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Upper and lower limb impact loading during artistic gymnastics foundation floor tumbling skills

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Abstract

The floor apparatus is associated with the highest rate of injury for male and female gymnasts in training and competition. This study aims to determine the magnitude of the upper and lower body impact loading when performing foundation floor tumbling skills and sequences. Fourteen sub-elite artistic gymnasts (male, $n = 9$; female, $n = 5$) performed eight tumbling skills and sequences while wearing four inertial measurement units (IMU; upper back, lower back, forearm, and tibia). The peak resultant acceleration (PRA) during all ground contacts was calculated. The forearm and upper back PRA were analyzed for hand contacts, while the lower back and tibia PRA were analyzed for foot contacts. Descriptive statistics (median and inter-quartile range), Wilcoxon signed-rank tests and Friedman's ANOVA were calculated between IMU positions and gymnastics skills. Distal IMUs (forearm and tibia) recorded significantly higher loading than proximal IMUs (upper and lower back) for all ground contacts. Proximal IMUs experienced dampening due to shock attenuation properties of the human body, as these positions are located further away from the impact site. Additionally, some foundation skills exposed gymnasts to higher loading when the skill was performed separately, while other skills exposed gymnasts to higher loading when the skill was performed in a tumbling sequence. Training foundation skills separately and as a part of a tumbling sequence exposes the upper and lower body structures to high levels of impact loading. These results can be used by coaches to help in the design of safe training programs.

KEYWORDS

acceleration, biomechanics, training

Highlights

- Distal segments (forearm and tibia) experienced significantly higher magnitudes of impact loading than the proximal areas (upper and lower back) during foundation gymnastics skills, most likely due to the shock attenuation properties of the human body when absorbing ground impacts.

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- During the round-off skill, gymnasts experienced greater lower back impact loading upon landing when performing the skill separately, but experienced greater upper back loading during the hand contact phase when performing the skill as part of a sequence (i.e., round-off to backwards handspring, and round-off, backwards handspring to backwards somersault).
- Impact loading differed between skills performed separately and skills that were performed within a tumbling sequence. Therefore, the loading experienced on the body was different due to the context in which the skill was performed (i.e., having to connect another skill afterward).
- Skill sequences should be considered as distinct or individual skills, rather than a combination of foundation skills, to better address the observed differences when prescribing and monitoring training loads.

1 | INTRODUCTION

Over 90% of registered gymnasts in Australia are under 12 years of age and are training at a recreational or sub-elite (non-elite) level (Gymnastics Australia, 2018). Gymnastics participation has many short- and long-term health benefits, including greater bone strength, increased muscle size and muscle function (Burt et al., 2012). However, even at the sub-elite level, gymnasts train for long durations and perform countless skill repetitions to perfect routines for competition (Barker-Ruchti, 2008). This level of training is not only considered a normal amount but also perceived as necessary to prepare gymnasts artistically, physically, technically, and psychologically for the higher competitive levels. These high training loads, combined with the participants' young age, give rise to growing concerns regarding injury risk.

Injury rates for sub-elite level gymnasts range from 0.5 to 4.1 injuries per 1000 h of participation (Caine et al., 2003; Kolt et al., 1999; Lindner & Caine, 1990), and the floor apparatus is associated with the highest rate of injury for both male and female gymnasts in training and competition (Lindner & Caine, 1990; O'Kane et al., 2011; Bak et al., 1994; Campbell, Rhiannon, et al., 2019). Specifically, landings and tumbling skills have been commonly associated with injury on the floor apparatus (O'Kane et al., 2011; Wadley et al., 1993), with landing position and associated forces from tumbling contributing to 13% of all reported floor-based injuries (Wadley et al., 1993). It has been suggested that exposure to both acute and cumulative high landing forces during floor tumbling are major contributors to injury risk in artistic gymnastics (Bradshaw et al., 2012; Daly et al., 2001; Kirialanis et al., 2002; Sands, 2000).

During competitions, routines are generally scored based on the difficulty and execution of the skills performed. However, sub-elite gymnasts are required to perform compulsory skills and routines across all apparatuses. These compulsory routines consist of foundation skills (e.g., round-off, handsprings, and somersaults), which are taught to gymnasts as a starting point before progressing to more advanced skills in higher competitive levels (Elliott et al., 2005). Because many gymnasts are required to perform compulsory foundation skills, a thorough understanding of whole-body loading when performing these skills is essential.

