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Making single point aerial circus disciplines safer

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Abstract

The purpose of this study was to measure the dynamic tension force between the apparatus and the hanging equipment of five aerial circus apparatus and to recommend minimal loading requirements in rigging and design. Forces generated by different acrobatic movements were measured and synchronized with video recordings. Sixteen students of the National Circus School of Montréal (Canada) participated in the study. Maximal forces were analysed and characterized with respect to the discipline, the type of movement and the schooling level of the student. The maximal force measured was 5.3 kN performed in the discipline of aerial straps, equivalent to 7.9 times the bodyweight of the performer. A minimal breaking strength of 22 kN for the hanging point and all the equipment holding the rig is recommended. A minimal breaking strength of 22 kN for straps, 17 kN for rope, and 12 kN for silk, aerial hoop and dance trapeze is recommended.

Keywords

Aerial circus discipline, maximal forces, safety, circus rigging, acrobat mass

Introduction

Aerial acrobats use their own force to lift their body and execute various movements requiring extreme strength and precision similar to gymnastics. Aerial acrobatics encompass all disciplines requiring the rigging of an apparatus at a height. Aerial hoop, aerial silk, aerial straps, dance trapeze and rope are among the apparatus used. Aerial hoop, also called *lyra*, is a circular apparatus made of metal attached by one or two wire ropes wrapped in cotton. Silk is made of two fabric panels hanging vertically from a hooking device. Dance trapeze is a horizontal bar made of various materials including metal, wood or carbon fiber and is hung from climbing, cotton, steel core cotton, or other rope. Straps consists of two bands several meters long, fastened at one end. Rope, also called *corde lisse*, is a cotton rope that hangs vertically. All five discipline apparatus are hanged at one point (Figure 1).

At the present, there is no data available on the forces generated by artists in aerial hoop, aerial silk, aerial straps and rope. The first time that forces were measured in circus is for the single point aerial dance trapeze[?]. Four basic movements were analyzed with the participation of 10 artists. The maximal force measured was 3.4 kN which represents a ratio of 4.94 with respect to the bodyweight. Aside from that, little scientific work was carried out in circus. The only biomechanical study was found in aerial cradle. Agnesina[?] estimated the reaction forces behind the knees in order to understand and to optimize the movement and to limit pathologies of the acrobat. A study over five years[?] described the injury patterns and injury rates from the Cirque du Soleil, a Canadian company with 20 current shows around the world. As a comparison, in gymnastics, many studies have been conducted to know the forces experienced by athletes or generated in equipment. For example, Hiley *et al.*[?] determined the forces at the pulleys and the tension in the ropes during maximal loading on a gymnastic safety support. The support described

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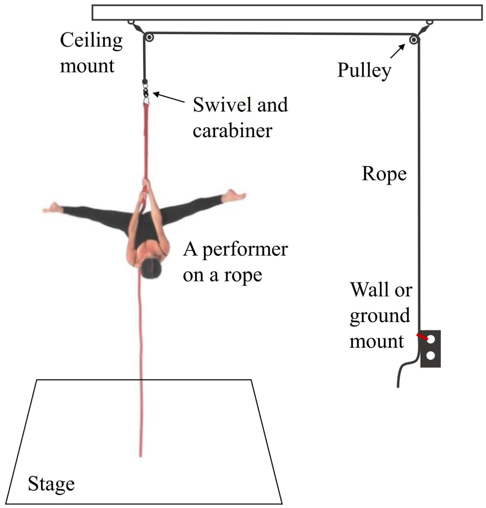


Figure 1. Circus rigging of an aerial apparatus. Reproduced with permission and retrieved from the The Circus Dictionary[?] .

in the article is also used in circus training, but data is still required in circus for safety reasons and movement execution improvement.

In the entertainment industry, a new safety standard covers performer flying systems. ANSI E1.43[?] is a United States national standard that establishes a minimum level of performance parameters for the design, manufacture, use and maintenance of flying systems. This does not include "any connection that ultimately relies on the strength or ability of the flying performer" nor "flexible medium onto which performers actively engage their bodies, such as strap act webbing, silk act fabric, and natural fiber ropes"[?] , typically used in circus situations. There are no specific safety standards for circus performance. The ANSI E1.43 standard provides some safety parameters in relation with the characteristic load which is the maximum force applied in normal conditions; however, with no data available on maximum force, it may be difficult for circus professionals to reach the requirements. As a comparison, in climbing, the most critical piece of equipment in terms of safety, also called the 'weakest link', is the rope. Climbing ropes are classified as personal protective equipment of category III (high risk) and therefore have to be tested and certified by a notified body. They must remain strong enough yet provide sufficient flexibility to minimise any peak impact load. They are submitted to the European EN892:2012[?] standard or the international UIAA101:2013[?] standard. Both require, among other things, that the peak force when dropping a 80 kg mass may not exceed 12 kN. Anchor nuts are usually designed to support a load of 12 kN. This value was determined as the maximum load that people can withstand without serious injury.

Despite the large number of circus artists, trainees and school programs, the tensile load exhibited on the performer by the apparatus is unknown. Riggers and designers lack proper dynamic measurements. Many questions remain among circus coaches and artists. They wonder if the rigging equipment and holding point is strong enough to support the load generated by acrobatic movements. They are also interested in knowing which type of movements generate more force, so they can adapt their performance if they feel that the hanging equipment or their body can not support high forces. About the difference between beginners and experienced performers, there are two schools of thought. The first “popular belief” is that, for the same apparatus and figure, beginners tend to generate more force than experienced performers because the experienced performers know how to use their body to minimize the force. The other belief is that only advanced movements generate high forces, therefore, beginners cannot generate high forces. Another question targets the difference between show and training. The common preconceived idea is that artists generate higher peak forces in show than in training because of the stress and adrenaline.

