A Preliminary Study of Ground Reaction Forces for Summersault Landings: implications for performance and injury risk

Zoe Cross, Prof Mark Watsford, Prof David Eager

University of Technology Sydney

zo3cross@gmail.com, Mark.Watsford@uts.edu.au, David.Eager@uts.edu.au,

ABSTRACT

This study provided an exploratory investigation of the ground reaction forces (GRF) of landing summersaults under repetitive conditions. The peak GRF and rating of perceived exertion (RPE) were assessed in one experienced female gymnast (21 yr, 1.59 m, 62 kg) landing 10 repeated summersaults on three consecutive days. The summersaults were interspersed by 2-minute rest periods which aimed to simulate the repetitions completed in a gymnastics training session to describe the peak and repeated GRF. Peak landing forces of 7107 ± 1214 N were recorded on Day 1. Results from Days 2 (8015 ± 1637 N) and Day 3 (7322 ± 2030 N) demonstrated that fatigue may influence landing performance. Individual trials reached a peak force of 9625 N, which corresponds to >16 times the gymnast's bodyweight. This value is higher than values reported in the literature. A tendency for a relationship between fatigue and variable landing forces was evident and by Day 3 the gymnast recorded RPE measurements of 7/10 and the landing force ranged between 9 to 14 times the gymnast's bodyweight. This research utilizes the GRF data to analyze the jerk force of the gymnast's landing. The jerk forces averaged at 21 k.m/s^3 with a peak of 29 k.m/s^3, indicating the possibility for large jerk forces to be generated upon landing. This research provided objective measures of the forces associated with landing summersaults. Further, the assessment of repetitive landings provided preliminary insights into the effects of fatigue on landing forces. Fatigue may increase the *likelihood of high or variable forces, which might subsequently elevate the injury risk to the lower extremities. Further research with larger sample sizes and other landing conditions are required to further understand fatigue and variability in landings.*

INTRODUCTION

Increased knowledge of aerodynamics and power has progressed artistic gymnastics to its current apex of difficulty. However, this has taken an associated physical toll on athletes with extreme injuries to the lower extremities occurring frequently in this sport. Risk factors are the level of dorsiflexion of the ankle whilst landing summersaults and high landing forces of up to 10 times bodyweight. Prior research has investigated the regularity of injuries to the lower extremities within gymnastics; however, the quantification of landing properties specifically the impact of fatigue on injury risk in the context of summersaults has not been examined. This research aimed to highlight factors and errors that could cause injury when landing backward summersaults in the context of Women's Artistic Gymnastics. This was determined by measuring the GRF when a gymnast landed from a summersault, with repeat trials recorded to simulate the repetitions completed during a gymnastics training session. The derivative of acceleration, also known as jerk, was utilized in this research to examine how much jerk force is involved in landing a summersault and relate this to possibilities of injury in the lower extremities (Eager et al., 2016). This research aimed to provide preliminary insights that can lead to further knowledge of injuries in this sport caused by repetition and fatigue during high impact landings.

EXPERIMENTAL METHOD

The experiment was undertaken with the gymnast completing 10 repeat trials of a round-off into a backward summersault, with a 2-minute rest between each trial. This procedure was undertaken on 3 consecutive days to reflect the repetitive nature of gymnastics training. The skill performed is portrayed in Figure 1. The gymnast landed the summersaults wearing conventional sport shoes on a 12mm thick Roll Down Matting made of polypropylene. The gymnast landed each summersault onto four 600x400 mm Kistler force plates[1] which recorded the GRF in the z axis (vertical axis), y-axis (frontal plane) and

[1] *Kistler Group 2023,* located in Switzerland

x-axis (sagittal plane). The force measurements were analyzed to find the acceleration and jerk force of the gymnast's landings. All trials were filmed using an iPhone and tripod, in order to correlate the landing position of the gymnast with the GRF generated. This footage was also utilized to measure the angle of dorsiflexion of the gymnast's ankle when landing. After each trial, the gymnast recorded their subjective effort using a rating of perceived exertion (RPE) out of 10.