Wearable sensors, such as accelerometers or inertial measurement units (IMU), can be used to measure body segment impact loading when performing gymnastics skills in a training environment (Beatty et al., 2005, 2007; Bradshaw, 2016; Bradshaw et al., 2016; Burt et al., 2007; Campbell et al., 2022). Impact load is typically measured from the peak resultant acceleration with respect to the gravitational constant (9.81 m/s^2 [g]; Campbell et al., 2021, 2022). Peak accelerations (measured at the pelvis) during hand contact have ranged between 4.5 and 7.4 g when performing handstand rebound drills and backwards handsprings (Beatty et al., 2005, 2007). Whereas peak accelerations during foot ground contacts (also measured at the pelvis) ranged between 2.2 and 7.8 g when performing round-offs, backwards and forwards handsprings, backwards and forwards somersaults and various jumping skills (Beatty et al., 2005, 2007). One study measured peak accelerations at the upper back and found that peak impact loads ranged from 9 to 17 g when landing from a backwards somersault off a 90 cm height (Bradshaw et al., 2016).

Limited research has investigated impact loading in a gymnastics training environment (Bradshaw, 2016; Burt et al., 2010; Campbell, Bradshaw, et al., 2019; Campbell et al., 2018, 2022). In particular, there is a paucity of research focusing on upper limb loading, despite the high incidence of upper limb injuries (between 20% and 54% of all reported injuries; Campbell, Bradshaw, et al., 2019). Additionally, very little research has investigated impact loading when performing gymnastics skills sequentially or within a routine context. This is particularly concerning considering that skills are trained in this manner, both leading up to, and when performed in competition. Therefore, gymnastics skills performed sequentially should be investigated in future research to best reflect applied practice (Burt et al., 2010). The primary aim of this study is to determine the magnitude of both upper (forearm and upper back) and lower body impact loading (tibia and lower back) when performing foundation floor tumbling skills. It is hypothesized that distal structures (forearm and tibia) will experience a greater magnitude of loading than proximal structures (upper and lower back) when performing foundation tumbling skills. The secondary aim is to determine if the magnitude of the impact loading changes when skills are performed in a tumbling sequence compared to performing the gymnastics skills separately. Based on common assumptions among gymnastics coaches (Patel

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et al., 2021), it is hypothesized that greater impact loading will be experienced when skills are performed as part of a tumbling sequence.

2 | MATERIALS AND METHODS

2.1 | Participants

An a priori power analysis was conducted using G*Power (3.1.9.7; Faul et al., 2007) to test the difference between two dependent group means using a two-tailed paired *t*-test and Wilcoxon signed-rank test. The alpha level was set to 0.05 and power at 0.8, with an effect size of 1.1 based on previous gymnastics acceleration literature (Campbell et al., 2020). Results revealed that a minimum of 10 participants were needed to reach the statistical power.

Fourteen sub-elite level gymnasts (male, $n = 9$; female, $n = 5$) were recruited from local gymnastics clubs located in Canberra, Australia (age = 14.7 ± 3.1 years, stature = 158.7 ± 13.4 cm, body mass = 50.8 ± 13.8 kg, training age = 9.4 ± 3.8 years and current gymnastics level = National Level 6–National Level 10). Participants were excluded from participating if they were injured or ill at the time of data collection, were allergic to strapping tape, or did not provide informed consent. If the participants were under the age of 18 years, then the informed consent was obtained from the parental guardian and assent from the participant. This project was approved by the University of Canberra and the Australian Institute of Sport Human Ethics Committees.

2.2 | Procedure

Volunteers were asked to complete a screening questionnaire (with assistance from a parent or guardian if under 18 years) to determine if they were eligible to participate in the study. Volunteers were eligible if they regularly practised six of the eight gymnastic skills and sequences investigated. If a participant could not perform a certain skill, they simply missed that skill or sequence during the subsequent study protocol. The screening questionnaire also collected information on age, training age (years spent training gymnastics), gymnastics ability (current gymnastics level) and weekly training hours, which were used for descriptive purposes.

The stature and body mass of the participants were collected using a stadiometer (Seca 220; Seca, Hamburg, Germany) and scales (DS-410; Teraoka Seiko Co., Ltd.), respectively. Participants were instructed to complete a self-selected warm-up like their training practices. The gymnast's leading side was determined by observing them perform a round-off skill (the leg the gymnast used to step into the skill was defined as the leading side). Four IMUs (Blue Thunder, 3-axis, ±16 g, 1000 Hz; IMeasureU, Auckland, New Zealand) were attached in the following anatomical locations; upper back (T2 vertebrae), lower back (mid-point between the left and right posterior superior iliac spine), the leading distal tibia (intersection of the middle and distal thirds of the antero-medial aspect of the tibia) and the leading forearm (intersection of the third and last distal quarters of the dorsal aspect of the forearm; Campbell et al., 2021, 2022). Data from the upper back and the forearm IMUs were analyzed for upper limb impacts, and data from the lower back and tibia IMUs were analyzed for lower limb impacts. IMUs were secured using a combination of double-sided tape (Creative hair products, Melbourne, Australia), Fixomull (BSN Medical, Hamburg, Germany) and sports strapping tape (Elastoplast, Hamburg, Germany).

