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Measurement of the Impact Loads to Reduce Injuries in Acrobatic Gymnasts: Designing a Dedicated Platform

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Abstract: Background: The main objective of this study was the development of a specific load platform that would meet the needs of gymnasts and acrobatic coaches. This new platform has larger dimensions and is an identical structure to the plywood floor surface normally used; it was designed to make competitions with gymnasts safer and more like a real training situation. During a landing, there is high body stiffness, especially in the knees and ankles, which can cause injuries due to the number of repetitions performed in this gymnastics specialty. **Methods:** A group of 10 volunteers, with a mean age of 14.7 ± 2.4 years, performed at least 10 valid vertical jumps on each platform. **Results:** Despite being a preliminary study, this specific platform was shown to be more suitable for gymnastic use, compared to the industrial one, which represents a significant advantage for the modality. In fact, this platform is similar to the surface used for training and competition, allowing athletes to perform the jump in a similar way, and for the results to be replicable during the practice of the sport. The standard deviation values were lower, which shows that the new platform was more suitable for acrobatic gymnastics. **Conclusions:** As the maximum vertical load induced during landing after a jump has a significant effect on the likelihood of gymnasts suffering injuries, the development of a new load platform specifically for acrobatic gymnastics is clearly an improvement in this discipline. Knowledge of the load transmitted to the body can help coaches and athletes in defining training, and avoiding the possible occurrence of injuries. Therefore, it is necessary to use a platform that can accurately evaluate the load transmitted to the acrobatic gymnasts during real training and competition conditions, which is achieved with this new platform.

Keywords: sensors; load platform; ground landing; acrobatic gymnasts; sports



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1. Introduction

Acrobatic gymnastics is a sport that includes physical exercises requiring balance, strength, flexibility, agility, coordination, and endurance, having started in the 17th century with the creation of the circus [1]. Acrobatic gymnastics is performed to the sound of music and on a 12×12 m practicable. In official competitions, acrobatic gymnastics offers five different possibilities for partnerships: male, female, and mixed pairs; women's groups (three gymnasts), and men's groups (four gymnasts) [2]. Due to the high number of jumps, there is constant and repetitive landing contact with the practicable, sometimes made from a significant height, and, consequently, the possibility of gymnasts suffering injuries [3], especially in the lower limbs, is considerable [4–6].

Assessing the loads involved during landings is very important to improve the athlete's performance, help coaches develop landing techniques, and, consequently, reduce injuries [7]. During the landing phase, due to the impact on the surface, differences were observed in the knee and quartile that are directly linked to the reaction force [8].

According to Slater et al. [9], the high-impact forces that arise in athletes' lower limbs during gymnastics landings contribute to the high injury rate. However, it is not just injuries to the lower limbs that can occur during landings; injuries to the lumbar spine of gymnasts are also very common, due to the rotation of the spine during the flexion and extension of the lower limbs [10]. Penitente et al. [11] conducted a study to determine the effect of impact on the average rate of loading during a forward hop jump. The vertical load of impact during the jump was characterized using the peak load, time to peak, and impulse. The performance of gymnasts is related to their jumping ability, the form of landing, and their jumping routines [12]. The high number of jumps they perform, which involves repeated stretching–shortening cycles of the muscles, can produce muscle fatigue of the lower limbs and lead to injuries [13–15]. According to Martínez-Martí et al. [16], the vertical jump can provide important information that can be used to analyze the muscular fatigue that happens during vertical jumps in acrobatic gymnastics. The ankle power and the ground reaction load reduce with fatigue, due to the fact that fatigue affects ankle biomechanics by reducing dorsiflexion, from initial contact to maximum knee flexion at landing, and power during the jump [17]. The main injuries in gymnasts occur in the lower extremities (42.3%), namely in knees (16.6%) and heels (12.9%) [18–20]. Therefore, understanding how the gymnasts perform landing is important for injury prevention. The identification of training routines and landing movement patterns that may be a risk factor for injury can help advise on how to change landing movements or training routines in order to prevent or eliminate the possibility of injury [21]. The high vertical impact loads on the lower limbs during landing, due to repetitive exposure, are one of the main injury factors. This probability of injury occurring can be reduced if gymnasts are instructed and trained in landing techniques [22,23]. According to Christoforidou et al. [24], to avoid injuries during landing, it is necessary to define the landing strategy considering the vertical reaction of the ground loads and shorter braking phase during the landing. In addition, jump heights have a great influence on landing forces, especially the ones developed by the muscles of the lower limbs. To reduce the possibility of injury, gymnasts are usually trained to land with stiff lower limbs, shortening the braking phase [22,25]. According to Wu et al. [26], landing is a crucial factor in gymnastics competitions because it is a complex movement under neuromuscular control, involving space–time prediction of the moment of contact with the ground, as well as the magnitude of the vertical ground reaction force being dependent on the gymnast's body weight. The landing should be performed to safely reduce all body moment to zero, which can be done with simultaneous placement of both feet on the ground [27].