Circus is a physical activity gaining in popularity and is constantly evolving. It is practiced by professionals and amateurs, including children, and equipment failure can lead to serious injury or death. In order to reduce risks, better knowledge of the actual dynamic loads on the apparatus and the rig is required. The aim of the present study is to measure maximal forces between the aerial apparatus and the hanging equipment of five circus disciplines and to recommend minimal design requirements in rigging and apparatus.

Definitions

Design and safety factor

In terms of safety, a “design factor” is used for the design of the apparatus, and a “safety factor” is used for hanging. The usage of safety factor or design factor in the entertainment industry is often confusing. The purpose of the following definitions is to clarify the vocabulary. “The safety factor is how much the designed part actually will be able to withstand. The design factor is what the item is required to be able to withstand. The safety factor is a ratio of maximum strength to intended load for the actual item that was designed”[?]. The safety factor provides additional protection above the manufacturers design factor. ANSI E1.43[?], an ESTA standard available to the public, specifies a minimum design factor for flying systems used: $6\times$ the characteristic load for harnesses, quick connect hardware and flexible lifting medium (e.g., rope, chain, band, webbing), $5\times$ the characteristic load for rigid lifting medium and $4\times$ the characteristic load for static load bearing components. Load bearing components are purchased elements, such as fasteners, rigging components and equipment, which are part of the load path. The characteristic load is the maximum force from normal operating conditions. It can be higher than the static load, specially in circus. As the artist performs acrobatic movement, the force applied to the flying system is higher than his bodyweight and can be referred as “dynamic forces”.

Circus apparatus and hanging equipment are submitted to both factors depending on whether it is manufactured or hanged. In circus hanging, riggers commonly use a safety factor of 10 for rigging people who are suspended[???]. In this case, the safety factor refers to the ratio of the breaking strength of an equipment, called “MBS or Minimum Breaking Strength” given by suppliers, to the static load that must be carried, i.e., the static weight of the performer and the apparatus. This factor can be changed to deal with various circumstances, including, but not limited to, how well the loads are known, how much experience the rigger has with the hardware, how long the hardware will be in use, how often the hardware might be inspected, etc. It is used when riggers have to choose between different equipment holding the circus apparatus or to decide if a hanging point can support the load. The factor compensates the fact that loads are dynamic and other unknown factors that affect equipment in service. A handbook[?] recommends considering dynamic efforts by adding a dynamic factor to the static load during the design phase of circus apparatus. In the literature, this factor has two possible values: 2 for a fixed rig and 5 for a swinging rig. Rope is a fixed rig whereas aerial hoop, silk, dance trapeze and straps are considered as swinging rigs according to the type of performance.

Categories of movement

Movements performed by aerial acrobats can be classified in one of six categories: fall, tempo, large swinging/rotation, spin, acrobatic and combination. During a fall, the artist deliberately lets himself fall knowing that the rig will catch him by one of his body parts. There are two kinds of falls: free fall and unwinding fall. The free fall is a direct fall in which the artist does not flip or there is just one flip to start the fall. An unwinding fall requires that the apparatus, previously rolled around the body, unrolls itself which make the artist flip until the apparatus catches the artist by one of his body parts. In a tempo, the artist holds the apparatus and swings like a pendulum without moving the apparatus. Large swinging or large rotation occurs as the artist swings the equipment from one side to another or in a circle. Then he can do acrobatic moves or position changes while the equipment is moving. A spin is the action of making the apparatus spin around the vertical axis. Acrobatic movements encompass everything else which implies dynamic movement, including : flip, circle, jump, drop and catch, circle around the bar, etc. Combinations are defined as any sequence that involve moves from different categories. For example, an unwinding fall followed by a flip. This list of movement types is not exhaustive. In fact many movements are difficult to classify as each artist wants to have unique performance and moves. Each discipline has its more common types of movement. A lot of different free falls and unwinding falls can be executed in silk and rope. Tempo and spin are more frequently done in aerial hoop and dance trapeze. Large amplitude swinging can be performed in aerial hoop, dance trapeze and straps. Acrobatic movements are present in every discipline.

Methods

Participants

Sixteen students from the National Circus School of Montréal (average age: 20.2 years, standard deviation s = 1.4; mean body mass: 64.9 kg, s = 6.4; 5 females and 11 males) gave their informed consent to participate in the study, which was approved by the ethical committee of Polytechnique Montréal. The participants distribution among disciplines was: 2 in aerial hoop, 4 in aerial silk, 6 in aerial straps, 2 in dance trapeze and 2 in rope. The higher education program of National Circus School is a 3-year program that leads to a professional career. The participants distribution among school years was: 2 in first year, 8 in second year and 6 in third year.

Circus equipment

The technical department of the National Circus School makes apparatus available for the students. Dance trapeze and aerial hoop are custom-made. Aerial silk, rope and straps are bought from circus rigs suppliers.

The dance trapeze is made of a solid steel bar that is 2.24 cm in diameter and 91.4 cm in length, hung by two 7x19 wire ropes 4.76 mm in diameter. The wire rope is wrapped in cotton rope to prevent hurting the artists hand. The bar is taped so that the metal is not in direct contact with the artist. Aerial hoop has an inside circle diameter of 99.1 cm and is made of a bent solid steel bar 2.24 cm in diameter and attached by one 7x19 wire rope in 4.76 mm diameter. Similar to the dance trapeze, the wire rope is wrapped in cotton rope and the bar is taped. Wire ropes have a breaking strength of 19 kN. The circus silk apparatus consists of a 10 m by 1.6 m piece of nylon fabric folded in half along the width. The supplier (Knitrama Fabrics Inc, Saint-Léonard, Canada) reports a breaking strength of 7.7 kN for a 1.6 m width of material. The rope is made of cotton 3 cm in diameter and 10 m in length with a spliced end and a leather protective cover. The straps include a pair of two aramid fiber straps 3 to 5 m long, 3.8 cm wide and 2 mm thick. The breaking strength provided by the supplier (Circus Concept, Québec, Canada) is 22 kN and 37 kN for the rope and the straps, respectively. There are two kinds of silk and straps on the market to satisfy the preference of the artist: stiff or elastic. The National Circus School only possess elastic silks and rigid straps. Thus, the measurements were done under these conditions.