Figure 1: The skill performed by the gymnast – a roundoff to backward summersault.

RESULTS

Considering the GRF in the x, y and z axis for all trials, a slight increase in the GRF over the trials was evident. When looking at the peak GRF in the z direction, 7107 ± 1214 N was recorded on Day 1. The results from Days 2 and 3 were 8015 ± 1637 N and 7322 ± 2030 N, respectively.

Variability in peak GRF in the z-axis and y-axis increased over all trials. The range of peak GRFs on Day 1 was over 2000N, by Day 2 and 3 this range was over 3000N. The range of peak GRFs in the y-axis increased to over 2000N by Day 3, compared to a range of under 1000N on Day 1.

Trial 2 on Day 2 of data collection yielded the highest GRF in the z-axis. As seen in Figure 2, the maximum GFR recorded was 9650 N, equaling approximately 16 times the gymnast's body weight. This was 470 N higher than the next highest GFR of 9170 N and over 2000 N larger than the average maximum GFR over all trials of 7300 N.

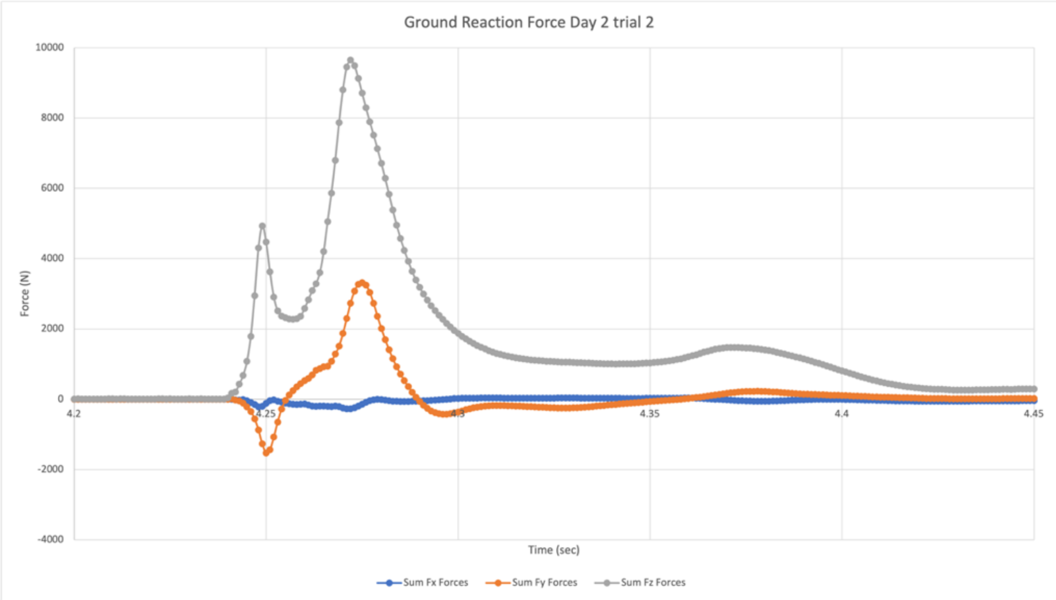

Figure 2: Depiction of ground reaction force data from landing a summersault (example shown is Trial 2 Day 2).

Trial 1 on Day 3 recorded the highest GRF of the y-axis. The data in the y-axis recorded over 3370 N in force, over 1000 N higher than the average peak GRF for all trials in the frontal plane of 2100 N.

From the data collected there was one trial that yielded a significantly lower GRF in the z-axis than any other trial. The GRF in the vertical axis for Trial 5 on Day 3 of data collection was 5290 N, almost 1000 N less than the next smallest recorded trial.

The jerk force was calculated from the GRF data collected, the values varied in the different trials, although the average jerk in the z-axis was over 21 $k.m/s^3$. The largest jerk value recorded in the z-axis was Trial 3 on Day 3 of data collection. The jerk measurement on this day reached a peak of over 29 $k.m/s^3$.