Participants were encouraged to practice each skill and tumbling sequence to ensure that they felt comfortable with the IMU placement and the testing environment. Eight foundation skills or tumbling sequences that sub-elite gymnasts regularly perform in training and competition were investigated (displayed in Figure 1). These gymnastics skills were selected for investigation because they are common foundation skills, which are compulsory requirements in sub-elite gymnastics routines. These skills are also commonly used as a starting point for gymnasts to progress toward intermediate- and advanced-level tumbling skills and sequences (Elliott et al., 2005). All gymnastics skills and sequences were performed barefoot on a standard sprung gymnastics floor (Gymnova, Marseilles, France). The backwards somersault was performed from two stacked foam boxes with a combined height of 90 cm (A8-221; Acromat, Adelaide, Australia). Participants were asked to perform three 'successful' trials of each skill or sequence, where the skill was performed without falling after landing. No more than five repetitions of each skill were attempted. The rest between each skill or tumbling sequence was guided by the participant. The gymnastics skills were tested in a blocked order, which was randomized between participants.

The IMU data were collected using an iPad (Mini 3, Model A1599; Apple, California, USA) and the IMeasureU Research Application (IMeasureU, Auckland, New Zealand). One video camera (Canon XF205, 50 fps; Canon, Tokyo, Japan) was used to capture footage of the data collection session. To synchronize the IMU signals and the video footage, similar methods to Wundersitz et al. (2015) were used; participants tapped each IMU three times within the video frame at the beginning of the data collection sessions. The offset between the taps from the video and IMUs was then calculated and used to synchronize the IMU and video footage.

2.3 | Data analysis

Video footage was coded using Kinovea software (0.8.15; Kinovea, Bordeaux, France) for the IMU sensor taps at the beginning of the session and each ground contact across all investigated gymnastics skills. Ground contacts were defined as occurring from one frame before visually identifying ground contact, to one frame after ground contact ended. LabChart software (v.7, ADInstruments, Dunedin, New Zealand) was used to code the IMU sensor taps at the beginning of the session for all the raw signals.

A custom Python script (v3.9.12; Python Software Foundation, Delaware, USA) was used to filter the raw IMU signals, calculate the resultant acceleration and export the peak resultant acceleration

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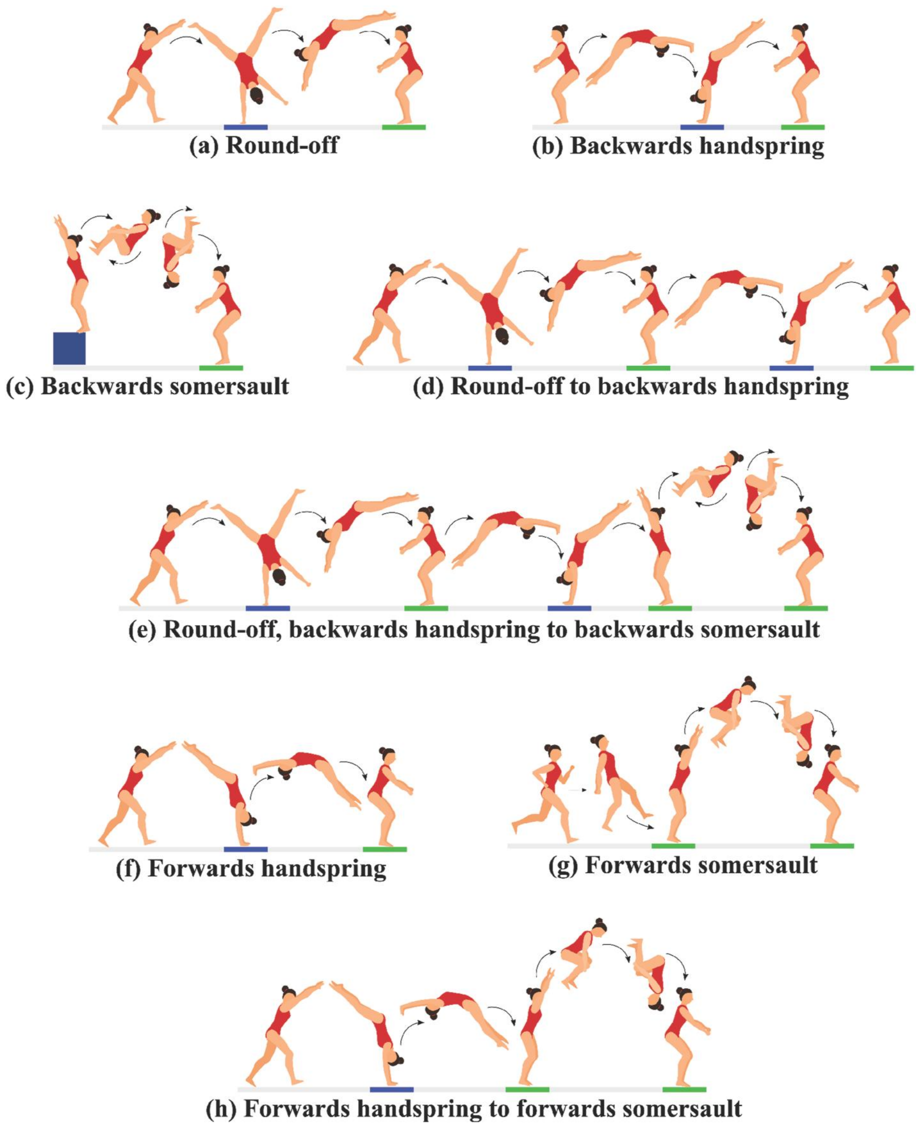

