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Analysis of landing performance and ankle injury in elite British artistic gymnastics using a modified drop land task: A longitudinal observational study

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ABSTRACT

Objectives: To determine whether differences in landing force and asymmetry of landing force exist between gymnasts at the time of data collection versus those that subsequently experienced an ankle injury 12-months later.

Study design: Prospective longitudinal observational design with baseline measures and 12 month follow up.

Setting: British Gymnastics National Training Centre.

Participants: Thirty-two asymptomatic elite level gymnasts from three artistic gymnastic squads ($n = 15$ senior female, $n = 10$ junior female and $n = 7$ senior male).

Main outcome measures: A modified drop land task was used to quantify measures of landing performance. Peak Vertical Ground Reaction Force (PVGRF) was used to measure landing force. The level of inter-limb asymmetry of landing force was calculated using the Limb Symmetry index (LSI). Other measures included injury incidence and percentage coefficient of variation (% CV).

Results: There was no statistical difference for landing force ($p = 0.481$) and asymmetry of landing force ($p = 0.698$) when comparing injured and non-injured gymnasts. Most participants (69%) demonstrated inter-limb asymmetry of landing forces.

Conclusions: Our findings observed inter-limb asymmetry of landing force in injured gymnasts, although uninjured gymnasts also exhibited asymmetry of landing force. Both magnitude of landing force and inter-limb asymmetries of landing force failed to identify the risk of ankle injury.

1. Introduction

Gymnastics is a popular sport involving the performance of dynamic exercises combined with technical precision and balance (Desai et al., 2019). Artistic gymnastics, the most common competitive discipline, involves gymnasts performing short routines on different apparatus requiring flexibility and strength (Mkaouer et al., 2018). At an elite level, gymnasts are exposed to intense loading, training 21–37 h per week (Edoaurd et al., 2018). The combination of technical skill, physical competency and high training loads means competitive gymnasts have a high risk of injury (Caine et al., 2013; Daly et al., 2001). Injuries to the ankle complex account for 17.9% of all gymnastic injuries and are commonly reported as the most frequently injured area (Kerr et al., 2015). Findings from the British Gymnastics Injury Audit completed in 2017, reported ankle injuries as the leading cause of both time loss and restriction in training and competition amongst artistic squads (27%). Injuries not only restrict gymnasts' active participation, but they are costly to the sport and can adversely impact a gymnast's psychological well-being (Ekstrand, 2016).

It is reported that roughly 70% of injury in gymnasts happen

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during landing tasks (Xiao et al., 2017) with ankle injuries most commonly occurring (Marshall et al., 2007; Westermann et al., 2015).) Landing requires gymnasts to absorb extremely high impact forces which are thought to put gymnasts at increased risk of injury (Bradshaw and Hume 2012). PVGRF as high as 7.1–15.8 times bodyweight are thought to put significant stress on the ankle joint and surrounding soft tissues during impact exposing gymnasts to injury (Slater et al., 2015; Wade et al., 2012). Elite gymnasts are required to perform in excess of 200 landing impacts per week (Gittoes & Irwin, 2012) causing repeated exposure to large impact forces (Kirialanis et al., 2003; Ortega et al., 2010). Injuries are thought to be caused by the interaction between high impact force and the inadequate means of attenuating joint loads during landings (Sands, 2000). The link between biological failure of healthy tissue and high impact forces has yet to be examined in gymnastics. A number of studies demonstrated that gymnasts experience higher impact forces compared to recreational athletes when landing from different drop heights but none have reported on injury rates (Christofridou et al., 2017; Seegmiller and McCaw, 2017). Quantifying the range at which impact forces may increase ankle injury risk is therefore not known due to the lack of studies investigating impact forces and injury rates.

Inter-limb asymmetry of landing force has been associated with ankle injury in gymnastics (Moresi et al., 2013). Inter-limb asymmetry of landing force is described as the difference between kinetic variable PVGRF of the right and left limbs during landing task (Zifchock et al., 2006). Gymnasts that display inter-limb asymmetries of greater than 10% are considered to have increased risk of injury (Campbell et al., 2019; Lilley et al., 2007; Moresi, Bradshaw, et al., 2013). The uneven distribution of impact forces between limbs is thought to cause altered mechanical stress on different body tissues, exposing one side over the other leading to ankle injury (Čuk & Marinsek, 2013). Only a small number of studies involving gymnasts have demonstrated inter-limb asymmetry of landing force during drop land tasks, reporting increased injury risk (Campbell et al., 2019; Moresi et al., 2013; Pajek et al., 2016). Studies focusing on dynamic gymnastic specific tasks including handstand and somersault tasks have demonstrated inter-limb asymmetry of landing force (Exell, Robinson and Irwin, 2016; Campbell et al., 2019). Sample sizes were small using mixed populations, and it is therefore unclear if findings are relevant to elite gymnasts. None of these studies considered prospective injury data collection and examined differences between injured and non-injured gymnasts. In the absence of high quality research and appropriate study designs (Campbell et al., 2019), it remains unclear whether higher landing force and asymmetry of landing force predispose ankle injury in elite gymnasts.

