

This item was submitted to [Loughborough's Research Repository](#) by the author.
Items in Figshare are protected by copyright, with all rights reserved, unless otherwise indicated.

Loads on a gymnastics safety support system during maximal use

PLEASE CITE THE PUBLISHED VERSION

<http://dx.doi.org/10.1177/17543371JSET84>

PUBLISHER

© Sage

VERSION

AM (Accepted Manuscript)

LICENCE

CC BY-NC-ND 4.0

REPOSITORY RECORD

Hiley, Michael J., A. Apostolidis, and Maurice R. Yeadon. 2019. "Loads on a Gymnastics Safety Support System During Maximal Use". figshare. <https://hdl.handle.net/2134/8749>.

This item was submitted to Loughborough's Institutional Repository (<https://dspace.lboro.ac.uk/>) by the author and is made available under the following Creative Commons Licence conditions.



For the full text of this licence, please go to:
<http://creativecommons.org/licenses/by-nc-nd/2.5/>

Loads on a gymnastics safety support system during maximal use

M.J. Hiley, A. Apostolidis & M.R. Yeadon

School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, UK

Abstract

Support systems can be used to prevent or reduce the impact during landings in various gymnastics disciplines. A support system typically comprises two ropes, three pulleys attached to steelwork in the roof space of the gymnasium and a belt around the gymnast's waist. The aim of the study was to determine the forces at the pulleys and the tension in the ropes during maximal loading for a dynamic gymnastics skill. Additionally the relationship between drop height and peak force, gymnast mass and peak force and the effect of the coach's actions was investigated. A gymnastics support system was instrumented with strain gauge based load cells. A coach attempted to arrest the fall of a gymnast equivalent mass (range 10 – 35 kg) over a range of drop heights (0.25 – 1.5 m). To establish the coach contribution, trials were repeated with the coach replaced by an equivalent mass and with the rope tied off to the floor. Peak forces of 1.3 kN were recorded for a simulated maximum loading gymnastics scenario (drop height 1.25 m, gymnast mass 35 kg). The coach's actions reduced the peak forces by 35% and 48% when compared with an equivalent dead weight and the rope being tied off, respectively.

1. Introduction

Support systems are used in a variety of applications including sports such as Acrobatic Gymnastics, a competitive sport in which a pair or group of gymnasts (3 females or 4 males) perform a variety of dynamic and balance skills. The dynamic skills typically involved the “base” gymnasts pitching (throwing) the “top” gymnast into the air to perform somersaulting and twisting skills. The support system is used during the initial stages of learning aerial skills and may also be used to assist with balance skills. When assisting aerial skills the support system can be used in three ways: (1) to assist the gymnast during take-off to help gain additional time of flight, (2) to prevent or reduce the impact when landing or (3) to prevent injury when the skill “goes wrong”. Once gymnasts are competent at performing the skill, support is no longer required. The arrangement of a support system typically comprises two ropes, one single pulley, one double pulley and a somersaulting belt or twisting belt, which allows both somersaulting and twisting (Figure 1). The pulleys are normally attached to steelwork in the ceiling of the gymnasium. The gymnast is attached to the system via the belt which is connected to the ropes using carabiners with “spinners” which allow the gymnast to somersault around the lateral axis without the ropes becoming twisted. The two ropes pass through the pulley system with the free ends forming a logline from which the coach operates the support system.

In the event of a potential poor landing, the coach will attempt to arrest the movement of the gymnast by exerting load on the logline. It is not always possible for the coach to bring the gymnast completely to rest before contact with the floor. In these cases the coach will attempt to reduce the velocity of the gymnast and provide additional time which may allow the gymnast to achieve a safer landing orientation (e.g. avoid landing head first). During such a situation the coach does not act as a “dead weight” since there will be some extension of the arms and elevation of the shoulders as the rope becomes taut. These actions are likely to reduce the initial load on the system, compared to an equivalent dead weight attached to the logline. Maximum loading of the support system will occur when the gymnast drops through a significant height and the coach attempts to arrest the movement within a short distance (e.g.

1 m). As the drop height increases there will come a point when the coach's actions become ineffective in arresting the gymnast. In these situations a support system should not be used.