There are several studies, including reviews, which have found that the landing load induced in gymnastics has a great influence on the possibility of injuries in athletes, in addition to being able to alter gymnasts' performance [28,29]. The loading platform is one of the most common tools in the analysis of reaction forces during human movement [30]. It is used both for sports performance analysis and for studying the behavior of patients suffering from some pathology, with a focus on health improvement [31]. This device allows the measurement of the action/reaction load exerted on the platform [32], which can help a sports coach to quantitatively evaluate the athlete's performance [33].

The number of repetitions of the exercises and the number of hours of training cause various injuries. To avoid injuries, it is important to identify the forces involved in each jump by trying to replicate the jumps performed in a training session. The need to evaluate the forces induced in the lower limbs during sports has led several researchers to try to develop a force platform adapted to the specific objective [34,35]. After studying what existed on the market, they did not identify any platform with the required dimensions. Thus, due to the specificity of acrobatic gymnastics, the coaches asked us to develop a platform with dimensions defined by them. Thus, the aim of this study was to build a platform that is a replica of a gymnastics federation-approved practice surface and allows for force values when making the jump. The development of a platform with a similar landing surface is very important because, according to Grapton et al. [36], specific injuries

can result from falls and incomplete landing, which may also depend on the type of landing surface.

This work uses two load platforms, one commercial, and one specific in-house-built, to measure the vertical landing load of acrobatic gymnasts when landing after a specific jump in acrobatic gymnastics. As is known, landing is a common athletic activity in the practice of gymnastics, which can induce impact forces with a magnitude of 2 to 12 times the body weight, often inducing injuries in the lower limbs. According to Vernetta-Santana et al. [10], the highest percentage of injuries in acrobatic gymnastics occurred in the lower limbs, mainly due to the landing. Thus, it is important to identify the impact forces on athletes during landings in order to define strategies to reduce the probability of occurrence of injuries. Due to the specificity of this sport and the likely landing area of the athletes, it is necessary, for the correct assessment of the forces transmitted to the athletes' lower limbs, to use a force platform that can replicate exactly what happens during training sessions and competitions; thus arose the challenge posed by athletes and coaches for the authors to develop this specific platform. Therefore, the development of a platform that can correctly assess these forces is clearly an asset for athletes and coaches to protect athletes' health.

Therefore, the main goal of this study was the development of a load platform that would respond to the needs of gymnasts and coaches by identifying the forces exerted by the lower limbs, together with the way landing was performed. The intention is, by evaluating the landing load values, as well as the type of landing in terms of foot position at the moment of the first contact with the ground, to help athletes and coaches define training strategies to eliminate, or reduce, the risk of injury, specifically, as referred before, in the lower limbs, namely muscle and ligament injuries, as the most frequent.

