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MAXIMAL DYNAMIC FORCES EXERTED BY ACROBATS ON NINE CIRCUS APPARATUSES

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La pratique du cirque est une activité très populaire pour laquelle peu de recherches en ingénierie ont été publiées. L'objectif de cette étude était de mesurer la tension maximale des câbles dans neuf disciplines de cirque: cerceau aérien, corde lisse, tissu aérien, mât pendulaire, fil de fer, mât chinois, trapèze ballant, trapèze fixe solo et duo. Les câbles de ces disciplines ont été instrumentés avec des cellules de charge et la tension a été enregistrée. Trente-quatre acrobates, professionnels et élèves d'écoles de cirque professionnelles, ont participé à l'étude et ont exécuté un total de 118 mouvements acrobatiques. Une analyse de la variance a déterminé les différences entre participants. Presque tous les mouvements et disciplines ont montré une différence statistiquement significative entre les participants. Les forces maximales ont été trouvées à 4.8 poids corporel en cerceau aérien, 7.3 fois le poids du corps en corde lisse, 5.6 fois le poids du corps en tissu aérien, 4.0 fois le poids du corps en mât pendulaire, 5.6 fois le poids du corps en trapèze ballant, 6.8 fois le poids du corps en trapèze fixe solo et 2.5 fois le poids du corps en trapèze fixe duo, et la tension maximale dans le câble a été trouvée à 15 kN dans le fil de fer et 2.8 kN dans le mât chinois. Ces résultats peuvent avoir des implications importantes pour la conception et le gréage acrobatique afin d'améliorer la sécurité des équipements de cirque.

Mots clés: gréage de cirque, acrobate, forces maximales, sécurité, charges dynamiques, facteur de conception

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Circus practice is a very popular activity that has had minimal engineering research published to date. The purpose of this study was to measure peak cable tension in nine circus disciplines: aerial hoop, rope, aerial silk, flying pole, tightwire, Chinese pole, swinging trapeze, and solo and duo fixed trapeze. Cables in these disciplines were instrumented with load cells, and tension force was recorded. Thirty-four acrobats, professionals and students from professional circus schools participated in the study and performed a total of 118 acrobatic movements. An analysis of variance determined differences in participants. Almost all movements and disciplines showed a statistically significant difference between participants. Maximal forces were found to be 4.8 BW (bodyweight) in aerial hoop, 7.3 BW in aerial rope, 5.6 BW in aerial silk, 4.0 BW in flying pole, 5.6 BW in swinging trapeze, 6.8 BW in solo fixed trapeze, 2.5 BW in duo fixed trapeze, and maximal tensions in cable were found to be 15 kN in tightwire and 2.8 kN in Chinese pole. These findings may provide substantial implications for acrobatic design and rigging to improve the safety of circus equipment.

Keywords: circus rigging, acrobat, maximal forces, safety, dynamic loads, design factor

Introduction

A report from the European Commission shows that there has been an increase in the number of circus companies and workers in this sector between 2003 and 2020, providing the figure of around 1,600–2,100 registered circus companies in 2020 in the European Union.¹ More locally, En Piste, an organization that brings together circus arts professionals and organizations in Canada, counts nearly 100 circus enterprises (companies, schools, social circus organizations and event diffusers) in Quebec² in 2020.

Circus injury patterns and rates have been investigated among professional artists,^{3–6} student artists^{7–9} and adolescents.¹⁰ Several longitudinal studies focused on the Cirque du Soleil company,⁴ National Institute of Circus Arts in Australia,⁷ National Center for Circus Arts in France⁸ and the Montréal Circus School.⁹ Although definitions of injury are inconsistent, equipment is mentioned as an external factor of injury.^{6,8,11}

The safety of acrobats is a major concern in the circus community as circus practice involves design and rigging of equipment that must withstand high loads.^{11,12} For example, the theme of this year's conference at the European Federation of Professional Circus Schools (FEDEC), a federation of 41 European and international professional circus schools, was "safety" to answer the needs of riggers in professional circus schools.¹³ Understanding the forces acrobats are likely to exert on the circus and rigging equipment is an essential

factor to ensure their safety. The American ANSI E1.43:2016 safety standard for entertainment technology provides guidance for the design, manufacture, use and maintenance of performer flying systems.¹⁴ While the standard is used for rigging, it explicitly excludes “any connection that ultimately relies on the strength or ability of the Flying Performer,”¹⁴ which is the case for most circus equipment. For example, the standard sets minimum design factors related to the working load limit (WLL), the characteristic load and the peak load for rigging. The WLL is described as “the maximum weight as defined by the Flying System Designer that a User is allowed to apply to a lifting medium in the performer flying system.”¹⁴ The characteristic load and the peak load are the maximum forces applied to the system resulting from normal use and abnormal use, respectively. However, with no data available on the characteristic load or the peak load, it is not possible for circus professionals to compute the proper target. Furthermore, rigging hardware used in circus could be sourced from many industries, including entertainment, climbing or industrial rigging. If equipment intended for one of these activities is to be repurposed for circus practice, it is crucial that the circus professional confirms that rigging will meet the specific mechanical demands to ensure the safety of the circus performer.