FIGURE 1 Foundation gymnastics skills and tumbling sequences that were investigated. Blue underlining indicates the hand contacts that were analyzed, while green underlining indicates the foot contacts that were analyzed.

(PRA) for all ground contacts. Gravity was not removed from the acceleration signal prior to data analysis. IMU data were filtered using a fourth-order zero-lag Butterworth filter with a cut-off frequency of 85 Hz (Campbell et al., 2020). Resultant acceleration was calculated using the following equation.

$$Resultant = \sqrt{x^2 + y^2 + z^2}$$

where, x is the acceleration in x-direction, y is the acceleration in y-direction, and z is the acceleration in z-direction. PRA results are presented in absolute gravitational units (g).

One participant did not perform the round-off, backwards handspring to backwards somersault tumbling sequence, and four participants did not perform the forwards handspring to forwards somersault combination. Therefore only 13 and 10 participants were analyzed for these tumbling sequences, respectively. The participants were instructed not to perform the skill sequences if they did not regularly practice those skills in training.

All PRA results were sorted into magnitude-based impact categories (Campbell et al., 2021). The impact categories were as follows: (i) very low impact (<4 g), (ii) low impact (4.0–6.9 g), (iii) moderate impact (7.0–9.9 g), (iv) high impact (10.0–12.9 g), (v) very high impact (13.0–15.9 g) and (vi) extreme impact (≥16 g).

2.4 | Statistical analysis

Statistical analysis was performed using SPSS (v.28.0.0.0; IBM Analytics, New York, USA). Data were tested for normality using descriptive tests, such as using plots (e.g., histogram plots, Q-Q plots, and box plots) and the Shapiro–Wilk test (Peat et al., 2005). Data were not normally distributed; therefore, non-parametric tests were performed.

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Descriptive statistics (median and interquartile range [IQR]) were calculated to describe the PRA for each ground impact that occurred for gymnastics skills and tumbling sequences. To determine if distal structures (forearm and tibia) experience a greater magnitude of loading than proximal structures (upper and lower back) during tumbling skills, Wilcoxon signed-rank tests were used to assess the PRA from different anatomical locations within each ground impact. Specifically, for all upper limb impacts the PRA measured at the upper back and leading forearm was compared, while for lower limb impacts, the PRA at the lower back and leading tibia was compared. To determine if loading increases when the skills are performed in a tumbling sequence, Wilcoxon signed-rank tests and Friedman's ANOVA were used to compare between-skill impacts, with the alpha level set at 0.05. Wilcoxon signed-rank tests were used if only two skills or tumbling sequences included the same foundation skill (i.e., [i] forwards handspring and [ii] forwards handspring to forwards somersault). Friedman's ANOVA was used to compare between skills if there were three skills or tumbling sequences that included the same foundation skill (i.e., [i] backwards handspring, [ii] round-off to backwards handspring and [iii] round-off, backwards handspring to backwards somersault). Post-hoc analysis of Friedman's ANOVA was conducted using Wilcoxon signed-rank tests with Bonferroni correction. The alpha level for all post-hoc analyses was set to 0.017. Rosenthal's *r* effect size (ES) values, used for non-parametric tests (Rosenthal, 1991), were calculated using the following equation:

$$r = \frac{z}{\sqrt{n}}$$

Where, *z* is the z-score, and *n* is the size of the study (i.e., the number of total observations; Field, 2009; Rosenthal, 1991). The ES values were interpreted as follows: trivial effect <0.1, small effect >0.1, medium effect >0.3 and large effect >0.5 (Orgilés et al., 2020; Rosenthal, 1991).