As seen in Table 1, maximum values of 7 (out of 10) on the Borg RPE scale are recorded, equaling very severe exertion (Williams, 2017). Notable reasons for this fatigue included a calf cramp which began on Trial 6 of Day 2 and pain in the gymnast's right ankle, which was noted from the beginning of Day 3.

Day 1	Trial	RPE (out of 10)	Notes	Day 2	Trial	RPE (out of 10)	Notes	Day 3	Trial	RPE (out of 10)	Notes
	1	3			1	3			1	4	Pain in right ankle
	2	3			2	4			2	4	
	3	4			3	4			3	4	
	4	5			4	4			4	5	
	5	5			5	5			5	6	
	6	6			6	5			6	6	
	7	6			7	6	Calf cramp		7	7	
	8	7			8	7			8	7	
	9	7			9	7			9	7	
	10	7			10	7			10	7	

Table 1: RPE measurements recorded during data collection.

This research collected data on the angle of dorsiflexion of the right ankle for all trials. As seen in Figure 3 the maximum angle recorded was over 70 degrees and the lowest recorded angle was just over 47 degrees,

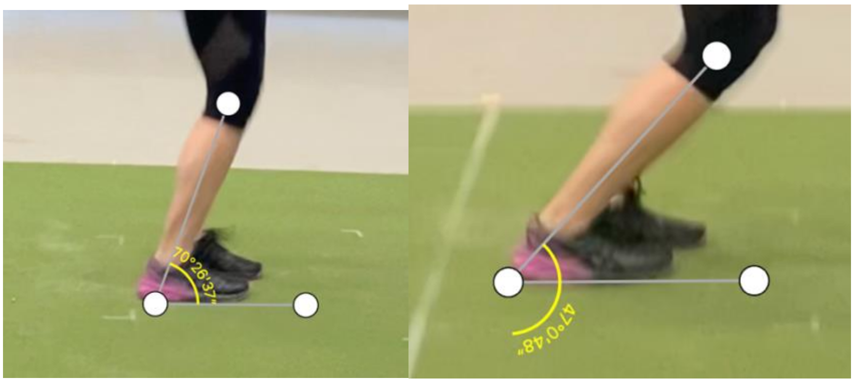

Figure 3: Dorsiflexion angle from the trial with the largest angle recorded (Trial 6 Day 1) compared to the trial with the smallest angle (Trial 5 Day 3).

DISCUSSION

The Relationship Between Fatigue and Force

This research aimed to create fatigue within the gymnast, in order to examine the impact this may have on the GRF. The main observation from the GRFs recorded that could highlight the impact of fatigue, was the variability in the landing forces. Day 3 of data collection recorded large variations of landing forces, from extremely high forces of over 8000 N to relatively low forces of under 6000 N. The range was far greater than Day 1 of data collection and highlights that fatigue may have impacted the consistency of the gymnast's landing. This correlates with prior literature indicating the variability and individuality of GRFs (Seegmiller & McCaw, 2003). There was also a greater variability in force in the y-axis by Day 3 of data collection, greater force in the frontal plane indicates instability in the gymnasts landing. Therefore, this data indicated that fatigue may decrease the stability of a gymnasts landing position, which could contribute to injury risk.

Landing Errors and Extreme Forces in Stand Alone Trials

The GRFs that were measured in this research conveyed that a variety of landing forces can occur during the landing of the same maneuver. Prior literature has stated that a gymnasts' landing force can often be "from 3.9 to 14.4 times the gymnast's body weight" (Marinsek, 2010). This research produced data that was both above and below this range.

The maximum GRF in the z-axis was 9650 N, equalling approximately 16 times the gymnast's body. When taking into the account the amount of force placed through the lower extremities on this landing, one can begin to understand why injuries of the lower extremities are so common in gymnasts (Hart *et al.,* 2018). Although, there was no clear reason as to why this trial had such high force measurements recorded, nor did the gymnasts note feeling greater force during this trial. This trial again highlighted the variability of GRFs when landing summersaults, as well as indicated that there is limited literature on the range of GRF that can occur during these high impact landings (Patel *et al.*, 2021).