New circus equipment is frequently created, and professionals sometimes use a “dynamic factor” to estimate the actual force applied by the performer to safely design new equipment. There are no standard values for the dynamic factor, resulting in it falling in a range of 3–10 depending on the practice.^{15,16} In rigging, a design factor is applied between the dynamic force (static force × dynamic factor) or directly the static force and the maximum strength of the equipment.^{17–19} Other terms frequently used for the design factor are “safety factor” or “factor of safety.”^{20,21} In engineering design, a safety factor is applied to the dynamic force while designing a piece of equipment. It expresses how much more force the designed part will actually be able to withstand compared to the dynamic force.²²

To ensure that the rigging and circus equipment are strong enough to withstand the acrobatics, riggers and circus designers need knowledge about the actual forces that are applied to the equipment. Very few studies have investigated forces applied by circus acrobats on their equipment. In a previous study, we measured dynamic forces at the rigging points of five aerial circus apparatuses.¹⁵ These results led to safety and design recommendations to enhance circus practice and optimize circus equipment. However, circus disciplines are extremely diverse and not limited to these five aerial apparatuses, so more data is still needed. While disciplines such as rings in gymnastics,²³ slackline²⁴ and vertical jumps with acrobats²⁵ have been covered in the literature, a multitude of other disciplines in circus still need to be investigated. Therefore, the aims of

the present study were (1) to assess maximal forces generated by circus acrobats for various acrobatic figures on nine circus disciplines, that is, aerial hoop, rope, aerial silk, flying pole, tightwire, Chinese pole, swinging trapeze as well as solo and duo fixed trapeze, and (2) to evaluate the differences of maximal force between participants.

Methods

Thirty-four acrobats (19 females and 15 males; age: 27.1 ± 7.3 years; height: 1.71 ± 0.10 m; body mass: 61.5 ± 9.2 kg, including 23 professionals, with years of experience: 9.1 ± 4.5 years, and 11 students from professional circus schools) from nine circus disciplines gave their written informed consent to participate in this study. The project was approved by both the ethical research committees of Polytechnique Montréal and of the National Circus School of Montréal. The number of acrobats by discipline were as follows: five in aerial hoop, five in rope, two in silk, two in flying pole, four in tightwire, five in Chinese pole, four in (solo) swinging trapeze, three in solo fixed trapeze and two duos (4 acrobats) in duo fixed trapeze.

The tests took place at the National Circus School of Montréal. Circus equipment are detailed in Appendix 1. Specific dimension and location of load cells are presented in Figure 1. Three different types of load cells (LSB350–1,000 pounds (lbs), LCF455–2,000 lbs and LSB400–10,000 lbs; Futek, Irvine, US) were placed at the rigging points of the circus apparatus (Figure 1) and connected to one data acquisition chassis (cDAQ-9184 and cDAQ-9191; National Instruments, Austin, Texas, US). A VPN router (DSR-250; D-Link, Canada) linked the load cells and the Basler IP camera (Basler BIP2–1920c; National Instruments, Austin, Texas, US) to the computer (G750JS; Asus). The force data and the video files were saved on the computer with the help of a LabVIEW 2015 program (LabVIEW software; National Instruments). The sample rate of 2,000 hertz (Hz) was used for all load cells. A wide shot of the acrobat was recorded by a second camera on a tripod. The setup for single-point aerial disciplines (aerial hoop, rope, aerial silk and flying pole) was similar to our previous study,¹⁵ except that the emitter was replaced by a cDAQ-9191 Wi-Fi chassis connected to the router. Load calibration certificates provided by the supplier indicated the sensitivity value for all eight load cells (4 LCF455, 3 LSB350 and 1 LSB400). Before the test with participants, adjusted values of load cell sensitivity were obtained by a manual calibration using two calibrated masses of 45.4 kg and additional weightlifting disks, previously weighted, for a maximum mass of 295.6 kg.

All measurements for a given discipline were carried out under the same experimental conditions including equipment, rigging point and starting height

(in aerial rope or aerial silk). Before data collection, each participant warmed up with their own regular routine exercises for a duration of 10 to 20 minutes. Acrobats performed four figures that were repeated four to six times. The figures were selected beforehand by coaches from the circus school with two instructions: the figures selected should be considered classic or standard, which are perceived as generating high loads. However, even though standard figures were selected, circus acrobats aimed for a unique performance, and the result was a non-standardized technique. Consequently, some figures could not be performed by all acrobats from the same discipline. Additional acrobatic figures chosen by the acrobats were also recorded once or twice to test figures they considered to generate high loads. Participants could take as much rest time as needed between each figure. The participants wore their regular clothes or accessories as required for their disciplines, that is, their regular custom-made shoes with thin and flexible leather insoles in tightwire, long sleeves to avoid burns in Chinese pole and flying pole and gaiters in swinging trapeze. Missed repetitions were not included in the data analyzed. A total of 673 data sets were collected for 118 acrobatic figures.

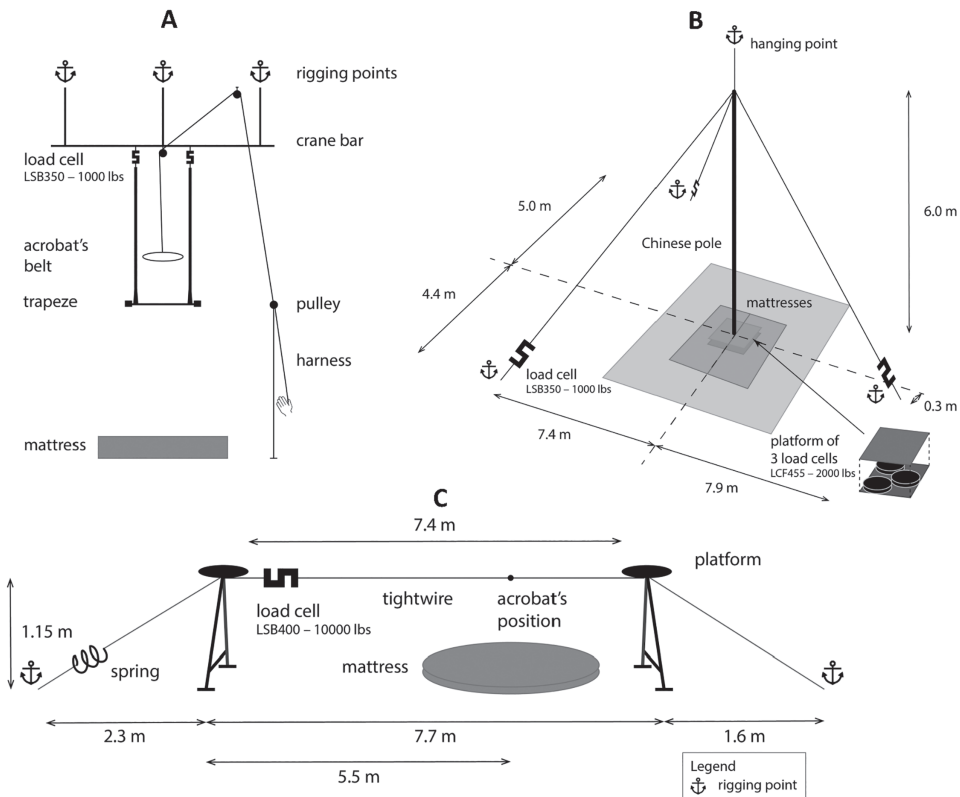


Figure 1. Setup for (A) trapeze; (B) Chinese pole and (C) tightwire.