2. Materials and Methods

2.1. Participants

Ten acrobatic gymnasts (eight females and two males) with 3 to 8 years of acrobatic gymnastics practice participated in the study. Table 1 shows the volunteers' age and anthropometric characteristics (body height and body mass), together with the mean and standard deviation (SD). The study was performed according to the Declaration of Helsinki, revised in 2013, and was approved by the ethics committee for the organic unit. All the participants are anonymous, and the personal data is confidential. They were fully informed of the nature of the study and gave written informed consent or, in the case of minors, their legal representatives signed the consent.

Table 1. Acrobatic gymnasts' anthropometric characteristics.

Athlete	Age (Years)	Body Height (cm)	Body Mass (kg)	Practice of Gymnastics (Years)	Gender
1	12	140	31.0	3	Female
2	13	146	41.8	5	Female
3	12	142	32.8	4	Female
4	12	147	35.1	4	Male
5	18	173	61.2	8	Male
6	14	150	38.4	5	Female
7	14	149	40.2	5	Female
8	17	153	43.2	4	Female
9	17	148	41.0	5	Female
10	18	158	57.8	8	Female
Mean ± SD	14.7 ± 2.4	150.6 ± 9.4	42.2 ± 9.4		-

2.2. Study Design

Each gymnast performed 10 valid vertical jumps, on each platform, in order to guarantee the test repeatability, which corresponds to a total of 100 valid tests.

At the beginning of this study, data acquisition was performed on a commercial platform to provide a reference and quantify the forces involved in jumping. This data acquisition was performed using a piezoelectric load platform, a Kistler model 2812A, with dimensions of 60×40 cm and a load capacity of 8 kN, Figure 1. The data obtained, using the BioWare version 4.0 software, were the loads in 3 directions, X, Y, and Z. The Kistler load platform was calibrated and programmed for a 5 s acquisition at 100 Hz.

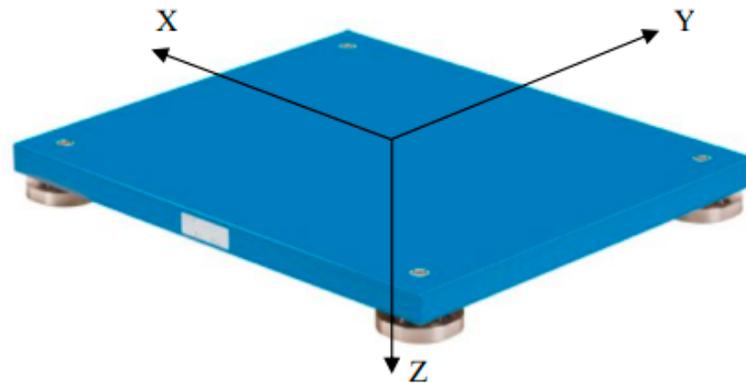


Figure 1. Kistler platform [<https://www.noraxon.com>, accessed on 10 July 2023].

The commercial load platform has some drawbacks for gymnastics use. In addition to the dimensions being quite small, the structure is metallic, which is a surface too rigid for the landings of acrobatic jumps, compared with the usual gymnastics practicable. Thus, coaches and gymnasts are not comfortable or feel safe using these platforms. Therefore, a new specific in-house platform was developed and proposed, which evaluates the vertical loads during the athlete's contact with the ground and is therefore more suitable for gymnasts.

A specific platform, 80×80 cm with a thickness of 15 cm, was proposed by the authors. This specific platform is an extensometric load platform that has, between the plates, load sensors (load cells, of single-point type, with electrical sensitivity of $1.0 (\pm 0.1)$ mV/V) based on strain gauges, which provide electrical signals relative to the applied loads. The top plate of the load platform must have the maximum possible rigidity combined with the minimum mass. The high rigidity required aims to reduce the bending of the surface during the use of the platform, guaranteeing a practically total transmission of the effort received on the surface to the force sensors. Plywood was used for the top plate of the platform since gymnastics practicable in normal practice are also made up of plates of this material (Figure 2). For this, four single-point load cells were used (Figure 3). The load cells were fixed with four screws in the top plate and in the base.