Different categories of movement

In the present work, a total of 49 movements were measured, and for each one, between 5 to 12 trials were performed by each student. The measurement distribution covers the different categories of movement (Table 1).

	Aerial silk	Aerial straps	Dance trapeze	Aerial hoop	Rope
Free fall	8		1		1
Unwinding fall	2	1	1		2
Tempo		4	3	3	
Large swinging		1		1	
Acrobatic movements	1	8	1	3	
Spin				1	
Combination		3	3		1

Table 1. Distribution of the different categories of movements by discipline.

Data collection

In order to determine the tension forces, a load cell (Futek, LCF455 - 2000lbs) was attached between the steel cable and the rig (Figure 2). The tension force measured provides the load the apparatus (dance trapeze, aerial silk, etc.) exerts at the connection to the rigging cable. It is not a direct measurement of the load at the hanging point on the ceiling mount nor the pulleys (Figures 1 and 2). However, the measured tension force should be similar to the load at the force anchoring the hanging cable at the wall or the ground mount considering the high rigidity of the steel cable (Figures 1 and 2). An emitter (National Instrument, WSN 3214) connected to the load cell sent the force signal to the receiver (National Instrument, WSN Ethernet Gateway). A few tests with a higher sampling frequency of 250 Hz were done

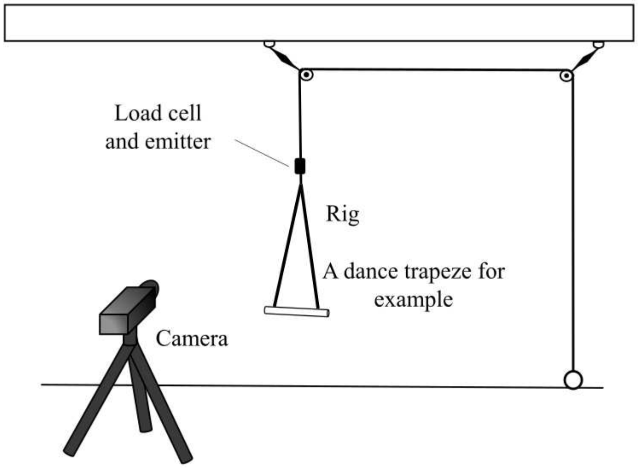


Figure 2. Locations of the load cell and the camera during measurement.

with basic movements performed in rope, in silk and in dance trapeze, to make sure that 100 Hz would give enough data points. In these preliminary tests, it was confirmed that time signals at 250 Hz and 100 Hz were in good agreement, and that time steps of 0.01 seconds was sufficient to adequately represent the force signals. Even for the shorter 230 ms impulse in Figure 3 (b), the peak is represented by 24 data points. In addition, all peak shapes are smooth and so, the error in evaluating the maximum force is small. It should be noted that in the present work, all the analyses are carried out in the time domain and therefore, there is no risk of aliasing errors. All performances were captured using a Basler IP camera operating at 25 Hz. The receiver and the camera were connected to a personal computer (Asus, G750JS). Force signal measurement and video recording were synchronized using Labview software.

The load cell sensitivity was attributed according to the certificate of calibration from the supplier. A test procedure was repeated every week during the measurement period. The load cell was loaded with calibration weights of 445 N and 889 N with recordings taken. The relative error was less than 0.8% each time. Data collection lasted three months from February to April 2015 at National Circus School of Montréal. Each student performed between 1 to 10 different movements at the end of their class. The procedure was repeated over a few weeks to have enough samples. For each movement described in Table 1, a minimum of 5 trials were done by each performer. A total of 302 trials were measured. The load cell was tared after the rig was hanged so that only the weight of the artist and the dynamic forces exhibited on the performer and the rig are considered. From a practical point of view, this approach was required to obtain consistent measurements: because each performer adjusted the height of the rig differently, the rig was more or less in contact with the landing mats on the ground and thus its suspended weight was different.

Data analysis

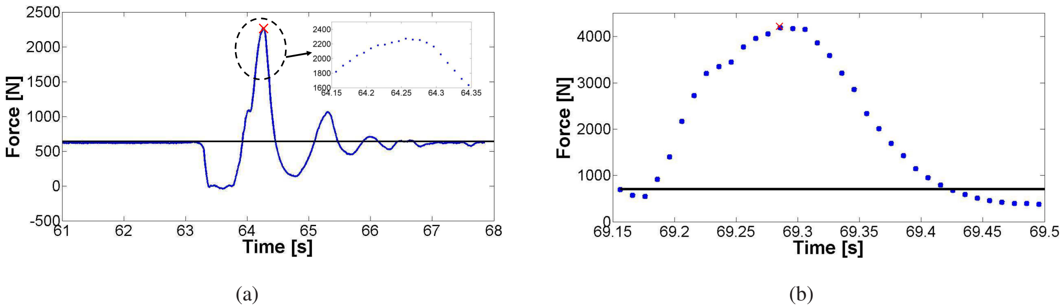


Figure 3. Examples of force signal measured: (a) force signals for a free fall in silk synchronized with the video (letters (a) to (d) refer to the images in Figure 4) and (b) measurement data points for a free fall in rope (also shown in a close-up view for the peak in frame (a)). The × indicates the measured maximal force. The black line represents the weight of the artist.

