 (2.6)	47.2 (2.6)*	65.6 (7.1)	68.7 (4.3)	5.9 (0.9)	7.1 (0.9)*	3.4 (0.5)	3.0 (0.2)*	39.9 (5.5)	32.2 (5.4)*
P2	17.5 (3.9)	19.9 (2.2)	46.7 (8.7)	44.2 (3.2)	66.0 (5.0)	61.0 (2.5)*	6.8 (0.5)	6.9 (0.8)	1.8 (0.2)	1.9 (0.1)*	24.1 (7.9)	28.2 (1.7)
P3	8.0 (3.8)	8.3 (1.8)	30.7 (8.2)	32.3 (2.5)	60.2 (4.4)	59.5 (3.8)	5.1 (0.8)	5.0 (1.2)	2.1 (0.3)	2.6 (0.2)*	29.7 (3.3)	37.3 (7.0)*
P4	16.7 (1.9)	19.3 (2.3)*	39.9 (2.1)	43.8 (4.0)*	76.5 (4.6)	81.6 (2.9)*	3.7 (0.9)	4.5 (1.0)	2.8 (0.3)	2.9 (0.3)	41.3 (7.5)	39.5 (11.2)
P5	9.8 (2.8)	14.5 (2.4)*	34.4 (4.7)	43.0 (5.8)*	80.4 (7.0)	91.0 (6.2)*	5.3 (0.2)	4.8 (0.8)	1.9 (0.6)	1.5 (0.1)	25.5 (8.5)	20.4 (3.8)
P6	15.6 (1.7)	16.1 (4.8)	48.5 (4.6)	46.8 (4.2)*	75.9 (10.5)	78.4 (9.3)	7.1 (0.7)	5.7 (1.3)	2.6 (0.4)	2.6 (0.3)	38.9 (8.2)	38.2 (4.3)
P7	18.3 (2.2)	13.7 (2.2)*	47.5 (11.5)	46.9 (6.3)	63.9 (1.5)	66.9 (2.4)*	2.9 (1.1)	2.6 (1.7)	2.3 (0.3)	2.2 (0.2)	30.4 (3.2)	27.8 (2.8)*

Notes: P, participant; $W_{LS,}$ women's landing strategy; $M_{LS,}$ men's landing strategy; $\theta K_{IC,}$ Knee angle at initial contact; $\theta K_{FZPEAK,}$ Knee angle at peak vertical ground reaction force; $\Delta\theta K_{ROM,}$ Knee range of motion; $\omega K_{IC,}$ Knee angular velocity at initial contact; $J\tau K_{EXT,}$ Peak knee extensor moment; $JPK_{PEAK,}$ Peak knee joint power.
Significant differences in technique are denoted by * ($p \leq .05$).

Table 4. Mean (SD) group and individual hip kinematics and kinetics of the right leg when performing the W_{LS} and M_{LS}.