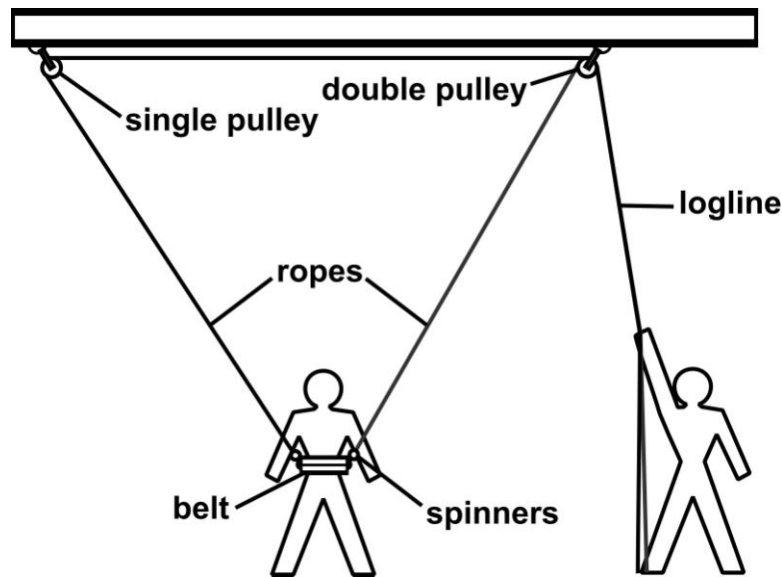


Figure 1. Arrangement of pulleys and ropes used in a gymnastics support system.

The current British Standard (BS 1892-2.8:1986) [1] provides information regarding the recommended layout and safe working load (SWL) of the pulleys and ropes. The rope is required to be made from 8.25 mm diameter 100% nylon braided trapeze cord, which should have a breaking load of 10 kN (BS 5053). The pulleys on the other hand are specified to have a safe working load of 300 kg (approximately 3 kN). It is also recommended that the ropes attached to the belt form an angle of 45° to the floor (BS 1892) with the gymnast stood at ground level.

At present there are no data available on the forces experienced during a normal or maximum loading case. Work has been conducted on climbing ropes and harnesses to determine the forces from experimental and theoretical perspectives [2, 3, 4]. In both cases the rope was tied off rather than being held by a compliant coach. McLaren [3] stated that it is widely accepted that in the case of a fall whilst attached to a safety line that the maximum load that the human body can withstand without serious injury is 12 kN. This refers particularly to climbing where the harness worn by the climber spreads the load through the pelvic region and thighs. In gymnastics the users are predominantly young children who are attached to the ropes via a belt around the waist. It might be expected that peak forces of 12 kN, equivalent to 35 body weights (assuming a mass of 35 kg), may lead to injury. In addition to the gymnast, it is not uncommon for coaches themselves to experience injury whilst using a support system. These injuries are particularly in the form of muscular tears to the biceps during the initial tensioning of the logline. Such injuries are likely to incur costs both in terms of rehabilitation and time lost in the gym. Understanding the forces in gymnastics situations may give insights into the possible causes of injury and how these risks might be reduced. It is also important to gain an understanding of what is humanly possible in terms of the coach attempting to arrest the fall of the gymnast. In a maximum loading case a coach may be under the illusion they will be able to prevent an injury to the gymnast, whereas in reality, given the variables of height dropped by the gymnast, gymnast mass and coach mass, this may not be the case. Informing safe use of support systems should lead to reduced occurrence of injuries.

The aim of the present study is to determine the forces during maximal loading for a dynamic Acrobatic gymnastics skill. Additionally the relationship between drop height and peak force, gymnast mass and peak force and the effect of the coach's actions will be established.

2. Methods

Sections in Methods outline the analysis of a dynamic Acrobatic Gymnastics skill in order to determine the peak drop height, the calibration of the load cells used to instrument a support system and the subsequent testing of the support system to determine the peak forces. The testing involved dropping a “gymnast” mass through a range of heights with a coach arresting the fall using the logline.