Maximal forces were determined for each sample using Matlab software. Only the maximal force of all the trials for a same movement and a same performer is saved for the analysis. An example of a force signal from a free fall in silk is given in Figure 3 (a). It is synchronised with the images of the video (Figure 4). As the acrobat hangs without moving (Figure 4 (a) and 3 (a)), the force signal takes the value of his bodyweight. When he lets himself fall, the tension is about zero (Figure 4 (b) and 3 (b)). The peak occurs when the rig catches him by his hips and his leg (Figure 4 (c) and 3 (c)). Force oscillations are observed in Figure 3 (c) due to the elasticity of the silk. The oscillations decay due to mechanical damping. Once the movement is over, the force signal returns to the bodyweight value (Figure 4 (d) and 3

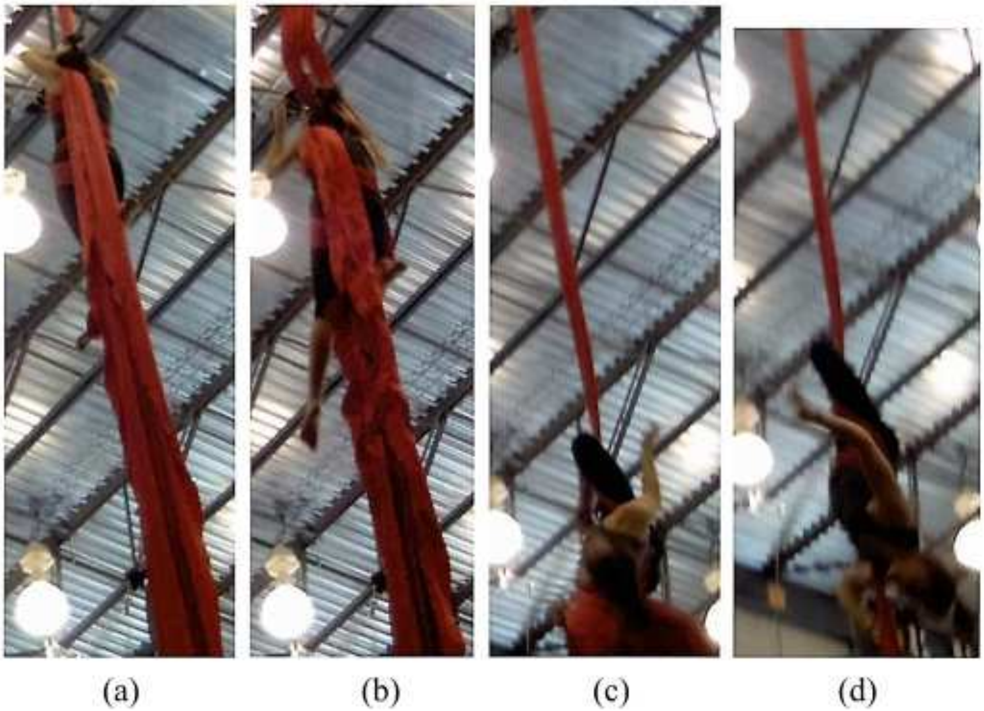


Figure 4. Free fall in silk (sequence from left to right).

(d)). **An example of a force signal from a free fall in rope presents the measuring points of a shorter impulse signal in Figure 3 (b).** The shape of the signals and the position of the maximal force were verified in order to remove any problematic data caused by transmission errors between the emitter and the receiver. Movements were categorized by the director of research of the National Circus School (see Table 1). As the force depends on the mass of the artist, maximal forces are also provided in bodyweight (BW) defined by:

$$Reduced\,force\,[BW] = \frac{Force\,[N]}{Weight\,of\,the\,artist[N]}. \quad (1)$$

Measurements number	T1	T2	S1	T3	S2
Date	11/05/15	28/05/15	29/05/15	04/06/15	04/06/15
Condition	Training	Training	Show	Training	Show
Place	Circus school	Tohu	Tohu	Tohu	Tohu

Table 2. Number, date, condition and place of the five measurements of the whole sequence.

Show and training measurement

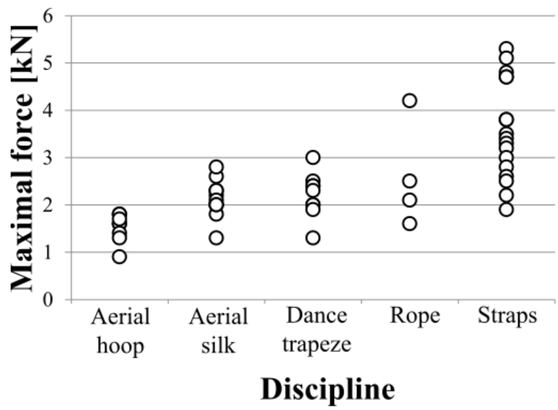
A whole act of rope discipline was measured five times with the participation of a final year student. The measurements were done for two conditions and in two locations: in training at the circus school, in training at the Tohu and in show at the Tohu (Table 2). Tohu is a performance hall in Montréal that typically presents professional circus shows. Ten dynamic movements were kept from the whole sequence for the analysis of the maximal forces. Each measurement was given an identification number (T is for training and S for show). The maximal force was found for the ten different movements at the five occasions. For each movement, the relative difference in the maximal force was determined for each performance pair. The average relative difference over all ten movements was then calculated.