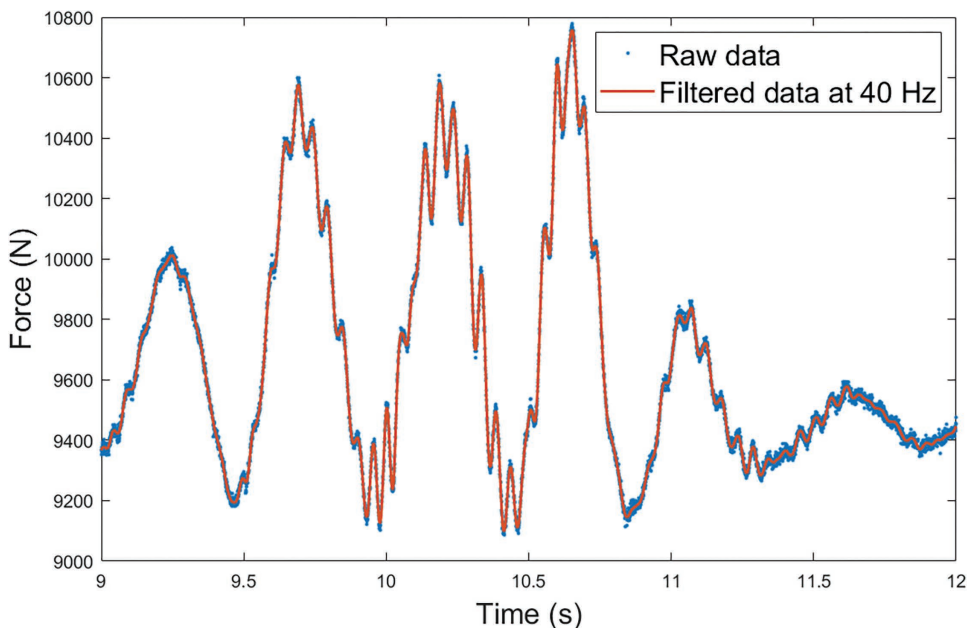


Figure 2. Raw and filtered force data for the movement “runs” in tightwire.

For the tightwire and the Chinese pole setups, the preload values in cables were included in the measurements. For the other setups, the circus equipment weight was excluded from the force measurements, as the load cells were tared once the setup was completed. A test protocol and a calculation were used to determine an equivalent vertical force expressed in bodyweight (BW) to the tension force in the cable in tightwire (Appendix 2).

Signal data was smoothed using a fourth-order low-pass Butterworth filter with a cut-off frequency of 40 Hz determined by residual analysis.²⁶ The filtering at 40 Hz did not over-smooth the data and was able to capture all the peaks in the force (Figure 2). Data analysis was done using a MATLAB script (MATLAB R2019a software; The MathWorks Inc., Natick, Massachusetts, US). For the three trapeze disciplines, force data was summed from both cables. For each trial, the maximal force was calculated and expressed in BW from the weight of the acrobat in all disciplines except Chinese pole. In duo fixed trapeze, the force was normalized in BW by the sum of the masses of the two acrobats. The forces in the three cables of the Chinese pole could not be calculated in BW because of the configuration.

In order to assess the differences among participants performing the same movement, one-way analysis of variance (ANOVA) was conducted to compare maximal forces. The statistical analysis was performed for each movement with a minimum of three participants who executed the movement at least four

times each. We kept six movements in tightwire, five movements in Chinese pole, three movements in aerial hoop and swinging trapeze and one movement in rope. When differences were detected, the Tukey test was used post hoc to identify specific differences between participants. The significance criterion was subjected to Bonferroni correction as $p < 0.05/n$, where n is the number of movements by disciplines. For example, significance was set at $p < 0.0025$ for the Chinese pole discipline because we conducted twenty analyses on this discipline (5 movements \times forces in the 3 cables and on the ground = 20). Shapiro–Wilk test was performed to check the normal distribution. All analyses were performed with the software R²⁷ and all graphs with the software MATLAB (MATLAB R2019a software; The MathWorks Inc.).

Results

Maximal forces

Table 1 shows the maximal force among all recorded trials. Higher maximal forces were generated in rope, solo fixed trapeze and tightwire disciplines, whereas lower maximal forces were found in duo fixed trapeze and flying pole disciplines (Table 1). The figure generating the highest force for each discipline is identified in Table 1.

In tightwire, the maximal force represented an increase of 65% with respect to the pretention load. For the Chinese pole discipline, an increase of 125% was observed in the load cells underneath the pole, as well as 58%, 72% and 47% in cables 1, 2 and 3, respectively.

Differences between participants

Figure 3 shows the result of the statistical analysis for the six movements in tightwire, five movements in Chinese pole, three movements in aerial hoop and swinging trapeze and one movement in rope selected for the study. Significant differences were found in all disciplines (Figure 3). The descriptions of movements in Figure 3 are presented in Table 2. Except for the slack drop in rope, the pirouette and front salto in Chinese pole, the movements that generated the maximal force presented in Table 1 were performed once by an acrobat or were not performed by enough participants to be included in the statistical analysis.