Analysis of a Dynamic Acrobatic Gymnastics Skill

An international level elite mixed pair (male base, mass 71 kg, height 1.68 m; female top, mass 37 kg, height = 1.47 m) were videoed (Sony handycam VX1000) performing a layout somersault pitch to catch (Figure 2). This skill was analyzed to provide comparative data for the subsequent drop testing. The particular skill was chosen as it requires a large time of flight so that the base can catch the top and also since it is a skill that would be performed using a support system during the learning stages. If a support system were used, the logline would be taut at the start of the skill (Figure 2a) with the coach holding the logline close to chest level, as this would allow the coach to assist with takeoff and landing, if required. The drop height was defined as the distance from the top's centre of mass (COM) peak height (Figure 2d) to the COM height at the start of the skill (Figure 2a). The trial was manually digitized (AVI-digitising software). All heights were determined from floor level with the waist band of the top's shorts used to estimate of centre of mass location (approximately at umbilicus level). Scaling of the digitized data was based on the known height of the base (1.68 m).

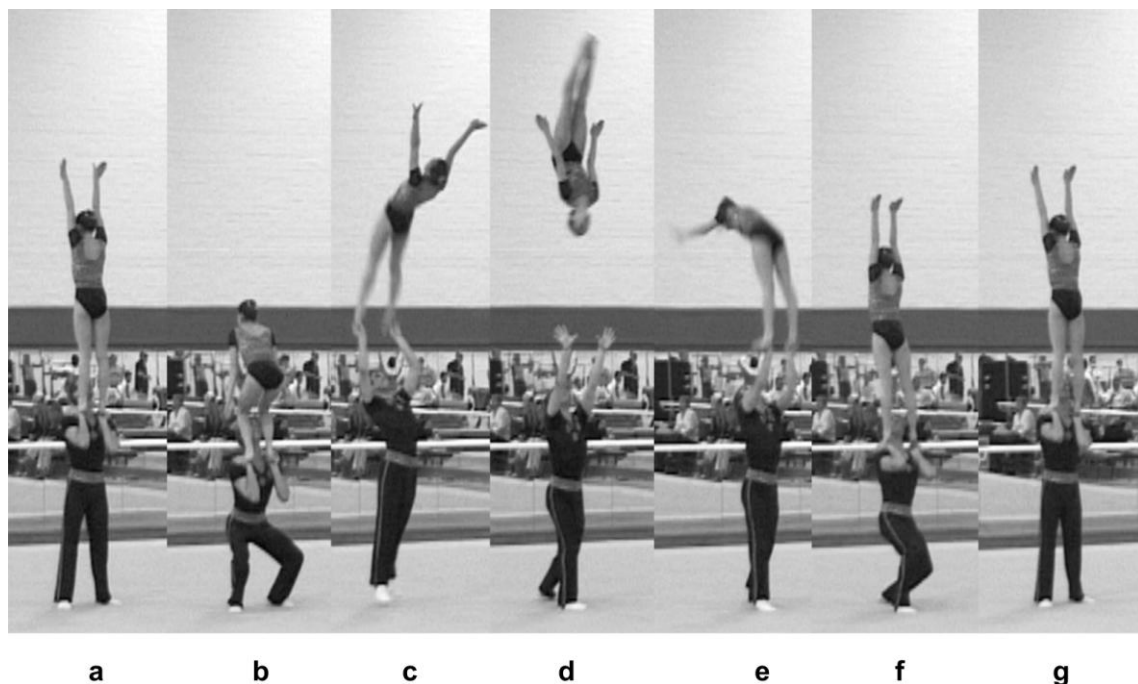


Figure 2. Layout somersault pitch to catch (sequence from left to right).

Calibration of load cells

The load cells were constructed from 7 mm mild steel with the middle section milled down to 3 mm. Two cross paired (90°) strain gauges (FCA-3, Techni Measure Ltd) were bonded to each side of the plate and wired to form a full Wheatstone bridge. The four load cells used were connected to a strain gauge amplifier (Modular 600), which was zeroed while there was no load on the load cells. The amplifier was connected to a computer via a 16-bit analogue to digital converter (Model A1-16-XE-50, National Instruments) and all data were sampled at 1000 Hz using Labview software. For calibration the load cells were hung from a metal bar and known weights were applied with the use of chains and carabiners. The load cells were loaded and unloaded to approximately 3 kN in steps of 0.5 kN with recordings taken from the strain gauge amplifier at each step. The calibration procedure was repeated twice. Linear regressions between the recorded strain gauge voltage (v) and known loads (N) were performed to determine the calibration curves for each load cell. All regressions were forced to pass through the origin.