Data collection from this specific platform was carried out using PicoScope 6 software and a digital oscilloscope, with the platform system connected to the four cells of the load/oscilloscope on a Vishay Measurements Group strain gauge bridge, the SB-10 Switch and Balance Unit, Model: SB-10. With this specific platform, it is possible to quantify the vertical load of ground reaction developed during landing, which can be compared with that obtained by the commercial platform. The load exerted on the platform creates a deformation in the plate that is transmitted to the load cell. This deformation creates a voltage variation, which is interpreted by strain gauges, generating an electrical voltage level corresponding to the load. The operation of a load cell on a load platform is schematized in Figure 4.

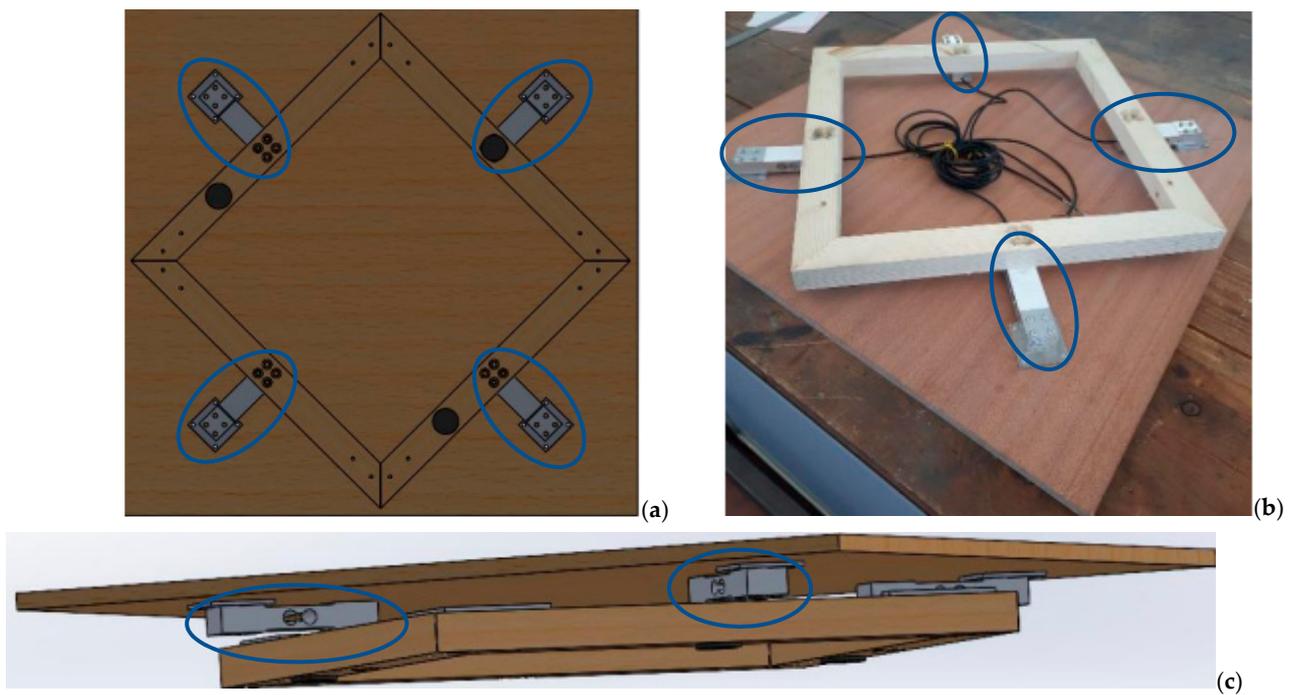


Figure 2. New platform: (a) schematic bottom view, CAD design; (b) real bottom-view model; (c) lateral view, CAD design.