The ANOVA revealed a significant difference between participants in all movements involving jumps in tightwire except for the seat drop in the middle of the cable (Figure 3A). The “runs” movement (mean: 2.0 BW) was 2.7 times lower than the 4 jumps movement (mean: 5.5 BW).

Table 1. Maximal force measured for the nine circus disciplines and corresponding figures.

| Discipline | Maximum force (kN) | Maximum force (BW) | Pretension (kN) | Associated figure | Description of the figure |
|------------------------------|--------------------|--------------------|-----------------|----------------------------------|--|
| Aerial hoop | 3.1 | 4.8 | - | Drop hip circle to front balance | With hands placed on the top of the hoop, the artist begins tempos with the hoop in front of the hips. As the artist is in the front half of the tempo, they perform a backward roll around the bottom half of the hoop to finish in a front balance position. |
| Rope | 4.1 | 7.3 | - | Slack drop | The artist creates a knot with rope and releases slack to drop from one height to another. |
| Aerial silk | 3.0 | 5.6 | - | Slack drop | The artist creates a knot with silk and releases slack to drop from one height to another. |
| Flying pole | 1.7 | 4.0 | - | Bicep to back salto | From a position holding the pole with the bicep, the artist performs a back salto and returns to the pole. |
| Tightwire | 15.0 | 6.9 | 9.1 | Salto | The artist jumps and completes a full back salto prior to returning to the wire. |
| Chinese pole Underneath pole | -6.3 | - | -2.8 | Front salto | The artist performs a tempo to gain height, performs a front salto and catches the pole between their legs. |

(Continued)

Table 1. (Continued)

| Discipline | Maximum force (kN) | Maximum force (BW) | Pretension (kN) | Associated figure | Description of the figure |
|--------------------|---------------------------|---------------------------|------------------------|---------------------------------|---|
| Cable 1 | 1.9 | – | 1.2 | Pirouette | The artist completes a full rotation vertically in parallel to the pole prior to returning to the pole. |
| Cable 2 | 1.9 | – | 1.1 | Front salto | |
| Cable 3 | 2.8 | – | 1.9 | Front salto | |
| Swinging trapeze | 3.7 | 5.6 | – | Swing to ankles, ankles to seat | The artist drops from a standing position to catch the trapeze ropes on their ankles on the back half of the tempo and returns to a seated position on the next back tempo. |
| Solo fixed trapeze | 3.7 | 6.8 | – | Cross-back slack drop | The artist creates a knot through a cross-back pattern with the trapeze ropes and releases slack to drop from one height to another. |
| Duo fixed trapeze | 3.2 | 2.5 | – | Big tempo back salto | In a big tempo from a long hang position from hands, the flyer completes a full back salto and catches the porter in a long hang in the swing of the tempo. |

Maximal forces varied from 2.5 to 4.5 BW in aerial hoop for the three movements selected for the statistical analysis (Figure 3B). The ANOVA showed a significant difference between participants for all 3 movements selected in this discipline. Maximal forces ranged from 3.5 to 5 BW in swinging trapeze (Figure 3C). The results revealed significant differences only between participants for the movement involving jump. In aerial rope, participant 6 generated a mean of maximal force of 6.8 BW, whereas the mean of maximal force for participants 8, 9 and 10 combined was 4.2 BW.

The mean of maximal tension forces in cable 3 in Chinese pole presented in Figure 3F was 2.0 kN for a pretension of 1.9 kN. Forces in cable 3 were higher than that in cables 1 and 2 because of the positioning of the cables. The mean of maximal forces was 1.5 and 1.4 kN for a pretension of 1.2 and 1.1 kN for cables 1 and 2, respectively. The difference between pretension force and the mean of maximal forces is not high (maximum of 0.2 kN for cable 2). The difference between pretension force (-2.8 kN) and the mean of maximal forces (-4.6 kN) is higher (difference of 1.8 kN) for the compression force between the pole and the ground. Participants 19 and 23 generated higher compression loads (Figure 3G) compared to the other participants, whereas maximal forces were found with participant 22 for cables 1, 2 and 3 (Figures 3D, E and F).

Discussion

The main purpose of this study was to assess maximal forces in nine circus disciplines applied to rigging by acrobats performing a variety of movements. To our knowledge, our study is the first one to provide force data in swinging trapeze, fixed duo trapeze, fixed solo trapeze, Chinese pole and flying pole disciplines.

In our previous study, we found a maximal force of 5.7 BW in rope for free fall, which is lower than what we measured (7.3 BW).¹⁵ During a performance of backward long-swings, the peak tension measured in the rings cables was 8.5 BW, which is similar to what we obtained.²³ However, the backward long-swing in rings is very different from that in the rope discipline. The former involves the gymnast performing a backward rotation while maintaining a straight body, from handstand-to-handstand position, whereas for the slack drop, which is a free fall, the body remains vertical. In a previous study, we did not mention what kind of free fall we assessed.¹⁵ Slack drop is a common and relatively easy movement to execute and does not require active participation during the fall. Once the rope is set up, the only action needed is for the acrobat to let go, therefore, the only factor contributing should be the height of the fall and the mass of the acrobat (as the rope has little elasticity). It is then unexpected that one participant generated higher maximal forces than the three others. We tried to standardize