This study will evaluate landing performance and compare outcomes in uninjured gymnasts versus those gymnasts that go on to experience an ankle injury. Studies investigating landing performance amongst gymnasts have used drop landing tasks from a box to investigate landing biomechanics and examine ground contacts (Collings et al., 2019; Seegmillar & McCaw, 2003). Both Exell, Robinson and Irwin (2016) and Campbell et al. (2019) examined landing performance by using actual gymnastic specific skills including saltos during completion of the drop landing tasks. In other cohorts including ACL injured populations, drop land assessment has been used to examine impact forces and injury risk (Hewett et al., 2005; Paterno et al., 2010). This study will use drop land from a box as an assessment technique to recreate the rapid impact forces imparted bilaterally on lower limbs during landing tasks (Fransz et al., 2013; McNitt-Gray, 1993). The task will be modified to include a mid-air 180-degree rotational turn as the gymnast complete drop land task to reflect airborne rotation around transverse axis which is relevant to how a gymnast will land in competition or training (Xiao et al., 2017).

Specific objectives are:

1. To determine inter-limb asymmetry of landing force in gymnasts during a modified drop land test using Limb Symmetry index (LSI).
2. To examine if differences exist between asymmetry of landing force in non-injured and injured gymnasts.
3. To determine if differences exist between PVGRF in non-injured and injured gymnasts.
4. To explore the consistency of individual landing performance.

2. Methods

2.1. Study design

A prospective longitudinal observational design was used. Testing took place during three squad profiling days April to June 2019. Landing performance was measured using the modified drop land test. Participants were monitored for one year to assess the number of ankle injuries sustained.

2.2. Participants and setting

Participants were recruited from the British Gymnastics programme. Inclusion criteria was being a member of one of the three British Artistic Gymnastic squads (male senior, female senior and female junior). Exclusion criteria included any gymnast who were unwell or had a lower limb injury limiting their ability to land at the time of testing. The testing location was Lilleshall National Sports Centre and data collection took place within the high performance gym. Participant characteristics for the cohort and specific squads are reported in Table 1.

2.3. Ethics

Informed written consent was obtained from all participants and parents/guardians (for participants under 16) prior to the commencement of testing. Written consent was gained from British Gymnastics and the English Institute of Sport (EIS) prior to data collection. Ethical approval was granted (12/04/2019) by the University of Birmingham School of Sport, Exercise & Rehabilitation Sciences Ethics Committee (ref: MCR290319-1).

2.4. Procedure

Participants were assessed by the lead author and assisted with the help of a PhD student (TP). Participant characteristics of age, height, and body mass index were recorded at baseline (Table 1). Participants were asked to report their preferred turn direction prior to starting testing as most gymnasts have a rotational preference (Heinen et al., 2012). A simple warm up was completed before testing commenced. The warm up consisted of light jogging forwards and backwards, side shuffles to raise heart rate lasting 5 min. A short 2 min rest interval was given before performance testing.

2.4.1. Modified drop land test

A Forcedecks FD4000 dual force-plate (Vald Performance, Brisbane, Queensland, Australia) including two fully synchronised walkway embedded force-plates (one force-plate for each limb) sampling at 1000 Hz was used to collect bilateral PVGRFs of the drop land tasks (Fig. 1). Ground reaction force data was passed through a third-order Butterworth low pass digital filter with a

Table 1
Anthropometrics (mean±SD) for participants (n = 32).

Group	N/%	Age (Y)	Mass (KG)	Height	Preferred turn direction (%)
Full Cohort	32 (100)	17.43 ± 3.70	53.16 ± 10.65	159.02 ± 8.31	Left: 47 Right: 53
Men's Senior	7 (22)	20.71 ± 2.43	66.73 ± 4.60	169.21 ± 3.34	Left: 57 Right: 43
Women's Senior	10 (31)	19.03 ± 3.02	56.01 ± 6/74	158.40 ± 7.31	Left: 60 Right: 40
Women's Junior	15 (47)	14.13 ± .74	44.85 ± 6.52	154.67 ± 6.44	Left: 33 Right: 67