Instrumentation of a gymnastics support system

In order to determine the forces during maximal use, the load cells were attached in series with each of the pulleys and logline of a gymnastics support system (Continental Sports Ltd) using carabiners (Figure 3). A common feature of the support systems produced by various manufacturers is that the double pulley is replaced by two single pulleys anchored at the same location. The load cells were assigned numbers: (1a) for the single pulley, (2a) for the pulley supporting the rope from pulley (1a), (2b) for the second branch of the double pulley and (3) for the logline (Figure 3). A “gymnast” mass was connected to the support system via a plate and carabiners upon which disc weights could be added to vary the gymnast mass. The height h_1 of the gymnast mass from the floor when the ropes became taut (Figure 3) was 1 m. This corresponded to a cable angle of approximately 45° (Figure 3), measured with a fluid filled goniometer. At this height the coach (male, mass 70 kg, height 1.80 m, who had given informed consent in accordance with the procedures of the university ethics committee) was instructed to hold the logline with the hands level with the sternal notch. In order that this position could be repeated for all trials a marker was placed on the rope. In order to perform repeated drops from a constant height the gymnast mass, connected to the support system, was suspended from an electro-magnet (Figure 3). The drop height h_3 was calculated as the height h_2 of the gymnast mass above the floor minus the height h_1 at which the ropes became taut. The height at which the ropes became taut was constrained to be 1 m due to the height of the steelwork in the laboratory roof space and the need for the 45° angle of the ropes.

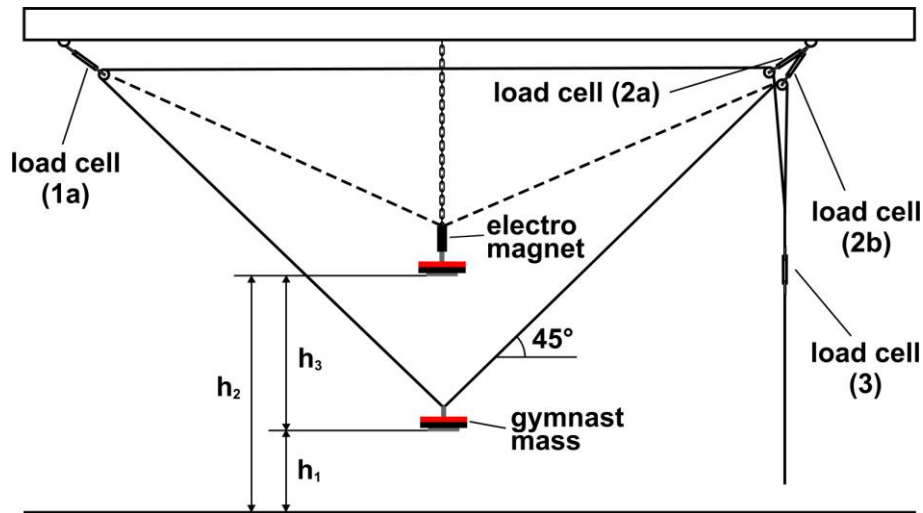


Figure 3. Locations of load cells and gymnast mass during dropping trials.

Determination of peak force relationships

In order to determine the relationship between drop height and peak force a series of drop tests were carried out. For the dropping trials a gymnast mass of 35 kg was chosen as representative of an elite level acrobatic gymnastics top – the mean mass of 7 international level female acrobatic gymnastics tops was recorded as $37 \text{ kg} \pm 3 \text{ kg}$. With an initial drop height of 0.25 m the coach was instructed to stop the fall of the gymnast mass as quickly as possible once the ropes became taut. On each trial the coach was given a countdown to the release of the gymnast mass, which was in plain sight. Data from the load cells were recorded from before the release of the gymnast mass until after it had been brought to rest. All strain data were recorded at 1000 Hz and converted into force using the load cell calibration curves. Once three trials had been completed the drop height was increased by 0.25 m. This was repeated up to a drop height of 1.5 m.

In order to determine the relationship between gymnast mass and peak force the same dropping protocol was used with a drop height of 1.25 m (representative of the drop height from video) for varying gymnast masses from 10 – 35 kg, in steps of 5 kg. The effects of the coach's actions were assessed by replacing the coach with a "dead weight" of 70 kg. A further assessment of the coach's actions was made by tying off the logline to the floor so there was no movement of the ropes after becoming taut. In each case three drops were performed from 1.5 m with a 35 kg gymnast mass in order to compare forces in an extreme situation.