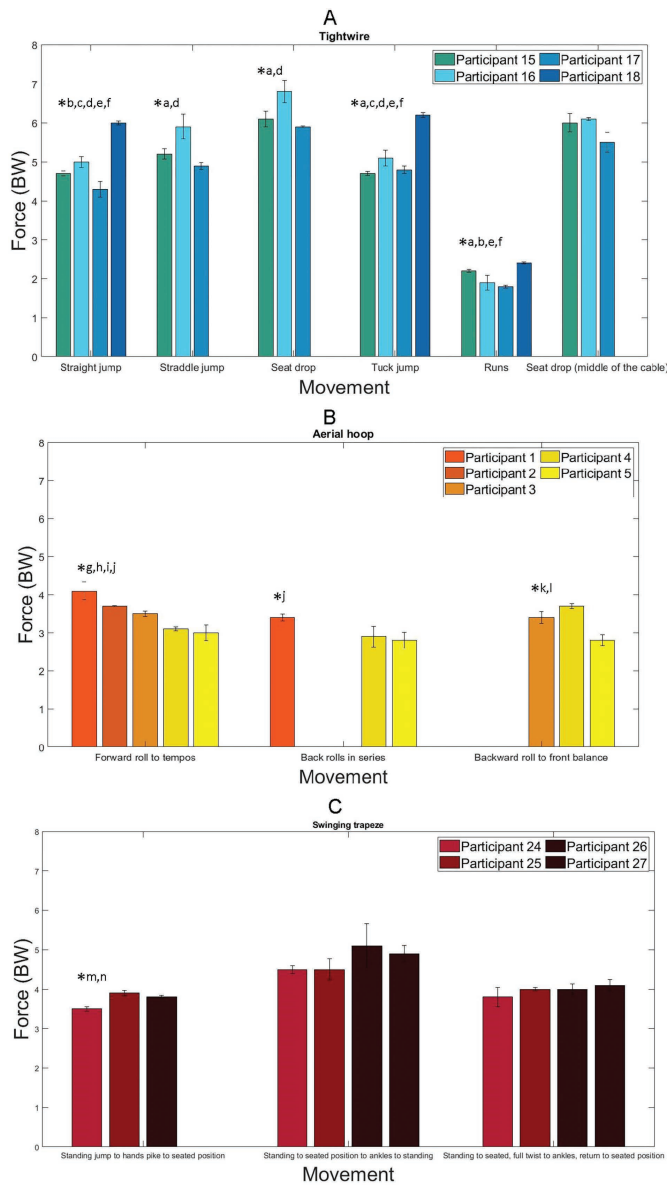


Figure 3. Mean and standard deviation of maximal force for the movements selected for the statistical analysis in (A) tightwire, (B) aerial hoop, (C) swinging trapeze, (D) Chinese pole—cable #1, (E) Chinese pole—cable #2, (F) Chinese pole—cable #3, (G) Chinese pole—compression force and (H) rope. *Significant difference ($p < 0.05/n$ with $n =$ number of movements per discipline) among movements. Post-hoc comparisons: significant differences ($p < 0.05$) between participant ^a15 and 16, ^b15 and 17, ^c15 and 18, ^d16 and 17, ^e16 and 18, ^f17 and 18, ^g1 and 2, ^h1 and 3, ⁱ1 and 4, ^j1 and 5, ^k3 and 5, ^l4 and 5, ^m24 and 25, ⁿ24 and 26, ^p19 and 20, ^q19 and 21, ^r19 and 22, ^s19 and 23, ^t20 and 21, ^u20 and 22, ^v20 and 23, ^w21 and 22, ^x21 and 23, ^y22 and 23, ^z6 and 8, ^{aa}6 and 9 and ^{ab}6 and 10.