Trial 1 on Day 3 recorded the highest GRF value in the y-axis (frontal plane). When examining the force information with the video footage in Figure 4, it is evident that the gymnast limited the dorsiflexion of their ankles upon landing, possibly due to the right ankle pain noted during the gymnast's RPE measurements. As well as this, both of the gymnasts' ankles rolled out slightly when controlling the landing position.

Figure 4: Initial landing position from Trial 1 Day 3.

This instability in the gymnast's ankles could be the cause of the large GRF on the y-axis and conveys a landing error potentially caused by fatigue. The gymnast altering their landing technique due to their ankle pain, created higher force in the y-axis due to the lack of stability in this landing. Ankles rolling away from the gymnast's center of mass indicates instability in the ankles and can cause injuries to the ligaments and tendons of the ankles. When landing at forces over 10 times the gymnast's body weight, any instability in the ankles poses a high chance of injury.

Although high GRF values were recorded, forces as low as 5290 N were also recorded on the final day of data collection. Figure 5 shows the landing position of this trial with the gymnast keeping their center of mass forward and most of their body weight held anteriorly. It is also evident that the gymnast placed almost no weight through their right foot, the ankle they noted was in pain.

Figure 5: Image of summersault landing from Trial 5 Day 3.

This trial highlighted that no relationship exists between fatigue and GRF, and that low GRF does not necessarily relate to a lower injury risk. This trial recorded an extremely low GRF as the gymnast did not dissipate their landing force into the floor using the conventional toe heel landing technique. Instead, the force was absorbed primarily by the gymnasts' lower extremities. Force dissipation via knee and hip flexion, places the lower extremities under extreme impulse force. This landing position has a very high potential of causing injury for the gymnast, even though the GRF recorded was so low.

Jerk Force in the Context of Landing and Injury

Jerk is often utilized in literature in the context of injury prevention in vehicles crashes and elevator safety. Although, this higher derivative is yet to be deeply explored in the context of high impact landings. This research aimed to produce preliminary jerk force data in the specific context of summersault landings. From examining the average jerk forces over all trials, it is evident that significant jerk force is generated upon landing summersaults. This can be attributed to the large change of acceleration from completing an airborne rotation maneuver, to landing on hard flooring.

The largest jerk value recorded was over 29 k.m/s^3. The trial that generated this high jerk value was a "stuck" landing, a term in gymnastics to describe a landing without any steps or movement after landing. This is the ideal type of landing in gymnastics, as minimal deductions can be taken. In order for the gymnast to perform this "stuck" landing, they made multiple small corrections to their landing position in order to maintain stability without moving their feet. As depicted in Figure 6, there was a large lift in the gymnast's heel and then the gymnast straightened their legs to try maintain stability without stepping their feet.

Figure 6: Gymnast trying to hold landing without moving their feet.

This resulted in a jarring landing, as the gymnast passes through many positions of their knees and ankles whilst their feet stay in the same position on the floor. When a gymnast decides to step out of a landing, they dissipate the jerk force by performing a large body movement to control the landing. In the case of this “stuck” landing, very sharp and small movements of the lower extremities occur to control the landing force. After analyzing the trial with the largest jerk which had a “stuck” landing, all other trials that had the same landing type were examined. Of the top 8 jerk values recorded over all trials, 5 of these were derived from a “stuck” landing. When calculating the average jerk value in the z-axis, the average for all trials was under 22 $k.m/s^3$, whilst the average jerk of all the trials with a stuck landing was over 24 $k.m/s^3$. This noticeable increase shows that stuck landings may indeed be related to large jerk forces. This concept highlights the trade-off between landing performance perfection and injury, which the sport of gymnastics has often struggled with (Mills *et al*., 2009).