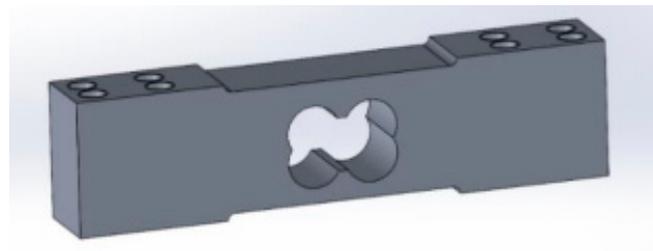


Figure 3. Single-point load cell.

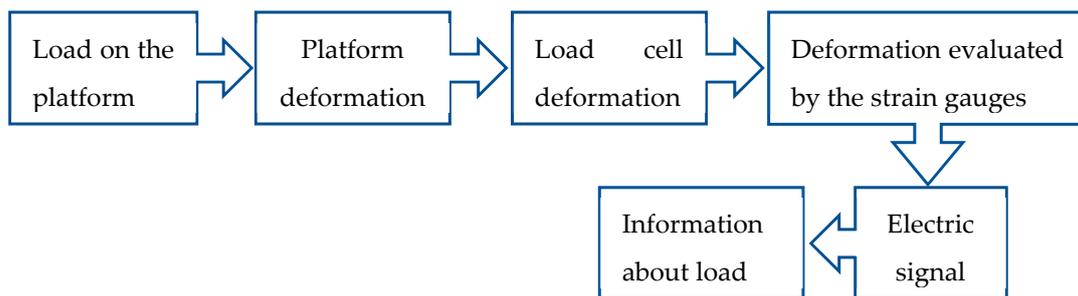


Figure 4. Operation of a load cell on a load platform.

For the calibration of the proposed platform, the load cells were initially calibrated individually. After that, the calibration was performed considering the four cells of the platform. For this calibration, known weights were used. The time interval for which the signal obtained was constant was analyzed (Figure 5) and represents the stabilization of the platform. According to the calibration results, it was concluded that 1 mV corresponds to 3.50 N of load.

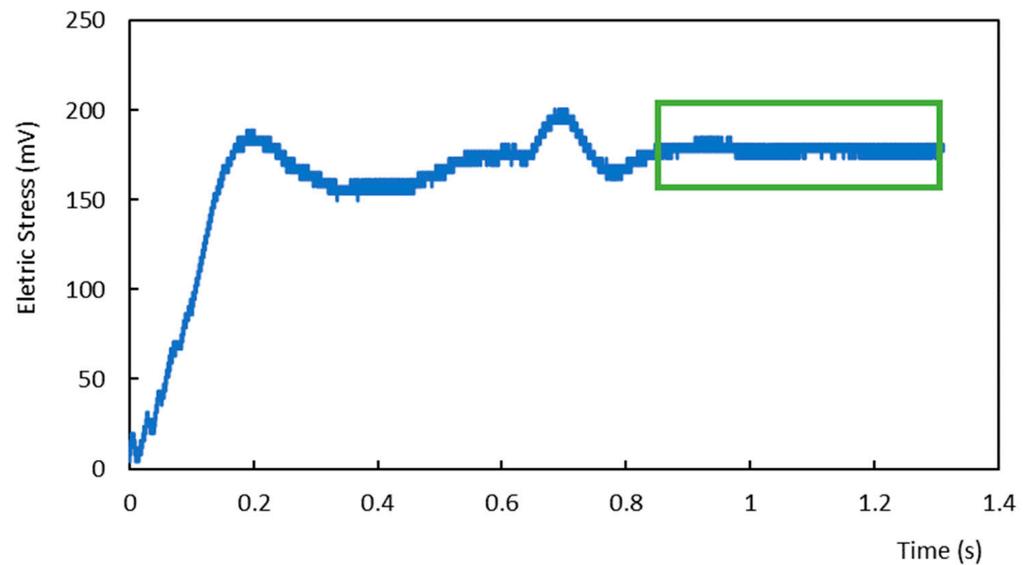


Figure 5. Example of calibration test for the in-house-built platform.