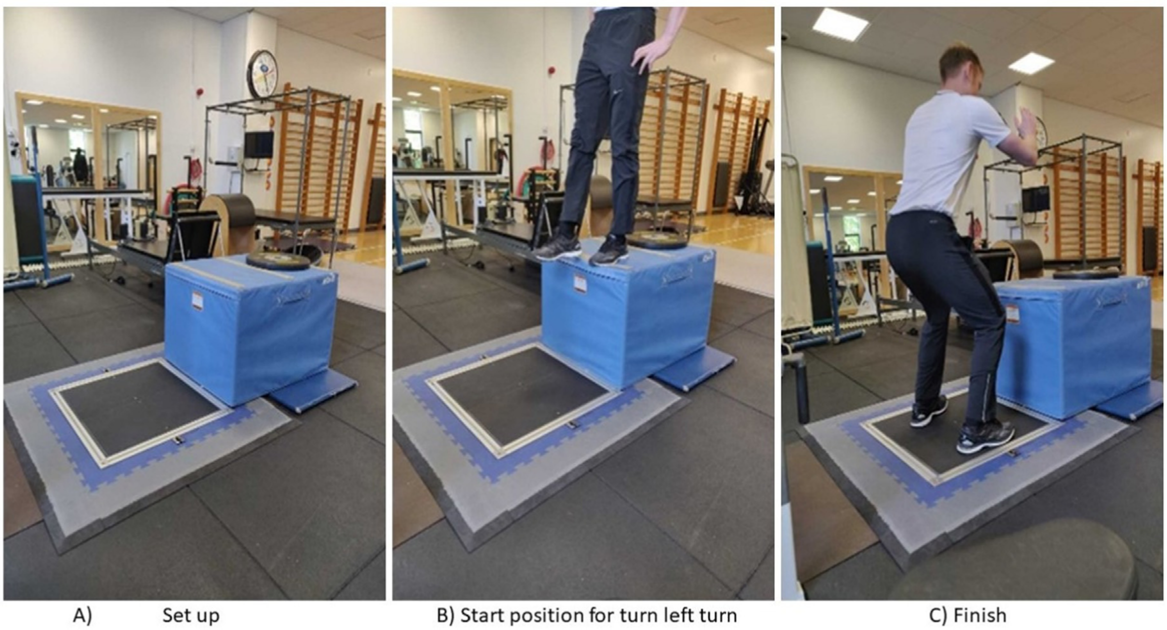

Fig. 1. Modified drop land test.

20 Hz cut-off frequency (Winter 2009). Tests were recorded in real time with a live force-time curve allowing for automatic detection of peak vertical landing force. The outputs were transmitted to a laptop as raw force-time data, which was then used to analyse the raw data. The threshold for determining impact was the maximum vertical force captured. Participants began by standing on a 60 cm platform facing the direction of the force plate. Instructions were given to stand on their preferred leg for turning. Participants were instructed to bend the opposite knee so that it was slightly flexed in a non-weight bearing position before completing landing protocol. Participants were then instructed to "*drop off the step completing a 180° turn in the air and landing with both feet on the force plate*". On landing, participants were required to remain stationary for 5 s and ensure accuracy in foot landing position on the respective plates. Participants performed three drop lands turning to their preferred direction only. The landing protocol developed was a combination of the drop land protocol used by Lilley et al., 2007 and Seegmillar & McCaw, 2003.

2.4.2. Data measurement

Landing data was graphed on the laptop monitor for each trial. Force data was scaled to force in N/kg to account for differences in body mass among subjects. The PVGRF which is the maximum vertical force for an individual limb during early landing (Huurnink et al., 2019) was collected for each limb (Objective 1). This was assumed to be the maximum vertical force at heel contact. The PVGRF for the left and right limb for the three trials were averaged to represent participants' **mean PVGRF** over the three drop land trials.

The Limb Symmetry Index (LSI) (%) was used to categorise participants into two groups; symmetrical and asymmetrical landings (Objective 2). It is the percentage of one limb PVGRF divided by the other PVGRF (Grindem et al., 2011). This was calculated by taking the average PVGRF of the three recorded trials on each limb; dividing the left limb average by the right limb average, and multiplying by 100 (percentage). Asymmetry was defined using a cut-off of 90% or less LSI in landing forces between limbs (Gokeler et al., 2017; Read et al., 2016).