Results

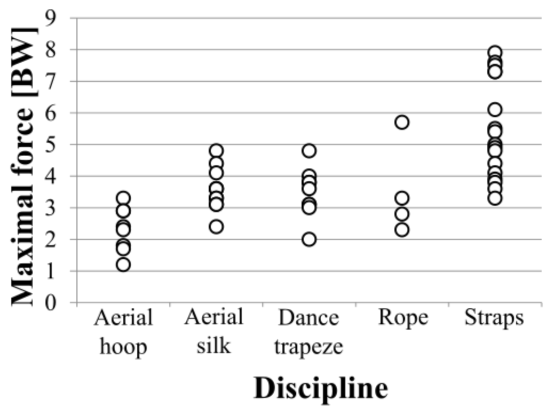
Maximal forces and discipline

A total of 4 movements were measured in rope, 11 in silk, 8 in aerial hoop, 9 in dance trapeze and 17 in straps. In Figure 5, each point gives the maximal force for one artist in one discipline. The maximal force varied from 0.9 kN to 5.3 kN for 49 different movements. The ratio of the maximal force to the bodyweight (BW) ranged from 1.2 to 7.9 bodyweights. Whether in kN or in BW, the distribution of maximal forces for any given discipline is fairly similar.

Higher maximal forces were generated in rope and straps. Five movements in straps yielded a force higher than 7 bodyweights. A free fall in rope generated a force of 5.7 bodyweights. The maximal force measured in dance trapeze represents a ratio of 4.8 with respect to the bodyweight, which is close to



(a)



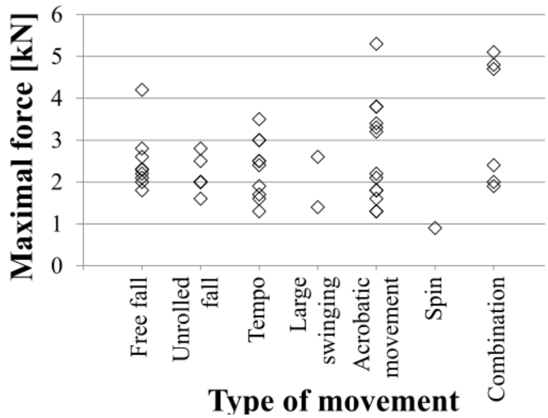
(b)

Figure 5. Maximal forces measured for each discipline in (a) kN and (b) bodyweight.

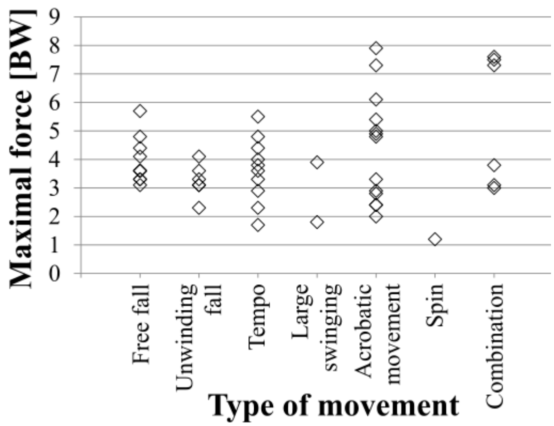
aerial silk and to the overall average. Aerial hoop generated the lowest maximal forces, ranging from 1.3 to 3.4 BW (Figure 5).

Maximal force and categories of movement

A total of 49 movements were measured among the five disciplines. Maximal forces ranged from 2 kN to 4.2 kN in free fall, from 1.6 kN to 2.8 kN in unwinding fall, from 1.3 kN to 3.5 kN in tempo, from 1.4



(a)



(b)

Figure 6. Maximal forces measured for each movement category in (a) kN and (b) bodyweight.

kN to 2.6 kN in large swinging, from 1.3 kN and 5.3 kN in acrobatic movements and from 1.9 kN to 5.1 kN in combination (Figure 6).

Maximal forces and schooling level

A total of 6 movements were executed by first year students, 24 movements by second year students and 19 by third (final) year students (Figure 7). Therefore more data is available for second and third year students. In both cases, the force varied from 0.9 kN to 5.3 kN. The maximal forces for first year students

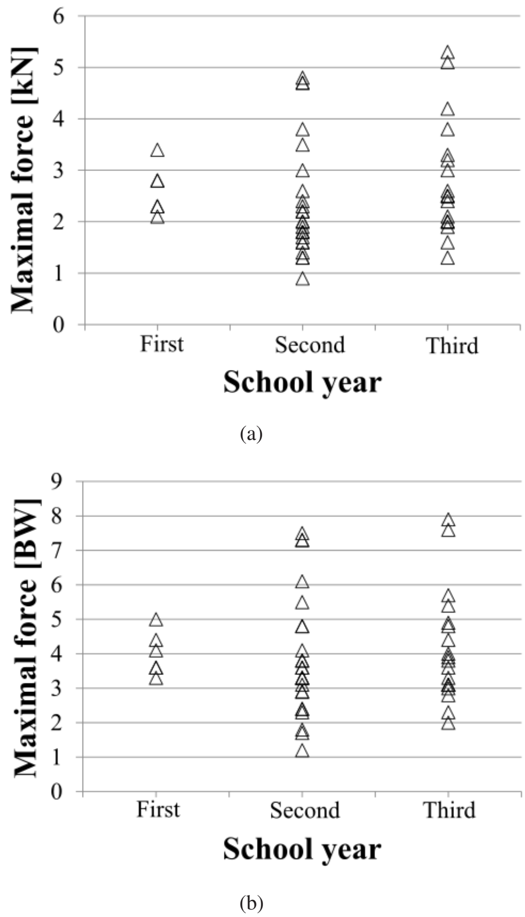
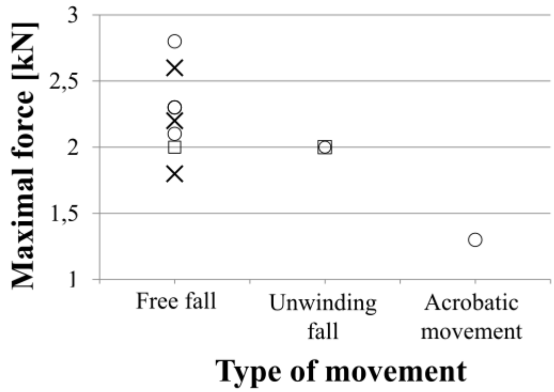