For both platforms, jumps were counted whenever their landings coincided with the zone corresponding to the load platform. The jumps and respective landings were filmed using two video cameras, one Sony (camera C1) and one Canon (camera C2), each with an acquisition frequency of 100 Hz (Figure 6).

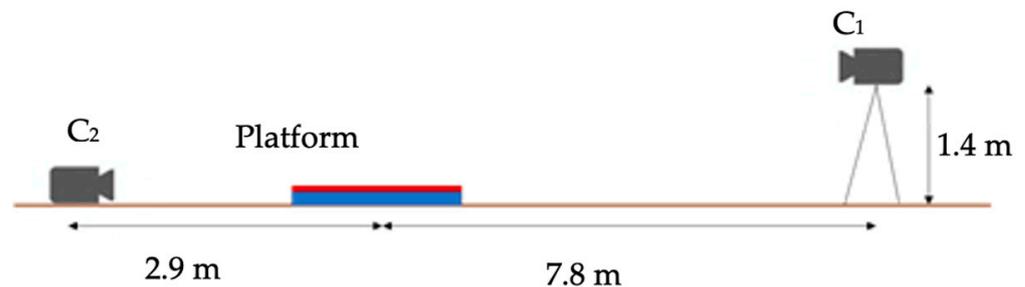


Figure 6. Test setup diagram.

Before the jumps were performed, the cameras were calibrated and positioned relative to the platform position allowing the initial jump calibration data to be obtained. The objective of camera C1 was to obtain the maximum height of the jump (Figure 7), and the main goal of camera C2 was to obtain images of the maximum flexion of the knees of the gymnasts (Figure 8) and to characterize the landing. The foot position at landing (first image of ground contact) of the gymnasts (on the forefoot, midfoot, or rearfoot) was evaluated (Figure 9). The way landing is performed, mainly by the lower limb joints, can have a direct influence on a greater or lesser predisposition to injury occurrence. It was considered that the maximum flexion of the knees occurred when the position of the greater trochanter was the closest to the ground (Figure 8). Tracker software (Open Source Physics—Video Analysis and Modeling Tool—5.1.5) was used to extract the values of the maximum height of the jumps, using the gymnast's heel as a reference, and also the distance of the greater trochanter to the ground. The calibration was performed according to the software instructions and using a reference rectangle (3×2 m) aligned with the sagittal plane of motion. The method of Direct Linear Transformation (DLT) allowed the transformation of 2D virtual coordinates to real coordinates.

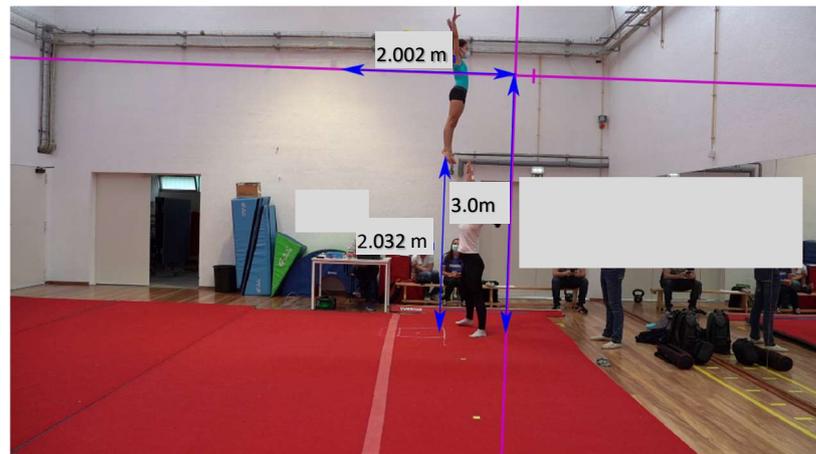


Figure 7. Determining maximum jump height.