3 | RESULTS

Descriptive statistics (median and IQR), impact categories, and within-impact Wilcoxon signed-rank results are displayed in Table 1. For all upper limb impacts, the forearm experienced significantly higher loading than the upper back. Whereas, for all lower limb impacts, the tibia experienced significantly higher loading than the lower back.

Friedman's ANOVA results and Wilcoxon signed-rank results for between-skill analyses are presented in Tables 2 and 3, respectively. Post-hoc analysis revealed upper back loading during hand contact in the round-off skill was higher when performing the skill in tumbling sequences, such as round-off, backwards handspring (*z*-score = −2.417, *p*-value = 0.016 and ES = 0.46 [medium effect]) and round-off, backwards handspring, backwards somersault (*z*-score = −2.691, *p*-value = 0.007 and ES = 0.53 [large effect]), compared to performing the round-off skill separately. In contrast, loading at the lower back during foot contact was significantly higher when performing the round-off skill separately, compared to both the round-off, backwards handspring (*z*-score = −3.296, *p*-value = 0.001 and ES = 0.62 [large effect]) and the round-off, backwards handspring, backwards somersault tumbling sequences (*z*-score = −3.180, *p*-value = 0.001 and ES = 0.62 [large effect]). Lower back loading during foot contact for the backwards handspring was significantly higher during the round-off, backwards handspring tumbling sequence compared to when performing the skill separately (*z*-score = −3.045, *p*-value = 0.002 and ES = 0.58 [large effect]) or in the middle of the round-off, backwards handspring, backwards somersault sequence (*z*-score = −3.110, *p*-value = 0.002 and ES = 0.61 [large effect]).

4 | DISCUSSION

This study primarily aimed to investigate the upper and lower limb impact loading when performing foundation floor tumbling skills and skill sequences. Injuries are commonly associated with the floor apparatus (Caine et al., 2003; Lindner & Caine, 1990; O'Kane et al., 2011; Caine et al., 1989), with the majority arising from the impact forces experienced during landing while tumbling (O'Kane et al., 2011; Wadley et al., 1993). Therefore, increased knowledge of the magnitude of impact loading in gymnastics floor tumbling is needed.

In the current study, the distal IMUs (forearm and tibia) recorded significantly higher magnitudes of loading than the proximal IMUs (upper and lower back) for all gymnastics skills and ground contacts. This is an expected finding, as the proximal IMUs would experience dampening due to the shock attenuation properties of the human body (Coventry et al., 2006; Lafortune et al., 1996; Pratt, 1989). When landing or contacting the ground, impact forces are produced, which causes a shock wave to travel throughout the musculoskeletal system away from the initial impact site (i.e., in a drop landing the shock wave would travel from the feet up to the head). The human body relies on multiple passive and active mechanisms to regulate shock transmission and protect the body from overloading internal structures. The bone, cartilage, synovial fluid, and soft tissues work passively, while joint rotations (kinematics) and eccentric muscle activity actively work to attenuate the impact shock (Coventry et al., 2006; Lafortune et al., 1996; Pratt, 1989). These mechanisms act to decrease skeletal shock at more vulnerable anatomical locations, such as the head and spine, thereby reducing the risk of impact-related injuries to these structures. The development of overuse injuries, such as micro-fractures and bone stress injuries is thought to be related to the body's inability to attenuate the associated shock from repetitive impacts (Coventry et al., 2006). The results from the present study indicate that the gymnasts reduced the impact of shock experienced at proximal structures when performing foundation gymnastics tumbling skills. Therefore, the gymnasts utilized landing strategies that reduced the loading at vulnerable internal structures (i.e., the spine), thereby potentially decreasing their injury risk in these locations.

TABLE 1 Descriptive statistics for PRA (g) and Wilcoxon signed-rank test within impact analysis results during ground impacts for all gymnastics skills/tumbling sequences.