Visual Indicators of Fatigue and Injury Risk

Another indicator of injury risk in summersault landings is the visual indicators of fatigue and errors in a gymnasts’ technique. The gymnast noted fatigue in their calves and pain in their right ankle. This muscle fatigue potentially influenced the height of the gymnasts' jumps and in turn the quality of their landing. As seen in Figure 7, a comparison is made between the height of an early trial from Day 1 and a trial from Day 3, after the gymnast noted the calf cramp.

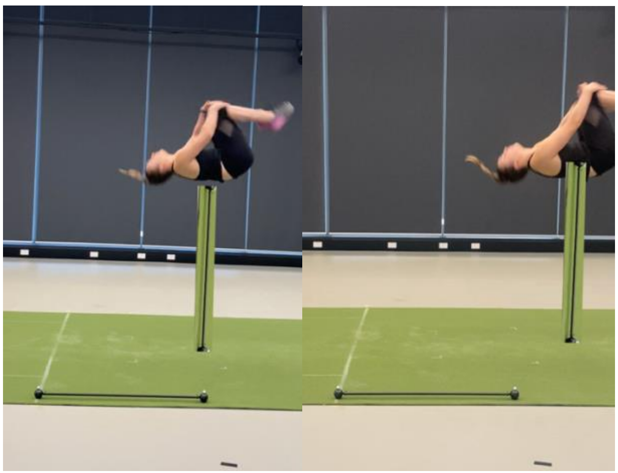

Figure 7: Comparison of height of summersault using 1m measurement (Trial 4 of Day 1 on the left, Trial 7 of Day 3 on the right).

The height of the summersault is substantially lower in the trial on Day 3. The higher the jump into the summersault, the more time the gymnast has in an airborne state. A longer period of time in this airborne state allows the gymnast to complete their rotation and stretch out their body in anticipation of landing. When adequate height is not achieved, a gymnast will often land a summersault with their center of mass leaning forward due to the lack of time to straighten their body after the tucked rotation (Meyers, 2021). An example of this landing can be seen in Figure 8 and notably the dorsiflexion of the gymnast's ankle is larger due to the center of mass angled forward. This extreme dorsiflexion of the ankle can conceivably be linked to the ankle pain noted by the gymnast by Day 3 of data collection.

Figure 8: Image of landing from Trial 5 Day 3 demonstrating the landing of a summersault which lacked height and rotation.

When landing rotational airborne maneuvers, a certain level of dorsiflexion of the ankles is experienced upon landing. Extreme dorsiflexion of the ankle combined with the forces upon landing summersaults, can place extreme strain through the ankle. As with many of the elements involved in landing summersaults, there was a large variability in dorsiflexion angle between trials. The angles varied over 20 degrees, again highlighting the variability of these summersault landings. There was a slight trend between fatigue and a smaller landing angle. Data collection on Day 1 and 2 all had angle measurements of approximately 60 degrees. By Day 3 this average had lowered to 56 degrees. Although this downward trend is not large in magnitude, these preliminary insights from this case study indicate how fatigue may influence this landing angle and in turn injury risk.

LIMITATIONS AND RECOMMENDATIONS

The findings of this exploratory case study contained several limitations, and the results must be considered with these in mind. Firstly, the cohort size for the case study was small. For results with greater validity, a cohort size larger than one gymnast would be required to better represent a range of gymnast's abilities and landing profiles. The surface used for this experiment was also a limitation, as it was not a gymnastics floor matting. The requirement for measuring landing forces meant that a floor surface with minimal cushion was used to minimize the dampening of the signal upon landing. Finally, the methodology used to capture video footage of the trials was limited in this case study. Given the preliminary nature, this research only had the capacity to use an iPhone for filming which resulted in fairly simple, discrete measurements limited to ankle angle. Greater time, money and cohort size would have enabled this research to examine the likelihood of specific injuries due to high landing forces. Further research is encouraged to examine these forces and angles further to enable greater insights into the factors that impact GRF.