Ankle injury incidence (n) during the 12-month follow up period was recorded using the definition of **injury impact** as used by EIS (number of days training and/or competition impacted by ankle injury, taking into account training restriction percentage). Injuries were reported separately in **severity categories** 1–7 days, 8–28 days, >28 days. All injuries were assessed and electronically recorded by members of the British Gymnastics medical team. Diagnostic imaging was used where required and in line with normal practice but was not a prerequisite for diagnosis and grading. Injuries were reported in line with the International Olympic Committee consensus statement (Bahr et al., 2020). (See appendix 1 for further definitions of data variables).

2.5. Statistical analysis

Descriptive statistics (group and individual means and standard deviations) from the three drop land trials were used to represent the PVGRF and LSI. Statistical analysis was performed using IBM SPSS Statistics for Windows Version 26 (SPSS, Inc., Chicago, IL, USA) with statistical significance set to 0.05 (Alpha).

2.5.1. Objective 1 (Determining inter limb asymmetry)

LSI was calculated for each participant to quantify differences in mean PVGRF between their left and right limb. A paired *t*-test was used to determine if the left mean PVGRFs were statistically different from the right mean PVGRFs for the drop land task irrespective of injury.

2.5.2. Objective 2 (Examining the differences between asymmetry in injured and non-injured gymnasts)

LSI was used to determine how many of the injured group were asymmetrical. An independent *t*-test was used to compare LSI between injured and non-injured gymnasts. Injured participants who demonstrated asymmetry and non-injured gymnasts who displayed asymmetry were best matched using age, height and gender to compare participants with similar characteristics.

2.5.3. Objective 3 (Examining the difference between PVGRF's injured and non-injured gymnasts)

An independent samples *t*-test was used to compare PVGRF in injured and non-injured gymnasts. Injured and non injured gymnasts were best matched using age, height, gender and limb with highest PVGRF to compare participants with similar characteristics.

2.5.4. Objective 4 (Determining reliability and the consistency of individual performance)

Coefficient of variation (%CV) was used to explore whether gymnasts were consistent in their landing performance across repetitions. The %CV of PVGRF was calculated as the ratio of standard deviation divided by the mean multiplied by 100 to yield a unit-less percentage.

3. Results

3.1. Objective 1: inter-limb symmetry

The LSI indicated that ten (31%) of the thirty-two participants had symmetrical results (defined as a deficit of 10% or less). Of the remaining twenty two (69%) participants that demonstrated asymmetrical results, eight demonstrated >10% asymmetry and fourteen >20% asymmetry. The mean (SD) % asymmetry was 12%. There was no statistical difference in mean PVGRF at baseline between left (4327.63 ± 774.81 N/Kg) and right (4538.09 ± 919.55 N/Kg) limbs ($p = 0.164$, 95% CI -545.57, 96.88) (Effect size 0.1).

3.2. Objective 2: LSI and injury

Eleven participants ($n = 11$) went on to experience an ankle injury during the 12-month follow-up period. From the outset, there were also eleven gymnasts who had a history of previous ankle injury but none of these gymnasts experienced a new or recurrence of an ankle injury during the 12 month surveillance period. Therefore these with a history of ankle injury with no new or recurrence were assigned to the non injured group. Female participants experienced nearly all of the ankle injuries ($n = 10$) The greatest number of ankle injuries occurred during floor routines ($n = 8$) with all injuries occurring during training over competition. Ligamentous injuries were the most common injury type ($n = 4$) (Table 2).

Evaluation of the LSI indicated that eight of the eleven participants who went on to experience an ankle injury demonstrated asymmetry in landing forces between limbs using a cut off of 90% or less LSI at baseline (72.7%). Four participants had an LSI illustrating >10% asymmetry and four >20% asymmetry. Of the remaining twenty one participants who did not go on to experience an ankle injury, interestingly fourteen (66.7%) of those demonstrated asymmetry. Please refer to Table 3. When comparing asymmetry of landing force between eight participants who experienced an injury against eight non-injured gymnasts best matched, there was no significant difference for LSI ($p = 0.698$) (Effect size 0.1).

3.3. Objective 3: PVGRF and injury

When comparing the eleven participants who experienced an injury and those that did not, there was no significant difference in their PVGRF at baseline ($p = 0$ 0.481) (Effect size 0.54).

3.4. Objective 4: consistency of landing performance

The %CV as a group demonstrated high variability between individual landing performances. This is shown by the high standard deviation of the mean scores and range for the group left (SD ± 6.99, %CV 12, range 27-0 %CV) and right (SD ± 8.35, %CV 13, range 33-1 %CV) landing forces.

4. Discussion

This study investigated landing performance in a cohort of thirty two elite artistic gymnastics. It focused on whether there was a difference in PVGRF and asymmetry of landing force in those that

Table 2
Injury epidemiology data.