Skill	Impact	IMU position	PRA (g) Median [IQR]	Impact category	Z-score	*p*-value	ES	ES category
Round-off	1st hand contact	Upper back Forearm	4.4 [1.1] 8.8 [5.1]	Low Moderate	−3.296	**<0.001**	0.62	Large
	1st foot contact	Lower back Tibia	17.8 [2.0] 22.9 [0.9]	Extreme Extreme	−3.296	**<0.001**	0.62	Large
Backwards handspring	1st hand contact	Upper back	8.7 [2.0]	Moderate	−3.296	**<0.001**	0.62	Large
		Forearm	18.5 [3.3]	Extreme				
	1st foot contact	Lower back	14.6 [4.2]	Very high	−3.296	**<0.001**	0.62	Large
		Tibia	23.8 [1.1]	Extreme				
Backwards somersault	1st foot contact	Lower back Tibia	20.0 [1.8] 25.1 [1.3]	Extreme Extreme	−3.296	**<0.001**	0.62	Large
Round-off, backwards handspring	1st hand contact	Upper back	4.5 [0.9]	Low	−3.296	**<0.001**	0.62	Large
		Forearm	8.3 [2.9]	Moderate				
	1st foot contact	Lower back	8.2 [0.7]	Moderate	−3.296	**<0.001**	0.62	Large
		Tibia	23.2 [1.6]	Extreme				
	2nd hand contact	Upper back	8.3 [1.9]	Moderate	−3.296	**<0.001**	0.62	Large
		Forearm	16.4 [3.8]	Extreme				
	2nd foot contact	Lower back	18.1 [2.6]	Extreme	−3.296	**<0.001**	0.62	Large
		Tibia	23.7 [2.0]	Extreme				
Round-off, backwards handspring, backwards somersault	1st hand contact	Upper back Forearm	5.2 [1.2] 7.7 [3.4]	Low Moderate	−3.110	**0.002**	0.62	Large
	1st foot contact	Lower back Tibia	8.3 [0.6] 23.0 [1.2]	Moderate Extreme	−3.180	**0.001**	0.62	Large
	2nd hand contact	Upper back Forearm	8.5 [2.6] 18.2 [4.5]	Moderate Extreme	−3.180	**0.001**	0.62	Large
	2nd foot contact	Lower back Tibia	15.4 [1.8] 23.9 [1.3]	Very high Extreme	−3.180	**0.001**	0.62	Large
	3rd foot contact	Lower back Tibia	18.2 [2.6] 24.2 [1.0]	Extreme Extreme	−3.180	**0.001**	0.62	Large
Forwards handspring	1st hand contact	Upper back	5.6 [1.6]	Low	−3.296	**<0.001**	0.62	Large
		Forearm	15.7 [4.8]	Very high				
	1st foot contact	Lower back	16.5 [0.7]	Extreme	−3.296	**<0.001**	0.62	Large
		Tibia	24.0 [1.2]	Extreme				
Forwards somersault	1st foot contact	Lower back Tibia	18.2 [2.2] 23.9 [1.4]	Extreme Extreme	−3.296	**<0.001**	0.62	Large
	2nd foot contact	Lower back Tibia	16.9 [2.4] 26.3 [1.5]	Extreme Extreme	−3.296	**<0.001**	0.62	Large
Forwards handspring, forwards somersault	1st hand contact	Upper back	6.7 [3.0]	Low	−2.805	**0.005**	0.63	Large
		Forearm	16.6 [3.3]	Extreme				
	1st foot contact	Lower back	16.3 [0.7]	Extreme	−2.805	**0.005**	0.63	Large
		Tibia	23.1 [1.8]	Extreme				
	2nd foot contact	Lower back	16.5 [0.9]	Extreme	−2.803	**0.005**	0.63	Large
		Tibia	25.3 [3.0]	Extreme				

Abbreviations: ES, effect size; IMU, inertial measurement unit; IQR, interquartile range; PRA, peak resultant acceleration.

Bold text indicates $p < 0.05$.

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TABLE 2 Friedman's ANOVA between single skills and tumbling sequences impact analysis results.

Impact	Gymnastics skill	IMU position	*p*-value
Hand contact	Round-off	Upper back	**0.006**
		Forearm	0.584
	Backwards handspring	Upper back	0.794
		Forearm	0.146
Foot contact	Round-off	Lower back	**<0.001**
		Tibia	0.375
	Backwards handspring	Lower back	**<0.001**
		Tibia	0.735

Abbreviation: IMU, inertial measurement unit.
Bold text indicates $p < 0.05$.

TABLE 3 Wilcoxon signed-rank tests between single skills and tumbling sequences impact analysis results.