3. Results

The drop height determined from the video recording of the Acrobatic Gymnastics skill was 1.24 m. Due to the simple reconstruction method measurement accuracy was likely to be around 0.05 m. The results of the linear regressions performed on the calibration data from each load cell produced similar coefficients (Table 1). The relationships between load and voltage were found to be linear with R^2 values all greater than 0.9998.

Table 1. Calibration coefficients for the load cells and standard error of the linear fit to the data

| Load Cell | Calibration Coefficient [N/v] | Standard Error of linear fit [N] |
|-----------|----------------------------------|--|
| 1a | 2805.4 | 2.4 |
| 2a | 2787.1 | 1.3 |
| 2b | 2801.1 | 7.3 |
| 3 | 2850.6 | 2.5 |

An example of the force time histories from a typical drop is given in Figure 4 (drop height 1.25 m). The data from the fourth load cell has been divided by two to give the tension in each individual rope. The peak force occurred in load cell (2b), the single pulley in the double pulley arrangement (Figure 4). The pattern of peak force (in terms of pulleys) was the same for all drop tests (Figure 5). The highest force occurred in load cell (2b) followed by load cell (1a) and then (2a). The tension in the ropes, was always less than the load at the pulleys.

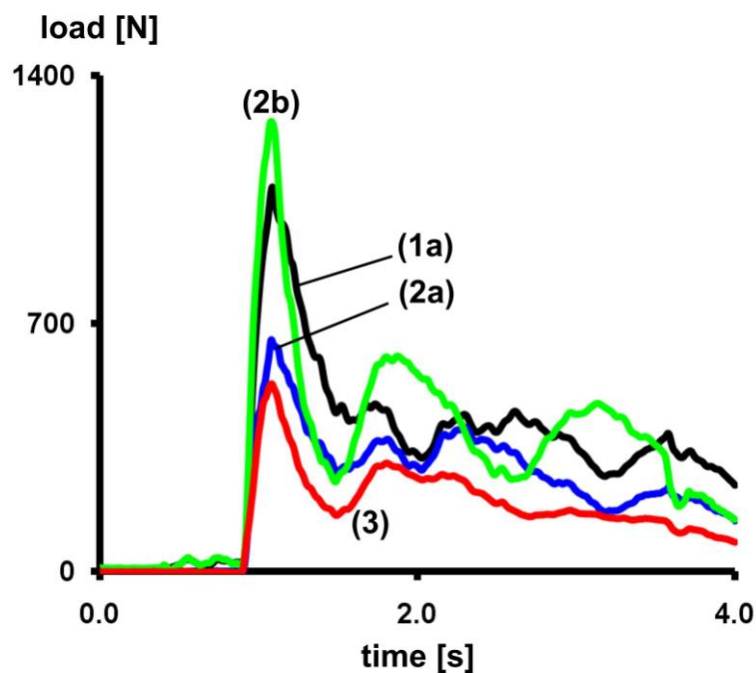


Figure 4. Time histories of the forces at the pulleys, (1a), (2a), (2b), and the tension in the rope (3), during a dropping trial (gymnast mass 35 kg, drop height 1.25 m).

At a drop height of 1.25 m the peak force (average of the three trials) was 1,300 N (Table 2). As might be expected the peak force increased with drop height. The relationship between peak force and drop height was found to be non-linear (Figure 5). The relationship between peak force and gymnast mass was also found to be non-linear and again as gymnast mass increased so did the peak forces (Figure 6).