	Injury (n)	Injury (%)
Location: Ankle	11	100
Gender: Female	10	91
Mode of onset (acute or chronic): acute	8	72.7
Tissue type:		
Ligament sprain		
Grade 1	2	18
Grade 2	1	9
Grade 3	1	9
Joint impingement		
Anterior	3	27
Joint Contusion	1	9
Fracture		
Medial malleolus	1	9
Peroneal tendonitis	2	18
Injury mechanism:		
Floor landing	8	73
Beam	1	9
Bars	1	9
Vault	1	9
Setting- Training: Competition	11: 0	100:0
Injury impact (no. of days):	311	n/a
Mean impact +/- SD:	28.27 +/- 23.77	n/a
Injury severity categories:		
1-7 days (Mild)	3	27%
7-28 days (Moderate)	4	36%
> 28 days (Severe)	4	36%

Table 3
Comparison of LSI between participants who went on to experience an injury and those that did not (absolute percentage of total).

Participants	n = 32	%
Symmetrical	10/32	31%
Asymmetrical	22/32	69%
Injured	11/32	34%
Non Injured	21/32	66%
Injured participants who demonstrated asymmetry	8/11	73%
Non injured participants who demonstrated asymmetry	14/21	67%

experienced an ankle injury during 12 month follow up period. The study found that twenty two participants demonstrated inter-limb asymmetry of landing force during modified drop land assessment. Eleven gymnasts experienced an ankle injury during the 12 month follow up period and of these, eight displayed inter-limb asymmetry of landing force. When comparing kinetic variables at the time of testing in those that went on to experience an ankle injury versus those that experienced no injury, no measurable difference between groups existed.

The findings would appear to oppose existing literature which points to a potential association between higher impact forces and ankle injury risk. A number of descriptive studies have put forward the hypothesis that increased impact load through one limb as contributing to increased rates of ankle injury (Kerr et al., 2015; Marinsek, 2010; Marshall et al., 2007). Previous research investigating higher landing force (Seegmillar & McCaw, 2003) and greater asymmetry of landing force (Campbell et al., 2019) reported both variables contribute to the increased rates of injury in gymnasts. Both studies measured landing performance during gymnastics specific tasks, observing high limb loads and asymmetry of landing force, indicating potential association between these factors and risk for injury. Similar to our study, the drop land assessment from 60 cm height was used to investigate differences in landing forces in both studies. Differences existed in terms of participants examined which included intercollegiate gymnasts (Seegmillar & McCaw, 2003) and competitive level gymnasts (Campbell et al., 2019) making comparison with elite level gymnasts difficult. Furthermore, it is difficult to infer injury risk as although both studies measure landing performance, neither evaluated differences in injured and non injured groups.

To the best of our knowledge, there has been no prospective injury studies which examine landing force or inter-limb asymmetry of landing force and identified whether differences exist between these factors and risk of gymnastic injury. The literature would appear to not have examined gymnasts who display increased loads and greater asymmetry at baseline measurement and determine whether this predisposes subsequent ankle injury. Despite the support for both higher impact forces and asymmetry of landing force as possible contributing factors to injury, it is difficult to determine if injuries are a consequence due to the lack of prospective research. Elsewhere, studies that have analysed impact forces and inter-limb asymmetry of landing force in athletic populations outside of gymnastics, have demonstrated significant associations with injury risk (Bates et al., 2013). Those that sustained ACL injury exhibited 20% increased PVGRF forces at baseline compared to uninjured participants (Hewett et al., 2005). Inter-limb asymmetries during landing have been shown to be associated with the occurrence of a second anterior cruciate ligament injury (Paterno et al., 2010). Unlike our study, the authors investigated differences in sagittal plane knee moment at initial contact reporting significant difference present in participants who sustained a second ACL injury. Both studies investigated landing and take off phases using drop vertical jump task analysis with both concentric and eccentric phase of the exercise likely to alter joint kinetics and muscle activation (Ambegaonkar et al., 2011). These differences may possibly explain the variation in results when comparing with our study.

4.1. Landing force

The findings in our study suggest there is no difference in landing forces between those who experienced a subsequent ankle injury and those who did not amongst a cohort of elite level gymnasts. This would suggest high impact forces may not be associated with injury which has previously been reported in epidemiology studies (Caine & Harringe, 2013; Sands, 2000). A study by Panzer et al., 1988, reported PVGRFs from landings were as high as 8–14 times bodyweight for each foot implying an increased risk of injury. Similarly in our study, we found increased loads in anterior posterior plane with gymnasts displaying PVGRFs as high as 10 times bodyweight. Task selection differed in both studies with double back backward somersault (Panzer et al., 1988) versus drop land assessment technique used to measure landing performance in our study, yet observations demonstrated gymnasts were exposed to high loads. However Panzer et al., 1988 did not examine the relationship between increased loads and actual resulting injury. Our study was unable to determine the possible link between higher landing force and whether it puts gymnasts at increased risk of ankle injury. However, the effect size for objective 3 (comparing landing force between injured and non injured) was 0.54 which is medium, which would indicate the difference between the groups is still in reality quite negligible limiting our practical application.