Impact	Gymnastics skill	IMU position	Z-score	*p*-value	ES	ES category
Hand contact	Forwards handspring	Upper back	−1.376	0.169	0.31	Medium
		Forearm	−0.051	0.959	0.15	Small
Foot contact	Backwards somersault	Lower back	−2.760	**0.006**	0.57	Large
		Tibia	−1.712	0.087	0.14	Small
	Forwards handspring	Lower back	−0.255	0.799	0.01	Trivial
		Tibia	−1.070	0.285	0.22	Small
	Forwards somersault	Lower back	−0.059	0.953	0.01	Trivial
		Tibia	−1.886	0.059	0.47	Medium

Abbreviations: ES, effect size; IMU, inertial measurement unit.
Bold text indicates $p < 0.05$.

Impact categories were used to describe the loading magnitude for each skill and sequence, as the categories make it easier for coaches and support staff to quickly compare impact loading between skills (e.g., a skill categorized as low impact involved less loading than a skill categorized as very high impact). While significant differences in the PRA magnitude were observed between distal and proximal IMU positions, many of these impacts were still classified within the same categories (i.e., lower back and tibia loading were both categorized as extreme during a forwards somersault take-off). Over half (62%) of the ground impacts investigated in this study exposed sub-elite gymnasts to extreme levels of loading (Table 1).

The magnitude of loading in this study was much higher than previously reported. Beatty et al. (2007) recorded peak pelvis (or lower back) acceleration when performing similar gymnastics skills using a Microstrain telemetric v-link data logger with two accelerometers (IC sensors 3031-050) mounted inside a Velcro-secured waist belt. They reported peak pelvis loading between 0.8 and 13.8 g when performing round-offs, backwards and forwards handsprings and backwards and forwards somersaults (categorized as very low to very high loading). While in the present study, when performing the same skills, lower back loading ranged between 14.6 and 20.0 g during landing (categorized as very high to extreme loading). Additionally, for most skills and tumbling sequences, the landing phase exposed the tibia and the lower back to extreme levels of loading (85% of all foot contacts were categorized as extreme loading; Table 1). Given that the IMUs only measure up to ±16 g in each axis, and that the high magnitude of loading is also occurring at the lower back (which is dampened by the shock attenuation properties of the human body during impact), it is plausible to conclude that the impact experienced at the tibia during landing could be much higher than the measured results presented in this study. This is speculation only, as higher magnitude IMUs or accelerometers would have to be used for certainty.

The secondary aim of this study was to determine if upper and lower limb impact loading differs when skills are performed separately or in a tumbling sequence. During floor routines, gymnasts are required to perform several running tumbling passes, which sequentially connect multiple skills. To the author's knowledge, this is the first study to directly compare impact loading when performing discrete gymnastics skills and when performing the same skill as a part of a tumbling skill sequence in a training environment. Contrary to the

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hypothesis, the results from this study suggest that different levels of loading are experienced for each skill type, with some gymnastics skills exposing gymnasts to higher levels of loading when performing a certain skill separately, while for other skills, loading is greater when performed as part of a tumbling sequence. Specifically, when performing the round-off (lower back loading during landing; single skill = 17.8 g, in both sequences = 8.2 and 8.3 g) and backwards somersault (lower back loading during landing, single skill = 20.0 g, in a sequence = 18.2 g), gymnasts experienced significantly higher impact loading when performing the skills separately, rather than as part of a tumbling sequence. Conversely, when performing the round-off (upper back loading during hand contact in all tumbling sequences; single skill = 4.4 g, in both sequences = 4.5 and 5.2 g), and backwards handspring (lower back loading during landing in the round-off to backwards handspring; single skill = 14.6 g, in the sequence = 18.1 g) impact loading was significantly higher when performing the skills as part of a tumbling sequence. Most impacts that exposed gymnasts to higher levels of loading occurred at the end of the skill or sequences during landing. The primary aim of a landing is to dissipate and distribute momentum and force (Marinšek, 2010), which could explain why the landing phases of the skills experienced higher levels of loading. This finding also relates to injury research in gymnastics, which states that the landing phase of tumbling skills is commonly associated with injury (Campbell, Rhiannon, et al., 2019; Wadley et al., 1993).