Table 2. Mean and standard deviations of the peak forces at each pulley and the tension in the rope during drops from increasing height

| Drop Height [m] | Peak Load [N] | | | |
|--------------------|---------------|----------|------------|----------|
| | 1a | 2a | 2b | 3 |
| 0.25 | 825 ± 49 | 496 ± 35 | 879 ± 78 | 376 ± 29 |
| 0.50 | 958 ± 52 | 586 ± 35 | 1084 ± 74 | 454 ± 25 |
| 0.75 | 978 ± 57 | 598 ± 34 | 1144 ± 100 | 471 ± 33 |
| 1.00 | 1054 ± 19 | 661 ± 8 | 1232 ± 18 | 515 ± 5 |
| 1.25 | 1107 ± 24 | 679 ± 17 | 1300 ± 26 | 539 ± 14 |
| 1.50 | 1157 ± 23 | 719 ± 13 | 1422 ± 37 | 575 ± 4 |

NB : numbers refer to the loads cells as described in the methods

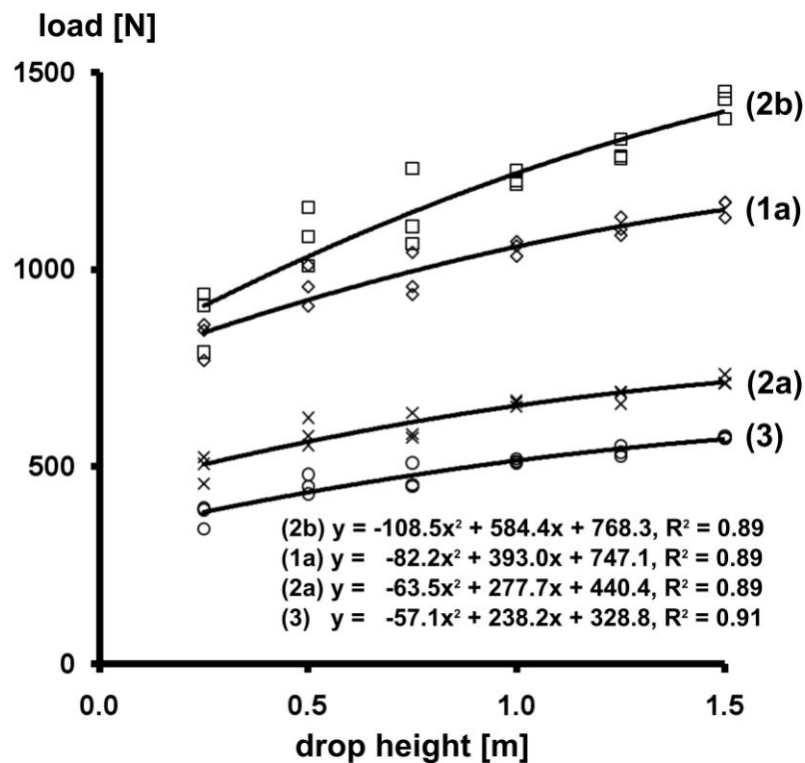


Figure 5. Relationship between peak force and drop height at each of the load cells (gymnast mass 35 kg).

The peak force at load cell (2b) and the peak tension in the ropes when the coach was replaced by an equivalent dead weight and when the rope was tied off (drop height 1.5 m, gymnast mass 35 kg) are presented in Figure 7. Compared with having the rope tied off the coach's actions reduced the peak force at the pulley and tension in the rope by approximately 48%, whereas the dead weight only reduced the peak forces by approximately 18% (Table 3). Similarly, introducing a coach reduced the average rate of force development by approximately 53% compared with the rope being tied off.

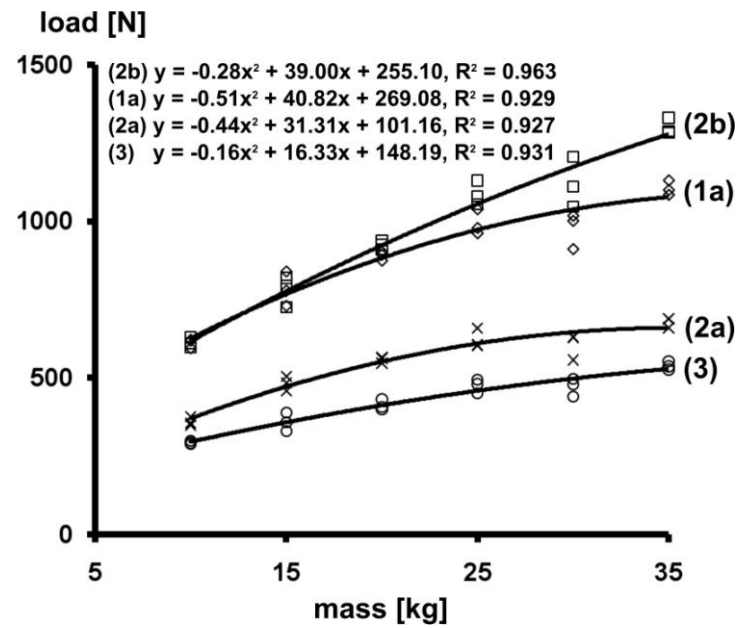


Figure 6. Relationship between peak forces and gymnast mass (drop height 1.25 m).