4.2. Asymmetry of landing force

Findings revealed that eleven participants experienced an ankle injury during the 12-month follow up period, with eight demonstrating LSI asymmetry. Interestingly, fourteen of the non-injured group also demonstrated asymmetry between limbs. This overlap in scores challenges the assumption that asymmetrical landings are a risk factor for ankle injury in gymnasts. Additionally, when comparing the injured and non-injured gymnasts no statistically significant differences for landing LSI were found. It is important to note that the effect size for objective 2 (comparing LSI between injured and non-injured) was 0.1 which is very small which would indicate the probability of finding difference between task is also very small limiting the practical significance of our finding.

Asymmetry would appear to exist when examining lower limb mechanics during landing related tasks in gymnastics. Lilley et al., 2007, found that 87% of junior national level competitive gymnasts exhibited inter-limb asymmetry whilst performing drop landing. Similarly Pajek et al., 2016 provide additional evidence with 80–90% of gymnasts who performed bilateral landings reported to demonstrate inter-limb asymmetry. Although slightly lower, one study reported levels of inter-limb asymmetry at 40–45% when gymnasts performed landing and jumping tasks (Moresi et al., 2013). In comparison with our study, this is perhaps the most similar with participants consisting of junior international level competitive gymnasts and similarly they performed landing tasks from 60 cm height. Our study found that 69% of participants displayed lower limb asymmetry. Unlike our study, none of the above studies investigated inter-limb asymmetry and the potential association between increased magnitude of load in one limb and injury.

Few studies have examined inter-limb asymmetry when gymnasts are performing gymnastic specific skills that involve landing. Exwell, Robinson and Irwin, 2016 reported upper limb asymmetry amongst gymnasts completing front handspring task. Most recently, Campbell et al., 2019 reported competitive level gymnasts displayed asymmetrical limb loading whilst performing seven gymnastic skills on floor. Similar to our study, they analysed ground contact for each skill and used a similar symmetry index equation (Zifchock et al., 2006) to determine the level of asymmetry. The gymnastics skills included front and back salto involving gymnasts flipping the legs over head, requiring the gymnast to stick on landing. The drop heights used for assessment were different than our study with gymnasts drop landing from 90 cm to 125 cm drop box. The relationship between inter-limb asymmetry and predictor of injury was not investigated in either of the above studies. It would have been useful to understand whether the asymmetrical limb loading displayed by gymnasts performing these specific gymnastic skills lead to higher risk of injury. Our study, in contrast to previous studies, where injury data was not collected did appear to suggest that the existence of inter-limb asymmetry does not relate to an increased level of ankle injury.

Our findings provide conflicting evidence when exploring the magnitude of inter-limb asymmetry. Five injured gymnasts demonstrated >20% asymmetry yet nine of the non-injured group also displayed >20% asymmetry. Typically, inter-limb differences >15% have been associated with increased injury incidence in athletes and non-athletes (Bishop et al., 2018). Our findings do not support the proposition that this magnitude of asymmetry is associated with increased ankle injury. Ebben et al., 2011 observed higher PVGRF and increased asymmetry during landing task and more recently due to this combination a lower magnitude of asymmetry of 0–5% has been put forward when considering safe return to sport. Perhaps, application of this magnitude of asymmetry may have provided different results, but this threshold was not examined in our study. However findings from Bishop et al. (2019) argue that the magnitude of asymmetry is highly variable and task-specific.

There would appear to be variability in task selection amongst studies examining asymmetry of landing force with some using drop land assessment and others using gymnastic specific skills. Although not investigating landing exercises, Cone & Lee, 2021 compared the asymmetry measured during the take off and landing phases of different jumping exercises, reporting that inter-limb asymmetry was higher during a phase of force absorption compared to force production. Application of these findings to gymnastic literature which has included a mixture of inter-limb asymmetries during both the eccentric (i.e. landing) and concentric (i.e. take-off) phases makes comparison amongst studies difficult. Furthermore, there has been variation in box height from which participants complete drop land task. Comparing the asymmetry measured and determining the optimal asymmetry magnitude for reducing the risk of injury therefore becomes difficult. Further analysis in the magnitude of asymmetry using consistent task selection could be helpful to identify consistent patterns.