This current study provides new insight as to how gymnasts adjust foundation skills when transitioning from practising discrete skills to when they are connected in a tumbling sequence. Of interest are the differences observed when performing the round-off skill. The round-off is considered one of the most important fundamental gymnastics skills (Farana et al., 2017), as it is performed at all gymnastics levels and used on multiple apparatuses to allow a gymnast to transition from traveling forwards to backwards (Farana et al., 2019). Round-offs are performed on the floor at the beginning of tumbling passes, on the beam when leading into mounts and dismounts, and at the beginning of certain vaults (i.e., Yurchenko vaults). The present study suggests that when a round-off is performed by itself, gymnasts experience greater lower back impact loading upon landing, but when performing the skill as part of a sequence, gymnasts experience greater upper back loading during the hand contact phase. This highlights that although gymnasts are physically performing the same skill, the loading experienced on the body is different due to the context in which the skill is performed (i.e., having to connect another skill afterward). Therefore, when prescribing and monitoring training loads, skill sequences should be considered as distinct skills, rather than a combination of foundation skills to better address the observed differences.

The findings from this study have direct practical implications for training prescription, as the skills investigated in this study are common foundation skills that coaches widely use to teach gymnasts how to safely progress to more difficult movement patterns (Hiley et al., 2019). For example, a gymnast must perfect a standing backwards handspring on the floor before they can begin learning how to perform that skill on a balance beam. Coaches need to understand that the loading experienced when performing some of these foundation skills is exposing gymnasts to higher magnitudes of loading than previously suspected. This is an important finding, as most coaches would believe that performing single repetitions of skills would expose gymnasts to less loading than when performing skill combinations and routines. Therefore, this information can be used to help inform guidelines around training prescription and how to offload certain body structures due to soreness or injury; for example, if a gymnast is experiencing upper back soreness, coaches can prescribe fewer repetitions of skills or movements that expose the upper back area to higher levels of loading (i.e., backwards handspring), and instead encourage slightly more repetitions of skills that expose the upper back area to lower levels of loading (i.e., forwards handsprings), if needed to perfect performance.

It should be noted that this study does have some limitations. The sample population included sub-elite gymnasts from a range of different gymnastics levels (National Level 6–National Level 10) with varying gymnastics experience (mean training age of 9.4 ± 3.8 years). This could have introduced variance, as novice gymnasts are known to be more variable in their technique and coordination patterns compared to elite-level gymnasts (Hiley et al., 2019; Newell et al., 2021; Williams et al., 2015). However, the authors believe that it was important to investigate sub-elite level gymnasts, as little research has been undertaken on this population, despite that this is where most participation occurs. Finally, the IMUs used in this study had an accelerometer capacity of ±16 g. Some IMUs (particularly the forearm- or tibia-mounted IMUs in the vertical axis) reached the 16 g capacity during the testing. This indicates that the PRA experienced at these segments is likely greater than 16 g when performing these skills or tumbling sequences, meaning the exact magnitude of peak acceleration is unknown. Nonetheless, any level of loading greater than 16 g is extremely high for this participation level, which is why these skills were subsequently placed into the extreme impact category. While the authors acknowledge that this is a major limitation, we still believe that the use of IMUs provides meaningful information on the impact load that gymnasts' experience in the training environment, especially since this technology will evolve and eventually overcome this limitation.

Future research is needed to fully understand training loads in artistic gymnastics. A particular focus should be placed on exploring upper and lower body loading on all gymnastics apparatuses, as gymnasts regularly train using multiple apparatuses within a single training session. In addition, kinematic information combined with acceleration data could provide additional insight into the findings and evaluate the relationship between technique and associated peak loading. Finally, future research should use wearable sensors that have a much larger capacity than the IMUs used in the present study to determine the exact magnitude of loading experienced when practising gymnastics skills.

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5 | CONCLUSION

This study provides new insight into impact loading patterns experienced at different anatomical locations when performing foundation gymnastics tumbling skills. IMUs were used at various anatomical locations (forearm, upper back, lower back, and tibia) to measure upper and lower body impact loading when sub-elite artistic gymnasts performed floor tumbling skills and sequences. Distal IMUs (forearm and tibia) recorded significantly higher magnitudes of loading than the proximal IMUs (upper and lower back), most likely due to the shock attenuation properties of the human body when absorbing ground impacts. Some foundation skills exposed gymnasts to greater magnitudes of loading when the skill was performed separately, while other skills exposed gymnasts to higher loading when the same skill was performed as part of a tumbling sequence. These results indicate that when gymnasts are practising foundation skills separately (a common method in gymnastics training), the upper and lower body impact loading is still quite high. These results have important implications for sub-elite gymnasts and their coaches, as this information can assist with identifying higher and lower loading tumbling skills and sequences, which can be used to help inform safe training program design.

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CONFLICT OF INTEREST STATEMENT

The authors report no conflict of interest.

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