Table 3. The peak force and average rate of force development at pulley (3) and in the rope under different logline conditions

| Logline | Peak pulley force [N] | Rate of force development [N/s] | Peak rope force [N] | Rate of force development [N/s] |
|----------|--------------------------|---------------------------------------|------------------------|---------------------------------------|
| coach | 1422 ± 37 | 8372 ± 353 | 575 ± 4 | 3159 ± 117 |
| 70 kg | 2190 ± 24 | 15962 ± 504 | 939 ± 2 | 6416 ± 79 |
| tied off | 2712 ± 21 | 17431 ± 566 | 1127 ± 8 | 6818 ± 28 |

Note : 35 kg gymnast mass dropped through 1.5 m

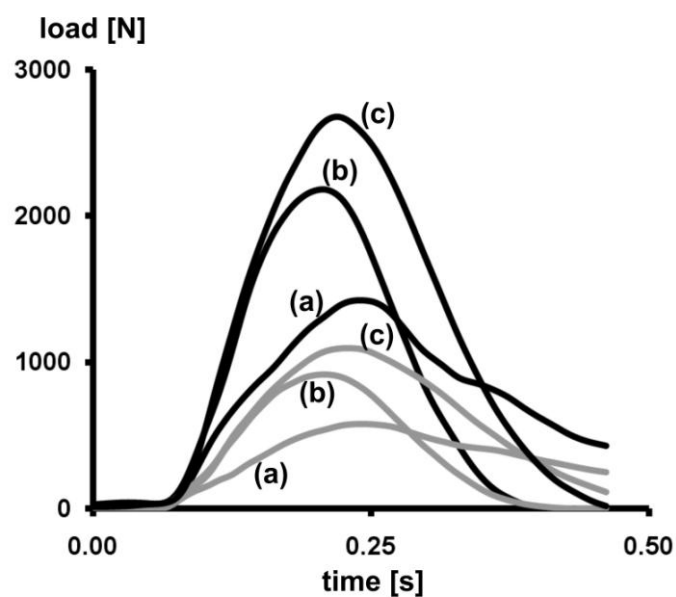


Figure 7. Time histories of the forces in the rope (grey) and pulley (black) for (a) the coach (b) the “dead weight” and (c) the rope tied off at the floor (drop height 1.5m gymnast mass 35 kg).

4. Discussion

The aim of the study was to establish the peak forces on a gymnastics support system under maximal loading situations. This was defined to be when the coach attempted to arrest the falling gymnast as quickly as possible. In normal use the coach will assist under sub-maximal conditions, only when the skill being taught goes wrong and there is a risk of injury is the support system used maximally.

It was found that as the gymnast drop height increased so did the peak forces recorded at the pulleys and in the ropes. The relationship between drop height and peak force was found to be non-linear. Theoretically from this quadratic relationship, given a gymnast mass and a coach mass, there would be a drop height beyond which the peak force on the system would not increase (e.g. from the equation in Figure 5 the peak force at load cell 1a would reach a maximum value at a drop height of 2.39 m). However, this does not mean that the coach can assist the gymnast sufficiently from greater drop heights. In practice, there would come a point where the coach would be lifted by the rope and the gymnast would hit the floor. The higher the drop the greater the velocity with which the gymnast would hit the floor. In the trials carried out in the present study the peak drop height of 1.5 m was implicitly selected by the coach. Beyond this height the coach was unable to prevent the gymnast mass hitting the floor. It is important that coaches are aware of these limits and do not operate support systems in situations where they will not be able assist the falling gymnast. A gymnast mass of 35 kg is relatively small compared with a male top (the mean mass of 3 international level male acrobatic gymnastics tops was recorded as 45 kg, range 33 – 60 kg) and in other gymnastics disciplines that use support systems, such as artistic gymnastics and trampolining, senior male gymnast may have considerably more mass (the average mass of 98 male artistic gymnasts competing at the Sydney 2000 Olympic games was 62 ± 5 kg, range 48 – 76 kg). It is very unlikely that the coach used in the present study would be able to prevent a senior male gymnast from hitting the floor from a drop height of 1.5 m. In the present study the coach only had a distance of 1.0 m to bring the gymnast mass to rest. More drops would be required to establish the exact nature of the relationship between peak force, drop height and gymnast mass. This would require a greater distance through which the coach was required to bring the gymnast mass to rest. However, there may be ethical implications regarding exposing a coach to potentially injurious forces.