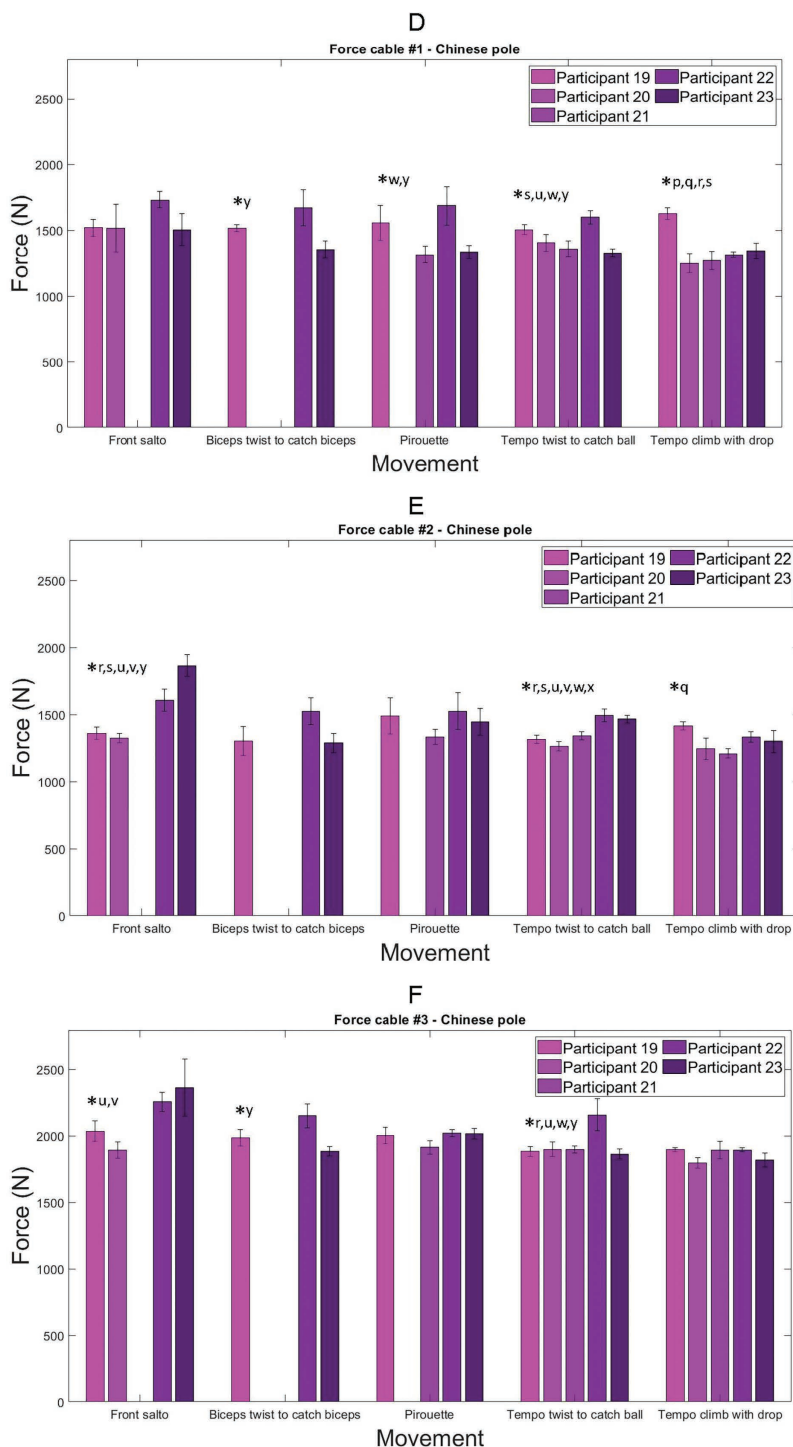


Figure 3. (Continued)

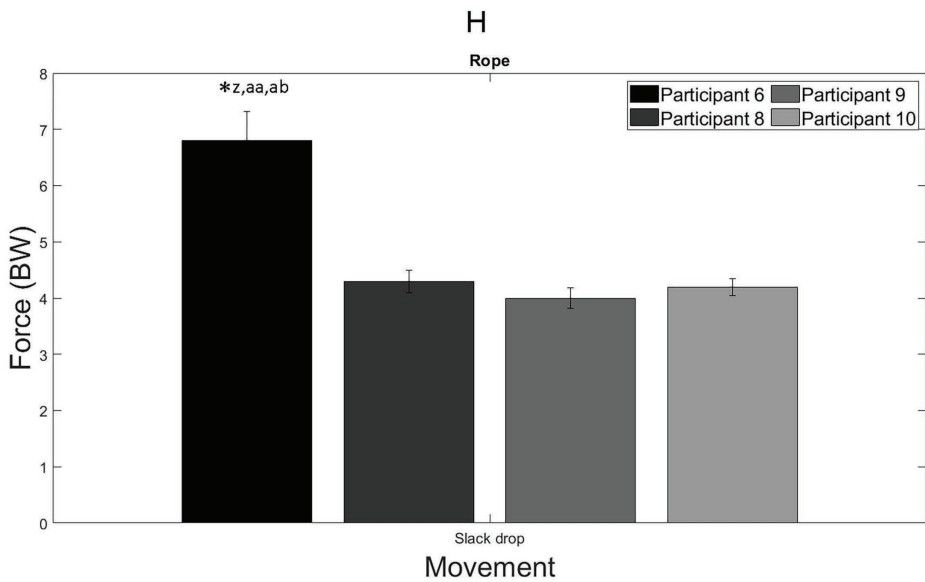
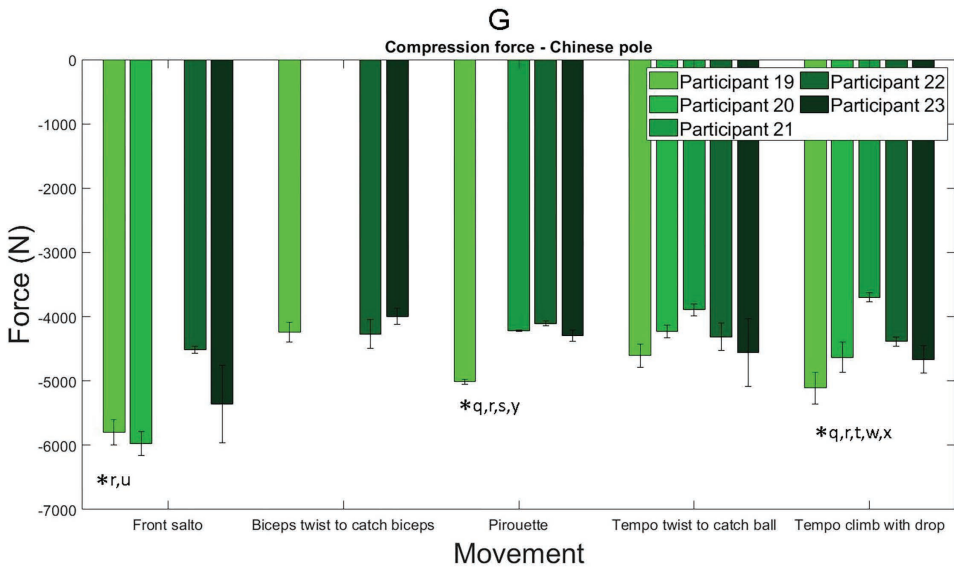


Figure 3. (Continued)

Table 2. Description of the movements presented in Figure 3.

| Movement | Discipline | Description |
|---|-------------------|--|
| Straight jump | Tightwire | The artist jumps with straight legs on the wire. |
| Straddle jump | Tightwire | The artist jumps with legs in a straddle position. |
| Seat drop | Tightwire | From a standing position, the artist drops to a seated position, rebounds from the seated position and returns to a balanced standing position. |
| Tuck jump | Tightwire | The artist jumps with legs in a tucked position. |
| Runs | Tightwire | The artist runs while balancing on the wire. |
| Forward roll to tempos | Aerial hoop | From a position inside the hoop, the artist places their hands on the lower half of the hoop, performs a forward roll and begins tempos underneath the hoop. |
| Back rolls in series (from elbows) | Aerial hoop | Placing the hoop behind the back, the artist holds the hoop in their elbows as they use the momentum of their legs to spin around the bottom half of the hoop. |
| Backward roll to front balance | Aerial hoop | With hands placed on the top of the hoop, the artist begins tempos with the hoop in front of the hips. As the artist is in the front half of the tempo, they perform a backward roll around the bottom half of the hoop to finish in a front balance position. |
| Standing jump to hands, pike to seated position | Swinging trapeze | The artist drops from a standing position to a position hanging from the arms on the front tempo, uses the next front tempo to invert in a pike position and returns to a seated position on the back tempo. |
| Standing to seated position to ankles to standing | Swinging trapeze | The artist drops to a seated position on the front tempo, with their ankles on the back tempo, and returns to standing on the following back tempo. |