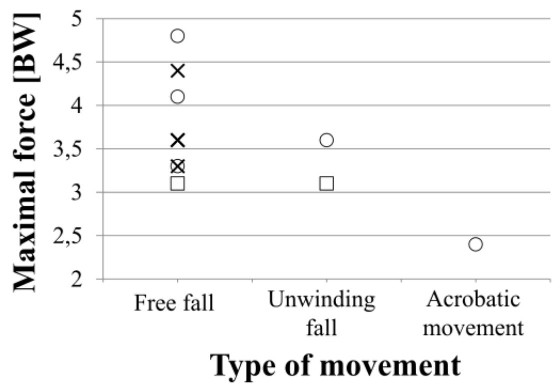
Figure 7. Maximal forces by the school year in (a) kN and (b) bodyweight.

are comprised between 2 kN to 3.4 kN. First year students have performed 4 free falls, one unwinding fall and one acrobatic movement.

The case of the silk is studied in Figure 8. The maximal forces are presented by the type of movement and by the school level. The majority of movements measured in silk are free falls because the silk is a long vertical apparatus and the elastic properties help minimize the load exhibited on the body. Two



(a)



(b)

Figure 8. Maximal forces in (a) kN and (b) bodyweight in aerial silk by the type of movement and by the school year : ✕ for the first year students, ❍ for the second year students and ❏ for the third year students.

second year students and one first year student generated the three maximal forces expressed in BW for free falls.

Comparison of maximal forces between training and show

Table 3 shows the average relative difference of maximal forces over all ten movements between each pair of measurement. The events are presented in chronological order. The results vary from -8.9% to

	T1	T2	S1	T3	S2
T1		3.9%	-8.9%	5.7%	-4.9%
T2			-2.8%	2.6%	1.8%
S1				0.1%	-4.6%
T3					3.5%
S2					

Table 3. The average relative difference in maximal forces between each pair of measurement during a whole act with rope (T is for training, S is for show).

+5.7%. The signs "plus" or "minus" define whether the event in the first column has a higher or lower maximal force than the events in the first row. For example, in training T1, a maximal force 3.9% larger than in training T2 was measured. However, the measured maximal force was 8.9% smaller in training T1 than in show S1.

Table 3 shows that the average relative difference between a given training and the following show is weak: there is a small difference of -2.8% between the training on the 28/05/15 and the show on the 29/05/15, and 3.5% between the training on the 04/06/15 and the show on the 04/06/15. As a comparison, the average relative differences between any two trainings ranged from 2.6 to 5.7%; the difference is -4.6% between shows S1 and S2. These results indicate that the variations are in the same range in all three cases and therefore, artist generate neither greater nor lower maximal force in show than in training.

Real design factor

The case of the National Circus School was analysed in the Table 4. The breaking strengths of each rig and the hanging point are compared to the maximal force measured in the present study. The real design factor, defined as the ratio of the maximal force measured to the breaking strength, is then calculated. The minimum real design factor at National Circus School of Montréal is 2.8 at the hanging point and also 2.8 in the design of the apparatus (Table 4), which seems to be enough for the present needs. It should be noted that the values were calculated without including the weight of the apparatus or the hanging equipment because the load cell was zeroed after the rig was hanged. The weight of the apparatus and

Discipline	Rig breaking strength (kN)	Hanging point breaking strength (kN)	Maximal force measured (kN)	Rig **design factor** (kN)	Hanging **design factor**
Straps	37	15	5.3	7.0	2.8
Rope	22	15	4.2	5.2	3.6
Silk	**7.7**	15	2.8	**2.8**	5.3
Dance trapeze	19[1]	15	3.0	6.3	5.0
Aerial hoop	19[2]	15	1.9	10	7.9

Table 4. Breaking strength, maximal force measured and real design factor for the circus equipment and the hanging point at the National Circus School of Montréal.

the hanging equipment does not exceed 20 kg which means it will add at most a force of 0.2 kN, which does not change much the results.

Discussion

The aim of this study was to measure the maximal forces for different types of movements at the hanging point of five aerial circus disciplines. Maximal forces were characterized with respect to the discipline, the category of movement and the schooling level of the student. The real safety factor (i.e. the ratio of the breaking strength over the maximal load) was calculated for each discipline and compared with the design factor or the safety factor recommended in the circus world.

Maximal forces and discipline

The maximal forces were generated in straps and rope. This is explained by the fact that they both are rigid apparatus (contrary to silk), causing short impulse response. Both dance trapeze and aerial hoop can be rigged using elastic rope but it was not the case in this study. The forces generated with a rig using elastic rope would have been different; it may have been more similar to the silk in this case. More research on the influence of the type of rigging equipment on forces is required. Dance trapeze and aerial hoop also are rigid apparatus; however, because of their shape and metal bar, acrobats perform different movements than in straps or rope. The maximal force measured in dance trapeze represents a ratio of 4.8 with respect to the bodyweight (Figure 5). The results are consistent with the maximal force measured by Vogel who found a ratio of 4.94[?], although the movement was different. Vogel measured the maximal force for a *sit-bounce*: the performer sits on the trapeze bar, pulls up off the bar as high as he feels safe and then drops straight down till he is sitting back on the bar. In this study, the maximal force was measured for a tempo. Aerial hoop generated the lowest maximal forces (Figure 5). The participants in aerial hoop did not perform very dynamic movements. They performed contortions. It was also very difficult for them to do the movements because of the reaction induced by the mass of the load cell.