CONCLUSION

The results from this exploratory research were descriptive of the complex nature of summersaults and the skill required to execute these airborne maneuvers safely. The array of data collected provided a preliminary insight into the high GRF generated from summersault landings along with the variability of forces. This case study research provided examples of multiple landing errors that can occur individually or together, in outlying trials or over multiple trials in an experienced female gymnast. Although this information could not prove these errors will cause injury, this research has presented a preliminary description of possible factors and errors that can cause a gymnast to put themselves at an elevated risk of higher landing or jerk forces.

REFERENCES

Eager D., Pendrill A-M., Reistad N. (2016) Beyond velocity and acceleration: jerk, snap and higher derivatives. Eur. J. Phy. 37(6) 065008. https://doi:10.1088/0143-0807/37/6/065008

Hart, E., Meehan, W. P., 3rd, Bae, D. S., d'Hemecourt, P., & Stracciolini, A. (2018). The Young Injured Gymnast: A Literature Review and Discussion. *Curr Sports Med Rep*, *17*(11), 366- 375. https://doi.org/10.1249/jsr.0000000000000536

Marinsek, M. (2010). Basic landing characteristics and their application in artistic gymnastics. *Science of Gymnastics Journal*, *2*.

Meyers, D. (2021, August 11). *The case against sticking the landing*. The Case Against Sticking The Landing. https://defector.com/the-case-against-sticking-the-landing

Mills, C., Pain, M. T. G., & Yeadon, M. R. (2009). Reducing ground reaction forces in gymnastics' landings may increase internal loading. *Journal of Biomechanics*, *42*(6), 671-678. https://doi.org/https://doi.org/10.1016/j.jbiomech.2009.01.019

Patel, T. S., McGregor, A., Williams, K., Cumming, S. P., & Williams, S. (2021). The influence of growth and training loads on injury risk in competitive trampoline gymnasts. *Journal of Sports Sciences*, *39*(23), 2632-2641. https://doi.org/10.1080/02640414.2021.1948259

Seegmiller, J. G., & McCaw, S. T. (2003). Ground Reaction Forces Among Gymnasts and Recreational Athletes in Drop Landings. *J Athl Train*, *38*(4), 311-314.

Williams, N. (2017). The Borg Rating of Perceived Exertion (RPE) scale. *Occupational Medicine*, *67*(5), 404-405. https://doi.org/10.1093/occmed/kqx063

BIOGRAPHY

Zoe Cross:

Zoe Cross is a Mechanical engineering and medical science student at the University of Technology, Sydney. Zoe has completed 5 years of study into her engineering and science degree, receiving a merit scholarship and first-class honors throughout her study thus far. Zoe has participated in the sport of gymnasts for over 17 years, as both an athlete and a coach. Her experience in this sport has contributed to her interests in biomechanics and risk management.

Prof Mark Watsford:

Professor Mark Watsford is the Deputy Head of School (Research) in the School of Sport Exercise & Rehabilitation at the University of Technology Sydney. He has over 20 years experience working in academic and professional sporting environments, compiling 85 peer-reviewed research papers and a range of research contracts. Mark has extensive experience with the physiological and biomechanical assessment of athletes, and has several research interests in the area of applied sports science. Mark supervises research students and publishes widely in a range of applied sports science topics from a variety of sports including Australian football, cricket, netball, rugby league and soccer. Mark holds industry accreditations as an Accredited Sports Scientist (Level 2) and Accredited Exercise Scientist, both with Exercise and Sports Science Australia.

Prof David Eager:

David Eager is the Professor of Risk Management and Injury Prevention at UTS. He is also the Professor of Mechanical and Mechatronic Engineering. David is an internationally recognised expert on the safety aspects of trampolines and playgrounds, play surfacing, and sports and recreation equipment. He is a bio-mechanical engineer and Fellow of Engineers Australia, Chartered Professional Engineer and on the National Professional Engineers Register. David has a PhD in Engineering (UNSW), 1st Class Honours Degree in Engineering (NSWIT); and Graduate Certificate in Dispute Resolution (UTS).