(Continued)

Table 2. (Continued)

| Movement | Discipline | Description |
|---|-------------------|---|
| Standing to seated, full twist to ankles, return to seated position | Swinging trapeze | The artist drops to a seated position on the front tempo, performs a full twist and catches on their ankles in the back tempo and returns to a seated position on the following back tempo. |
| Front salto | Chinese pole | The artist performs a tempo to gain height, performs a front salto and catches the pole between their legs. |
| Biceps twist to catch biceps | Chinese pole | From a position holding the pole with the bicep, the artist performs full rotation horizontally toward the pole and catches the pole behind them with their elbows. |
| Pirouette | Chinese pole | The artist completes a full rotation vertically in parallel to the pole prior to returning to the pole. |
| Tempo twist to catch ball | Chinese pole | The artist performs a tempo, performs a full rotation horizontally and catches around the pole in a ball position. |
| Tempo climb with drop | Chinese pole | The artist climbs by jumping up the pole one leg at a time and drops. |
| Slack drop | Rope | The artist creates a knot with rope and releases slack to drop from one height to another. |

the technique used by all participants, but we observed on the video recordings that participant 6 had a higher drop height because they created a bigger knot with the rope.

The maximal force measured in aerial hoop was 4.8 BW which represents an increase of 41% in comparison to a previous study.¹⁵ We reported the maximal value for a movement called “circle around the bar” in which the acrobat, leaning on the bar, does a 360° rotation without losing contact with the bar. In the current study, the maximal force was generated with a movement called “drop hip circle to front balance,” which consists of beginning with tempos and performing a backward roll around the bottom half of the hoop to finish in a front balance position. The “drop hip circle to front balance” is a little more advanced movement than the “circle around the bar” because it is more dynamic, and there is a release and catch of the bar. In the previous study, the participants in aerial hoop did not perform very dynamic movements because they mostly performed contortion figures.¹⁵ In aerial silk, the force measured in our study (5.6 BW) represents an increase of 17% relative to our previous study.¹⁵ However, the silk used was not the same. The silk from Knitrama Fabrics Inc. in our previous study is known to be more elastic than the one in this study from Beau Fab Inc., and a more elastic silk helps absorb loads.

Although there is a tension force in the cables to maintain the verticality of the Chinese pole and to tighten the cable of the tightwire, maximal force can rise up to 72% from the pretension force. Pretension and maximal forces depend on the length of the cable and the preference of the acrobat. If the tightwire distance is longer, tension force would need to be higher to achieve the same tightness. Pretension in slackline was found not to exceed 7 kN,²⁴ whereas the pretension in our study was set at 9.1 kN. However, maximal force during vertical falls with a mass of 58 kg with leash lengths of 2 and 2.5 m was measured at approximately 14 kN in slackline,²⁴ which is similar to what we measured (15 kN). Two materials were tested in slackline, high-stretch nylon and low-stretch polyester, which are much more elastic than steel cable used in tightwire. A spring was inserted in the setup of the tightwire to absorb forces, as is normally the case, but if there were no spring, forces would considerably be higher. Professionals are encouraged to use a spring in tightwire as steel cable does not elongate much. If we consider the high force generated (15 kN), anchoring points must hold these forces so that the tightwire is secured. A linear regression was used to find an equivalent vertical force in BW. The relationship between added mass and tension force was found to be linear. One limitation is that the maximal mass used to find this relationship was 220 kg, so the relationship above 220 kg is unknown. However, as the cable is rigid, the overall mechanical system is expected to be linear. With regard to the Chinese pole, the asymmetry in the setup of the cables was reflected in the forces. Cable 3, which was isolated on one side, had higher force in pretension,

maximal force and mean of maximal force compared to cables 1 and 2. Forces under the pole reached a maximum of 6.3 kN. Riggers should be careful to consider maximal authorized punctual loads of the stage when installing a Chinese pole as the diameter of a pole creates a very centralized force load.

Flying pole and duo fixed trapeze generated the lowest forces. Flying pole is a more recently developed circus discipline,²⁸ and the performance is very different from other aerial disciplines. The fact that the pole is suspended in the air by one end makes it difficult for the acrobat to jump from it the way they did in traditional Chinese pole or to do free falls like in the other aerial disciplines. Given the kind of movements performed in flying pole, it is perhaps more surprising that a force of 4 BW was generated. Even in the bicep to back salto, the acrobat keeps contact with the pole with their biceps, so there is a support but not an impulse. Duo fixed trapeze is a very challenging discipline with dynamic movements. The reason for a low force measured in the cables compared to solo fixed trapeze is that the base (proximal) was in catcher's position, that is, they had the bar in front of their hips, wrapping legs around the outside of the ropes to create a lock behind their knees. In the catcher's position, the base was able to absorb a majority of forces from the flyer (distal). In fact, the force didn't transmit much to the cables but was instead absorbed by the shoulders of the base. Future studies may investigate the workload and the workload-injury relationship of the proximal acrobat.

The reasons to explain the difference in the mean of maximal forces between participants are not straightforward (Figure 3). Brewin et al.²³ highlighted the importance of the gymnast's technique and how it would potentially increase or decrease the peak force at the shoulders during backward long-swing in rings. Brewin et al.²³ claimed that if a gymnast uses a less proficient technique, they typically experience larger peak forces. In this study, almost all movements and disciplines apparatus showed a number of statistically significant inter-participant differences in cable loading. These between-participant variations may be attributed to underlying individual differences in body mechanics (strength, flexibility, coordination, smoothness, sequence of joint movements, technique, etc.) and demonstrate the potential benefits of including a larger number of participants in future circus studies. Future research could include kinematics to examine other factors that may influence forces in circus apparatuses.