	θH_{IC}		θH_{FZPEAK}		$\Delta\theta H_{ROM}$		ωH_{IC}		$J\tau H_{EXT}$		JPH_{PEAK}	
	W_{LS}	M_{LS}	W_{LS}	M_{LS}	W_{LS}	M_{LS}	W_{LS}	M_{LS}	W_{LS}	M_{LS}	W_{LS}	M_{LS}
Group	32.5 (9.0)	32.6 (9.0)	45.9 (10.5)	46.5 (8.8)	43.8 (8.1)	46.7 (9.5)*	2.3 (0.9)	2.4 (1.1)	1.9 (0.6)	1.8 (0.6)	27.1 (14.7)	20.6 (11.1)*
P1	22.4 (2.9)	24.5 (3.1)	38.7 (5.9)	46.0 (4.7)*	39.8 (5.5)	49.9 (2.6)*	3.2 (0.4)	4.2 (0.5)*	1.9 (0.4)	2.1 (0.2)	34.1 (10.4)	27.3 (8.3)
P2	45.1 (4.5)	47.3 (3.5)	62.2 (8.3)	60.6 (3.8)	42.8 (4.8)	41.0 (2.4)	2.6 (0.4)	2.5 (0.4)	1.9 (0.3)	1.6 (0.2)*	15.9 (5.3)	12.6 (3.2)
P3	23.6 (1.9)	25.3 (3.5)	36.5 (2.6)	35.9 (3.3)	45.7 (2.2)	46.9 (2.7)	2.6 (0.3)	2.3 (0.6)	1.5 (0.3)	1.1 (0.3)*	21.1 (3.3)	20.7 (8.5)
P4	38.2 (2.7)	43.2 (4.2)*	46.0 (3.4)	52.4 (4.3)*	54.2 (5.4)	56.3 (4.6)	1.9 (0.8)	2.7 (0.5)*	1.2 (0.2)	1.3 (0.3)	25.3 (16.4)	26.1 (13.7)
P5	23.2 (2.1)	26.8 (2.6)*	35.5 (4.2)	42.4 (4.2)*	47.7 (2.8)	53.5 (2.8)*	1.8 (0.3)	2.0 (0.5)	2.3 (0.3)	2.1 (0.3)	25.3 (7.3)	12.6 (4.3)*
P6	37.0 (2.3)	32.0 (6.0)*	50.3 (2.8)	44.9 (7.1)*	47.2 (3.5)	51.8 (5.2)*	2.9 (0.5)	2.6 (1.2)	1.7 (0.4)	1.4 (0.3)	18.3 (6.1)	14.3 (4.4)
P7	36.5 (2.5)	30.5 (3.0)*	50.4 (7.6)	44.0 (5.1)*	29.3 (2.1)	27.8 (2.2)	0.9 (0.3)	1.0 (0.4)	2.9 (0.5)	2.7 (0.5)	44.5 (15.7)	30.6 (12.8)*

Notes: P, participant; $W_{LS,}$ women's landing strategy; $M_{LS,}$ men's landing strategy;$\theta H_{IC,}$ Hip angle at initial contact; $\theta H_{FZPEAK,}$ Hip angle at peak vertical ground reaction force; $\Delta\theta H_{ROM,}$ Hip range of motion; $\omega H_{IC,}$ Hip angular velocity at initial contact; $J\tau H_{EXT,}$ Peak hip extensor moment; $JPH_{PEAK,}$ Peak hip joint power. Significant differences in technique are denoted by * ($p \leq .05$).

Discussion

Landing is a fundamental skill in artistic gymnastics and practised continually throughout all levels. The rules that govern the permitted techniques are stipulated by the FIG code of points. However, these are not consistent between men and women and as such, result in different landing strategies being employed. Therefore, the aim of this study was to quantify the differences in the lower limb biomechanical demands on female gymnasts, landing in different landing positions, namely, the two strategies dictated by the FIG (Fédération Internationale de Gymnastique, 2020a, 2020b) with the purpose of informing a possible policy change to reduce the potential of injury during landings. It was hypothesised that the utilisation of the W_{LS} during a drop landing task would exhibit loads and kinematics that were associated with increased injury potential compared with the M_{LS}. At the group level, no significant differences were reported in the kinetics between W_{LS} and M_{LS}, although individually, three participants did demonstrate significant differences in their loading responses dependent on the strategy performed.

The lack of generalisability due to small sample sizes has often been reported as a common limitation in biomechanics research (Knudson, 2017). However, in order to reflect complex human behaviour, a single-subject (SS) design was used. This approach has successfully been employed by James and Bates (1997) and helps to prevent the masking of potentially injurious response patterns or providing false support for the null hypothesis (Bouffard, 1993). Drop landings are a key training activity for gymnasts of all levels and, as such, represent a task that gymnasts undertake with high repetition throughout their training cycle. This current study has focused on this landing style to investigate load responses in the absence of more complex landing manoeuvrers such as those following somersaulting or twisting skills. The current study selected the drop landing due to the fact it is a fundamental skill within the sport of gymnastics and it removes the confounding addition of angular motion, hence maintaining high levels of ecological validity.

The majority (70%) of the gymnasts showed a general trend in the reduction of F_{ZPEAK} with an increased landing duration when performing the M_{LS}. Longer landing phase duration (T_{FZPEAK}) and reduced F_{PEAKZ} have been shown to lower the mechanical strain across joints, decreasing the risk of ACL injury in females (Nordin, Dufek, James, & Bates, 2017).