Maximal force and categories of movement

As it might be expected, spinning about a vertical axis does not generate a high pulling force (Figure 6). A spin will not generate a high tension force at the hanging point as the acrobat remains in the vertical axis while rotating. The centripetal force is perpendicular to the measured hanging force. The three highest forces in dance trapeze are achieved with tempo movements. The highest force in aerial hoop is generated for an acrobatic movement called "circle around the bar". The artist, leaning on the bar, does a $360°$ rotation without losing contact with the bar. In straps, the highest force, i.e. 7.9 times the bodyweight, is obtained with an acrobatic movement called "giant circles". The artist, whose hands are tied with the straps, begins by swinging back and forth and, when he gets enough height, does several $360°$ rotations. The "giant circles" resembles to the backward giant circle in high bar and the backward longswings performed on rings. Kopp and Reid[?] used strain gauges mounted on the bar and the maximal force measured ranged from 3.45 to 3.70 times the bodyweight. Kerwin and Hiley[?] estimated reaction forces from the displacement of the high bar obtained from a video analysis and obtained a vertical force of 4.53 bodyweight for an accelerated giant circle. The peak tension measured in the ring cables is close to 9 bodyweights for Nissinen[?] and 8.5 bodyweights for Brewin *et al.*[?], and occurs as the gymnast passes through the bottom of the swing. The force measured for almost the same movement but with aerial straps are more similar to the force measured in rings than in high bar. Rings and aerial straps indeed have a closer shape than the high bar. Consequently movements that generate the higher maximal forces in dance trapeze, in aerial hoop and in straps contain swinging motion; whereas in rope or in silk, it is mostly free falls that generate the highest peak force. However in free falls, there are issues pertaining to data comparability, because there is no standardization of the height of the fall: the performer tends to fall from the largest amplitude possible. It should be mentioned that the free fall that generated the highest peak force in rope was executed with the largest length of rope possible. So that would explain the very high force. At the National Circus School of Montréal, the maximum height from the hanging point to the ground is 9 m. The artist however does not fall the complete 9 m since 1 to 2 m of the rope is in contact with the landing mats, and the artist keeps 1.5 m of the length at the top and the bottom for safety reasons. A larger range of fall would be difficult to achieve due to the limit of the length of the apparatus. For the unwinding fall, the fall depends on how the silk or the rope is wrapped around the body. The only variation could come from on how tight the performer rolls the apparatus around the body.

More research on the influence of the height of fall on the peak force could help to know the real forces exhibited on one of the body parts of the performer and how to adapt the training so that he could support the loads. Maximal forces in combined movements have a large dispersion in Figure 6: three movements generated a force around 5 kN and the three others around 2 kN. For some movements, the second move cannot be done without doing the first one. For example, to do a "salto" in rope, the artist first needs to swing, then he has enough momentum to let go of the rope, do a flip and catch the rope again. The second movement, which is an acrobatic movement, cannot be done without the tempo before, this is why high force is generated. If different movements are carried out one after another without connection, the maximal force is then low.

Maximal forces and schooling level

As the student learns more movements, the range of maximal forces increases. The student learns more movements from different types which can generate either higher or lower maximal forces. It should be noted that free falls can be done by beginners because it does not imply great action from the performer. Free falls in silk generated the highest maximal forces irrespective of the schooling level (Figure 8). Concerning the belief that for the same move, beginners tend to generate more force than experienced performers, it is difficult to have a clear conclusion. Only two movements were in common between many students: a free fall was done by three students in silk and an acrobatic movement was performed by six students in aerial straps. The free fall was measured for one student in first year and two in second year. The ratio of the maximal force to the bodyweight were respectively 4.5 for the first year student and 4.1 and 3.5 for the second year students. The acrobatic movement in straps was performed by one first year student, three second year students and two third last students. The ratio of the maximal force to the bodyweight were respectively 5.0 for the first year student, 3.8, 6.1 and 7.3 for the second year students and 4.8 and 5.3. These results suggest that the peak force is influenced not only by the level of skill, but also by other parameters.

Comparison of maximal forces between training and show

The overall differences between show and training are small in Table 3, and vary from 0.1% (between S1 and T3) to -8.9% (between T1 and S1). As a comparison, it should be recalled that differences of 100% and more were observed when comparing disciplines or movements, and differences of 185% were observed from one student to another. The results show no statistically significant difference between the five trials. Several facts can explain those results. The participant is a senior student (almost a professional): he has good self-control and does not seem to be affected by stress. The movements in his act should not have a lot of variability due to the lack of swinging movements. The maximal value is -8.9% between the training executed on the 11/05/15 and the show executed on the 29/05/15 in Table 3. This larger difference could be due to the longer time interval between the two trainings and the fact that measurements were not done at the same location. In fact, all the values comparing training T1 to the other measurements are slightly higher than the rest. It is possible that the different location where the measurements were conducted has an influence on the generated forces. The training T1 was carried out at the National Circus School, and the other performances were done at the Tohu. The mechanical behaviour of the hanging structure may be different from one location to another.

Design factor

For the equipment holding the rig, such as carabiners, ropes, swivels etc, riggers use an installation design factor of 10 based on the weight of the artist and the rig[???]. However, the maximal force measured in the present work is 7.9 bodyweight without considering the weight of the rig. Even if the rig does not have a high weight compared to the dynamic forces measured, the real design factor in this case might not be enough. So the factor 10 used by riggers really is a minimum value to consider. Riggers must keep track of how acrobatic techniques and artist's weight evolve in the future and in case of any doubt, they need to use a higher value for the factor.