4.3. Landing performance

It is imperative when analysing drop land performance that clinicians examine whether inter-limb differences are consistent or there are natural fluctuations in performance variability due to normal movement variability. We found considerable variability of within subject landing performance. It is often assumed that >10% indicates a high %CV and a lack of consistent of performance. The increased %CV values for left and right landing forces (12 & 13%CV) suggests there was not a consistent landing pattern, evidencing inconsistency in individual performance. This might provide a partial explanation as to why no differences were found between the injured and non-injured gymnasts. Further monitoring of the drop land test should consider whether a significant change in performance has occurred or whether the changes lie within the normal variability to achieve landing performance.

We used a drop landing task from a 60 cm box to investigate landing performance in our study. It is a commonly used test to investigate the biomechanics of landing and how an athlete manages landing impact forces (Collings et al., 2019). In our study, we varied this test to include a 180° rotational turn in the air with the rationale of producing different biomechanics possibly more closely related to movements performed by gymnasts. However there still remains a question mark as to whether the task itself provides data which can be generalised to the movements that actually occur during gymnastic training or competition situations. Another rationale for choosing this minor variation in landing task included little research to date has considered the injury biomechanics of landing performing skills that involve gymnastic skills. Exwell, Robinson and Irwin, 2016 reported participants demonstrated asymmetry in the lead leg whilst performing a hand stand. Campbell et al., 2019 reported lower limb asymmetry existed whilst participants completed a front salto (forward 360° flip). There is some concern that the completion of drop landing task including step off technique produces asymmetry. Collings et al., 2019 when exploring the justifications for selecting drop landing task reported one of the limitations of this assessment included that it creates kinetic asymmetries between limbs. This would certainly appear to be evident in the studies in gymnastics which have used drop land assessment as highlighted throughout our study. Therefore the choice of drop land task would appear to have a significant impact on the results of this study as well as those of previous studies. Future analysis should attempt to build on the observed asymmetrical loading patterns which appear present in drop land assessment and complete prospective studies linking with injury to identify optimal threshold of asymmetry.

4.3.1. Clinical implications

Our findings can help to give direction to clinicians and researchers where best to focus future ankle injury reduction strategies in gymnastics. Our study found female gymnasts experienced 90% of the injuries. Consistent with the literature, injury rates are thought to differ between male and female gymnasts, depending on the events and the various apparatus. Research has found female gymnasts are more likely to experience lower extremity injuries while their male counterparts have higher levels of upper extremity injury (Westermann et al., 2015). Due to the upper body dominant skills of the male events, they are much more likely to experience shoulder, wrist and hand injuries. Women are more likely to have ankle and foot injuries given they perform a greater amount of landing and dismount tasks versus their male counterparts (Sands, 2000). Future research may be best served targeting inclusion of female gymnasts when trying to understand injuries associated with specific landing skills. Profiling female gymnasts at an individual level may help to inform ankle injury prevention and risk mitigation strategies. We recommend repeat investigations following-up for longer period to add to our dataset and provide objective data that is consistent and reliable which allows for informed decision making regarding injury risk stratification. Selecting a consistent task (drop land with 180° turn) in preference to any other type of landing would produce similar biomechanics data and allow for meaningful comparison/test findings against previous selected protocol. It may be helpful to consider including additional variables relating to injury biomechanics of landing to better understand landing biomechanics and assess any link with increased rates of injury.

The findings consider whether examining landing performance at baseline can help our understanding as to why ankle injury occurs. By comparing performance outcomes at baseline against those that subsequently experience an injury may help to identify differences which may be associated with injury. The authors acknowledge that the identification of injury risk factors as a whole is complex and multifactorial (Bahr, 2016) but repeated observations can be useful to identify whether certain factors are consistently present in subsequent injured gymnasts. Despite mechanisms of injury being usually multi-factorial (Bradshaw and Hume, 2012), it is estimated that approximately 70% of the injuries in competitive gymnastics occur as a result of landing and dismount tasks during floor exercise (Marshall et al., 2007). It makes sense that medical staff involved in injury prevention strategies for gymnastics, would however attempt to understand landing biomechanics and quantify impact forces including trying to analyse the link between mechanical load and injury risk. Limited information exists to date in gymnastics on how best to design landing tasks including task justification and optimal use of biomechanics analysis. Future investigations are needed to generate more data that are meaningful and find ways to better quantify magnitude of impact force and asymmetry during landings which can be effective in terms of identifying gymnasts and limbs at a higher risk of injury.