In general, an inverse relationship between F_{PEAKZ} and T_{FZPEAK} was identified in all individuals across the two landing conditions, similar to the findings of previous research (Seegmiller & McCaw, 2003). The within gymnast response to these landing conditions was highlighted by the loading rate results, which showed 70% of individuals exhibiting larger loadings rates for the W_{LS} whilst 30% demonstrated significantly increased loading rates when performing the M_{LS}. These findings suggest the M_{LS} to be a preferable strategy in decreasing the likelihood of soft and hard tissue injuries of the lower extremity during landing (Slater, Campbell, Smith, & Straker, 2015). Interestingly, P2 and P3 demonstrated the opposite kinetic responses when performing the M_{LS}, and as such this strategy maybe potentially harmful for them. The lack of group significance between landing strategies can be explained through the gymnast's utilisation of distinct, individual neuromuscular strategies when responding to differing informational constraints and supports the theory of individual movement responses to even a well-practised task (Irwin & Kerwin, 2009; James & Bates, 1997). Hence, we highlighted the need to ensure coaches consider individual variations when instructing.

A significant increase in knee sagittal ROM when performing the M_{LS} was reported at the group level, although from an individual perspective there was one participant (P2) who displayed a reduced ROM at the knee when utilising the M_{LS}. The difference in the knee kinematics may infer a control strategy whereby the knee facilitates a delay in T_{FZPEAK} during landing to decelerate the centre of mass over a larger ROM (Newell, Liu, & Mayer-Kress, 2001). This is a key strategy for reducing the load on landing and may decrease the likelihood of soft tissue injury to the passive structures of the body during impact.

This study supports the existence of independent response patterns amongst individuals when performing landing (Nordin et al., 2017). Participants appear to sit along a strategy continuum, utilising uniquely favoured responses to cope with the changing informational demands (Irwin & Kerwin, 2009). For example, P1 and P3 almost sit at the extreme, opposite ends of this continuum with P1 favouring the M_{LS} and P3 favouring the W_{LS} to attenuate load and complete the task demands safely. Whilst the other participants sit more toward the M_{LS} as the preferred landings strategy. Degeneracy occurs due to self-organisation theory (Newell, 1985), where individuals employ a seemingly infinite combination of functional degrees of freedom to achieve the same movement objectives (Newell, 1985). The differential individual responses across many of the reported variables cancel each other when averaged, producing an aggregate group response misrepresenting individual behaviour (Bates, 1996). These individual findings recognise the appropriateness of a single-subject design alongside examining group differences.

The finding of this study would suggest changes in the rules that allow a more flexed landing position for both men and women to reduce injury potential in artistic gymnastics is recommend as previously recognised by Slater et al. (2015). This points to a suggestion that a less constrained landing strategy may be more beneficial to the safety of the performer, i.e. allowing greater lower limb motion. Based on the group analyses, the men's strategy of landing would appear to be close to this proposal, however, the analysis of individual strategies emphasises the importance of considering how gymnasts self-organise during this task Irwin & Kevin (2009), and as such this needs to be considered before recommending generalised changes. An example of individual responses was observed between P1 and P3 who demonstrated similar kinematic landing strategies, however, contrasting knee joint moments and powers. These differences might be explained by passive moments about the joints (Silder, Whittington, Heiderscheit, & Thelen, 2007) a finding that was observed in other gymnastics tasks (Kerwin & Irwin, 2010). The importance of self-selected versus task-defined landing strategies was described by Gittoes et al. (2013). These findings highlight the need for a multi-disciplinary approach to the landing rules in the sport of gymnastics.

In summary, this study examined the lower limb biomechanical demands placed on female gymnasts during drop landings employed with two different strategies (W_{LS} vs M_{LS}). With the current rules of landing constraining the performer differently in each condition, it highlights a need to examine if one is predisposing gymnasts to an increased potential of injury. Different inter-individual response patterns reported in this study create difficulties in proposing generalised changes for all. However, a larger ROM at the knees and hips during the M_{LS} facilitates a safer landing configuration. The main finding is one that supports the use of a less constrained landing strategy as displayed in the M_{LS}. Individual responses to the W_{LS} and M_{LS} showed a high level of inter-individual variation, and even with the informational constraints imposed by the FIG (Fédération Internationale de Gymnastique, 2020a, 2020b), the performers demonstrated varied self-organisation to achieve the performance outcome of the tasks. This research has implications for the FIG in terms of examining landing restrictions in addition to providing useful insights about the self-organisation and degeneracy during landings.

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