The present study provided novel and valuable information, but a few limitations should be noted. Even though the current study used a small sample size per circus disciplines, the variety of movements recorded may be large enough to be representative of each discipline. Future research involving more repetitions per acrobat may generate more information on selected movements. It should be noted that the findings of this study cannot be expected to describe force production in acrobat of all levels or all sizes. We selected experienced artists who are

professionals or students from professional circus schools. In addition, this study did not address the ability of the musculoskeletal system to absorb energy upon impact or to generate high forces, even though muscular activity may modify forces. The data recorded does not necessarily represent the forces the acrobat is subjected to, but the knowledge of their magnitude could be valuable to assess the risk of injury, to adapt the training and to provide a safe environment.

Requiring acrobats to perform on inappropriate circus equipment, rigging equipment or structure may have safety implications. Design factor,^{14,17,18,19} dynamic factor^{15,16} or safety factor^{20,21,22} should reflect the real value of the force generated by the acrobat. Furthermore, the fact that there were statistical differences in dynamic loading as exhibited by many of the participants within many movements of the disciplines suggests that a larger sample size would permit to measure an even wider range in dynamic loading.

Conclusion

In summary, this is the first time that forces exerted in circus equipment are documented in swinging trapeze, duo fixed trapeze, solo fixed trapeze, Chinese pole and flying pole disciplines. Maximal forces were 4.8 BW in aerial hoop, 7.3 BW in aerial rope, 5.6 BW in aerial silk, 4.0 BW in flying pole, 5.6 BW in swinging trapeze, 6.8 BW in solo fixed trapeze and 2.5 BW in duo fixed trapeze. The maximal forces of 15 and 2.8 kN were recorded in the cable of the tightwire and in one of the cables of the Chinese pole with pretension forces of 9.1 and 1.9 kN, respectively. Ultimately, this wealth of information could be used as the basis for a recommended maximum user weight for each of the pieces of apparatus. It can help riggers and designers to make safe decisions when utilizing and fabricating circus equipment, as the ones presented in this study. However, riggers and designers should adapt their decisions to their situations, since each installation, performance and acrobat is unique. In addition, professionals need to be sure that the structure of the building can adequately support these forces. Quantification of maximal forces exerted in circus apparatuses involving high-level acrobatics potentially gives coaches and acrobats the knowledge of the performance skills and may help to develop training goals. Future research should focus on the relationship between technique through kinematics and peak forces.

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Appendix 1 – Circus apparatuses and equipment used for the data collection

The apparatuses were from the National Circus School. The trapezes, aerial hoop, Chinese pole, flying pole and tightwire were custom-made, whereas the aerial silk and rope were bought from circus equipment suppliers. The trapezes were made of a solid stainless-steel bar that was 2.2 cm in diameter and 87 cm, 73 cm and 1.25 m in length, for the swinging trapeze, the solo fixed trapeze, and the duo fixed trapeze disciplines, respectively. The trapezes were suspended by 2 wire ropes 4.8 mm in diameter. The wire rope was braided in cotton rope to avoid any potential injury to the artists' hands. The length of the cables in swinging trapeze is crucial for the timing in performance; therefore, the cables were shortened to 3.77 m to place the load cells and have the adequate total length (Figure 1). The bar was taped so that the artist does not touch the metal. Additional weights of 5.4 kg were mounted at each end of the bar for higher stability. A coach specialized in swinging trapeze from the National Circus School operated the safety system. The acrobat was attached to the system via a "twisting belt" (a belt that allows twisting movement) that was connected to a rope called the tether. The tether passed through pulleys on the crane bar and the ceiling (Figure 1A) so that the coach can attempt to assist or stop the movement of the acrobat by exerting a load on the tether in the case of a missed movement. The solo and duo fixed trapeze did not require the safety tether, but a high mattress was placed underneath to ensure safety. The aerial hoop had a circle diameter of 95.3 cm and was made of a bent solid stainless-steel bar 2.3 cm in diameter. Similar to trapezes, it was attached by wire rope braid in cotton rope, and the bar was taped. The aerial silk was a 9.14-m piece of nylon fabric folded in half along the width (Beau Fab Inc., Montreal, Canada). The aerial rope was made of cotton 3 cm in diameter and 10 m in length with a cotton cover (Circus Concept, Sherbrooke, Canada). The Chinese pole was made of a steel pipe 6.1 m in length and 4.8 cm in diameter, covered with neoprene fused to the pipe to improve grip. Chinese poles are normally held by 3 cables spaced equally in a circle around the pole; in our case, the 3 cables were not spaced equally due to space limitations (Figure 1). Short ratchet straps were placed on the cables to adjust the tension of the cables. Tension was set by the riggers (circus technicians) of the National Circus School as they usually do. The tension balances the static forces on the pole to put it vertically. Flying pole consisted of a suspended steel pipe 4.9 m in length and 4.1 cm in diameter, also covered in neoprene. Tightwire was composed of a non-rotating steel cable of 1.3 cm diameter. Tension was acquired with a tirfor which is a manual cable puller (Tirfor, Tractel®, Montreal, Canada), and a spring on the cable allowed a better absorption of impacts. One participant also performed a few movements of higher technical difficulty on a lower tightwire, 55 cm high instead of 1.15 m in Figure 1, for safety reasons.

Appendix 2— Test protocol and calculation of the equivalent vertical force in tightwire

To determine a force, equivalent to the vertical force generated by the acrobat in tightwire, a static test was carried out. Weightlifting disks were suspended progressively at both foot locations of the cable, in the middle and at two-thirds of the length, where acrobats performed the movements. The masses produced incremental loads up to a maximum of 220 kg, while the load cell recorded the equivalent tension force in the cable. The relationship between the force recorded in the cable and the vertical loads was found to be linear on the basis of 5 points ($R^2 = 0.99$). A linear regression relationship was then used to calculate the vertical force data as a function of the force in the cable to find the equivalent maximum force generated by acrobats.