Our study is one of the first to consider potential associations with injury and although no direct relationship was found with impact forces and asymmetry of landing force, findings serve as a catalyst for further investigation. Further examination of landing performance in gymnastics is warranted to understand if findings are attributable to decreased performance consistency or lie within normal limits. Ongoing and continuous biomechanics testing can be compared against our findings to provide further insight into landing performance and this also has the potential to establish trends which may possibly be related to injury. If repeated observations demonstrate an absence of significant differences between the uninjured and subsequent injured gymnasts, this can be useful to direct clinicians to focus their attention on other areas. If differences were to become apparent at an individual level, this allows clinicians to consider whether landing force or asymmetry of landing force may possibly relate to ankle injury. Regular testing can look to provide insight into injury biomechanics of landing at an individual level and guide clinicians to be able to target the observed differences by way of considered interventions. By identifying measurements, which highlight gymnastics who may be at higher risk of injury this can help to target an individual's landing technique with the opportunity to enhance efficiency or also provide technical advantage.

4.3.2. Strengths and limitations

The size and nature of the cohort is a strength of the study, where data was collected from thirty two elite level artistic gymnasts. The study attempted to identify potential risk factors of ankle injury by using a prospective design, something which has been lacking in the research. However our study has some limitations. Landing from a 60 cm box is unlikely to replicate the falling heights at varying transient speeds with which gymnast's experience nor the continuum of free flowing routines. Our study analysed foot contacts using one kinetic variable only, examining PVGRF. Other kinetic parameters including time to PVRGF, horizontal ground reaction forces, and rate of loading have all been used in previous studies to provide information on impact forces and asymmetry of landing force. In addition, our study did not investigate gymnasts ability to maintain balance or stability using metrics including time to stabilisation, Dynamic Postural Stability Index (DPSI) and directional components (medial-lateral and anterior posterior) after a landing (Wikstrom et al., 2005). This may have been particularly useful given four out of eleven (36%) of the injuries were ankle ligamentous sprains with these outcome measures being important for assessing dynamic postural stability (Fransz et al., 2018). Future analysis, which collects additional kinetic variable data, may be helpful to assess injury biomechanics of landing.

5. Conclusion

Both magnitude of landing force and inter-limb asymmetry of landing force did not appear to differ between those who went on to experience an ankle injury and those who do not in this population. Inter-limb asymmetry of landing force existed in a large number of gymnasts during performance of the modified drop land test. The findings indicate that both variables failed to identify the risk of ankle injury. It would appear that these two variables are lacking in sensitivity and specificity in order to detect the risk. When determining whether to use magnitude or inter-limb asymmetry to examine ankle injury risk there appears not enough evidence to support them at this point. Future research should consider consistent task selection and include other outcome measures to evaluate landing performance and injury risk.

Ethical approval

This study was approved by The University of Birmingham School of Sport, Exercise and Rehabilitation Sciences Ethics Committee MCR290319-1 (12/4/2019).

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Declaration of competing interest

Lee Herrington is journal editor. No other authors have conflicts of interest to declare.

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Abbreviations

BAG	British Artistic Gymnastics squad
BG	British Gymnastics
DFROM	Ankle dorsiflexion range of motion
EIS	English Institute of Sport
HHD	Hand held dynamometer
LSI	Limb symmetry index
PVGRF	Peak vertical ground reaction force
SD	Standard deviation
TP	Tejal Patel −English Institute of Sport (PHD Student)
WBLT	Weight bearing lunge test

Data sources and methods of measurement

PVGRF	GRF are considered very important and fundamental parameter in gymnastics when evaluating landing performance (Niu et al., 2014). The raw PVGRF for each limb of the drop landings was collected using a dual force plate and were normalised and expressed as a proportion of the subject's bodyweight (N). The mean PVGRF's for the left and right limbs for the gymnasts preferred turn direction (three drop lands) were calculated. All data were filtered through a fourth-order Butterworth filter at a sampling rate of 1000 Hz.
LSI	The LSI is valued when objectively trying to quantify inter-limb asymmetries for the purposes of injury risk and occurrence (McGrath et al., 2015). The LSI was calculated based on the average PVGRF of the left limb scores, divided by the average PVGRF of the right limb scores, multiplied x 100 to obtain a percentage difference between limbs. The limb symmetry index was also used to assess differences between left and right side DF ROM and ankle strength measurements.
Ankle injury reporting	Ankle injury was defined as any incident or period occurring during gymnastic related activities that occurs at the ankle and restricts the gymnast from participation in normal training or competition. Injuries were categorised according to (1) affected side (2) injury type; and (3) length of time absent (days). Injury duration of more than three weeks was classified as severe.

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