It was found that the actions of the coach made an important contribution to reducing peak forces and rate of force development (Figure 7). Compared with the rope being tied off, the dead weight reduced the peak forces and rate of force development. However, the reduction was relatively small compared to the effect of the coach. The coach's actions increased the time to peak force (Figure 7), thus reducing the peak force required to bring the gymnast mass to rest.

In the current British Standard [1] the rope is required to be have a breaking load of 10 kN and the pulleys are specified to have a SWL of 300 kg. The pulleys used in the present study (Barton Marine, 45 mm standard block) have a SWL of 385 kg. The manufacturer also produce a double pulley unit, which has the same 385 kg SWL. If a double pulley unit had been used rather than two single units in the trial where the coach was modeled as a dead weight, the peak force would have approached the equivalent of 343 kg. When the logline was tied off this value increased to 418 kg which would have exceeded the SWL of the double pulley. Using two separate pulleys rather than one double pulley ensures that the SWL is not exceeded during normal operation of the support system.

However, the values reported above for the British Standard are still somewhat peculiar. Given the recommended angle of the ropes in relation to the upward vertical (with gymnast stood at ground level $\approx 45^\circ$), if the rope were at its working limit the load through the single

pulley (assuming a vertical logline) would be approximately six times its safe working limit. Similarly for a double pulley this would equate to 11 times the 3 kN safety limit (given a single unit double pulley). There does not seem to be a logical connection between the safe working limits of the pulleys and the ropes; the values appear to be somewhat arbitrary and given the above analyses suggests that for larger gymnasts the double pulley rating is too low and the rope rating may be excessively high. From Table 2, on average, the tension in the rope was only 42% of the peak force recorded at pulley (3).

The present study has provided data on the forces experienced during maximal loading situations of a gymnastics support system. It has already been highlighted in the discussion that more research is required. The present study has been limited by: the range of coach masses used, the range of drop heights used, distance from taut rope position to floor contact and range of gymnast masses used. As identified previously, overcoming the majority of these limitations would potentially place the coach in an injurious situation. It is therefore recommended that either a physical coach model and/or a computer simulation model of the system be developed to address these issues. A combination of both physical and computer modeling could be used as it would allow evaluation of the computer model and the investigation of a variety of different scenarios (including the effect of pulley separation). The results from a physical model could also be used to inform British Standards testing procedures along the lines of the Artificial Athlete Stuttgart and Berlin [5].

In conclusion, it was found that the peak forces at the pulleys increased with both the drop height of the gymnast mass and the size of the gymnast mass. In both cases the relationships were non-linear in nature. The actions of the coach were also found to have a large effect on the magnitude of the peak forces when compared with using an equivalent dead weight and when the rope was tied off. The coach's actions reduced the peak forces by 35% and 48% when compared with the dead weight and the rope being tied off, respectively.

References

- [1]. BS 1892-2.8:1986. Gymnasium equipment –Specification for trampolines, mini trampolines and safety harnesses (trampoline spotting rig) (London: British Standard Institution 1986).
- [2] Ernst, D. and Vogel, W. Determination of the redistribution shock load in climbing double rope systems. *Engineering Failure Analysis*, 2009, **16**, 751-764.
- [3]. McLaren, A.J. Design and performance of ropes for climbing and sailing. *Materials: Design and Applications*, 2006, **22**, 1 – 12.
- [4] Pavier, M. Experimental and theoretical simulations of climbing falls. *Sports Engineering*, 1998, **1**, 79 – 91.
- [5]. Nigg, B.M. and Yeadon, M.R. Biomechanical aspects of playing surfaces, *Journal of Sports Sciences*, 1987, **5**, 117-145.