A minimal breaking strength of 22 kN for the hanging point is recommended, which represents an installation design factor of 4 relative to the maximal force measured here, considering the fact that human lives are at stake. The tension force measured at the connection of the apparatus to the hanging cable should be similar to the one experienced by the wall or the ground mount (Figure 1 and 2) for cables of high rigidity. The recommendations are valid for the hanging equipment such as hanging cables and carabiners, as well as the circus apparatus, but not for the ceiling mount. A minimal breaking strength of 22 kN represents $33\times$ the static load which is considerably higher than the factor 10 recommended in rigging. A minimal breaking strength of 22 kN for straps, of 17 kN for rope, and 12 kN for silk, aerial hoop and dance trapeze is recommended, which represents a component design factor of 4 relative to the maximal force measured. The number of five trials carried out in the study is not enough to ensure the repeatability of the maximal forces. So the factor of 4 relative to the maximal force measured here allows to cope with these uncertainties. It should be mentioned that the number of measurements was limited in aerial hoop. Nevertheless, as the shape (and the material) and the movement executed are similar in dance trapeze and aerial hoop, the present recommendation is also extended to aerial hoop. More data collection on aerial hoop would help to validate the recommendation.

The "dynamic factor"[?] recommended to consider the dynamic effort is really below the reality. Rope, which is fixed rigs, has generated maximal force of 5.7 bodyweights respectively, contrary to the dynamic factor of 2, prescribed in the literature. Straps, silk, dance trapeze and aerial hoop, which are swinging rigs, have generated a maximal force of 7.9, 4.8, 4.8 and 3.3 bodyweights respectively, contrary to the dynamic design factor of 5. In the future, a higher dynamic factor is necessary to represent the real dynamic forces. In the literature, this factor has two possible values: 2 for a fixed rig and 5 for a swinging rig. The distinction is hazardous since the rigger can never guarantee that an act will or will not induce swinging motions.

Adequate breaking strength for circus equipment is necessary but excessive strength can be undesirable for two reasons. On one hand, greater mass of the equipment is not wanted, specially in the entertainment industry. On the other hand, higher stiffness means smaller redistribution of the peak impact load in the equipment, which can also contribute to a higher impact force displayed on the artist. In climbing, the standard EN 892[7] requires that the maximum force on the climber during the first fall may not exceed

12 kN and that the ropes have to hold a minimum number of twelve falls of a 80 kg mass falling without breakage. The breaking load of 12 kN is based on a humans ability to sustain serious injury beyond such loads. It appears that the compromise between supporting the load and not hurting the climber is well recognized in climbing but not in circus. More research on the subject for each circus discipline would help to define this compromise.

The maximal force measured of 5.3 kN was obtained with a quite advanced movement in straps ("giant circles"). Beginners would not do such movement, but they are able to do free falls in rope or silk and tempo in aerial hoop and dance trapeze. Free falls and tempo can generate very high forces (4.2 kN and 3.5 kN, respectively). Free fall execution by a beginner or an experienced performer is not different. For the free fall, the performer tends to fall from the largest amplitude, so the height of fall is the same for a beginner and an advanced. The results of this work shows that beginners can generate high forces. Circus equipment and the hanging points must be secured for recreational as well as professional use.

Limitations of the study

The present study was limited by the number and types of participants, circus apparatus and places in which measurements were done. It is acknowledged that the number of acrobats in each discipline was small. Measurements with circus professionals and children or other amateurs would allow extending the range of acrobats. One of the limitations comes from the morphology of the participants. The students of the National Circus School of Montréal have approximately the same shape and size: they all are small and quite fit. The heavier participant weighs 75 kg. Acrobats with different sizes and mass may give other ratio of the maximal force to the weight than the ratio found in the present study.

Another point which has not been considered is the influence of the learning process and performance environment. The participants were all students of the School and they continue learning new techniques during the measurements period. Second and third year students generated higher force than first year students, but they also generated lower force depending on the movement. In fact, advanced students know many more movements, or many more different type of movements that produce either higher or lower maximal force. It would be interesting to analyse how maximal force evolves during the learning process.

Also, the measurements were carried out at two locations only, including the Tohu, and with the circus and hanging equipment of the National Circus School of Montréal only. In addition, there is not a significant difference in maximal forces between show and training in rope, or with student ranking. More research is required to take into consideration the influence of the circus and hanging equipment or the hanging point.

Conclusion

It was found that aerial circus artists generated a tension force many times their bodyweight at the hanging point. An overall maximal force of 5.3 kN was measured in the straps discipline. This force represents 7.9 bodyweights, proving that the equipment and holding structure must support many times the weight of the acrobat.

With the data collected, minimal design requirement in rigging and apparatus is defined. Despite the different "design factors" recommended in the circus world for hanging or design purpose, a unique limit of the breaking strength can be considered. A minimal breaking strength of 22 kN for the hanging point is recommended. Similarly, a minimal breaking strength of 22 kN for straps, of 17 kN for rope, and 12 kN for silk, aerial hoop and dance trapeze is recommended. For each case, the value represents a real design factor of 4 with respect to the maximal force measured.

Depending on the discipline, maximal forces were generated with different types of movement. In dance trapeze, aerial hoop and straps, movements with swinging generated the highest force (tempo for dance trapeze and acrobatic movement for aerial hoop and straps), whereas free falls generated the highest force in rope and silk. It should be noted that free fall is easily done by beginners, so the proposed design guidelines must be applied for amateur as well as professional installation.

In conclusion, this paper has presented the first comprehensive measurements of the actual forces generated by circus artists on the rigs. The data collected in this work and the new proposed design guidelines should be used to make hanging and equipment design practice safer.

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Notes

1. Breaking strength considered for dance trapeze is that of the wire rope hanging the bar.
2. Breaking strength considered for aerial hoop is that of the wire rope hanging the bar.