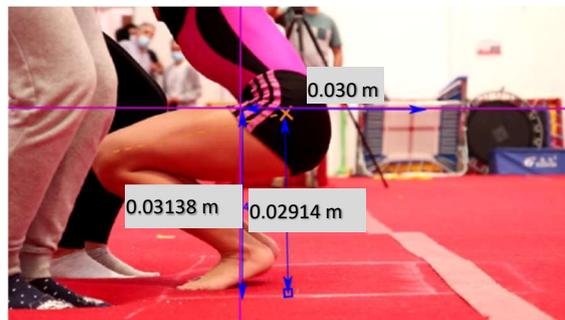


Figure 8. Maximum flexion of the knees.



Figure 9. Foot position on the landing of the gymnasts: (a) forefoot; and (b) midfoot.

To understand the relationship between the maximum vertical load and the form of landing, the ratio between the maximum vertical load on landing and the weight of the gymnast was computed (Equation (1)).

$$\text{Ratio} = \frac{\text{MaximumLoad}(N)}{\text{GymnastWeight}(N)} \quad (1)$$

2.3. Statistical Analysis Methods

The data were analyzed using Statistical Package for Social Science (SPSS) software 25.0 (IBM Corporation, Armonk, NY, USA), considering a significance level of 0.05 to identify statistical differences. The Student's *t*-test was computed to compare the performance of the gymnasts considering the foot positions at landing. The Pearson correlation was used to analyze the correlation between the variables (peak vertical force with maximum jump height, reception duration, momentum, distance from the greater trochanter to the ground, and weight).

3. Results

The variables under analysis, which vary by the platform used, are the maximum vertical load, the time of contact with the ground, and the ratio between the gymnasts' weight and the maximum vertical load. The position of the foot on landing, the distance of the greater trochanter to the ground, and the maximum height during the jump are important variables in this jump; however, they are not measurable with this platform, and they are different between gymnasts.

Figures 10 and 11 show an example of load versus time curves for the commercial and specific platforms, respectively, considering the same gymnast, which is representative of everyone else.

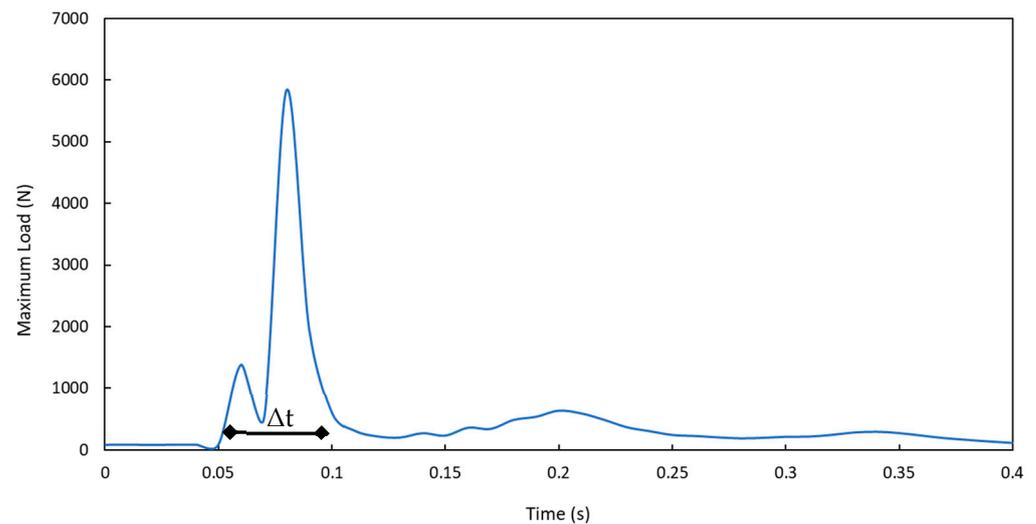


Figure 10. Maximum vertical load versus time for the commercial platform.

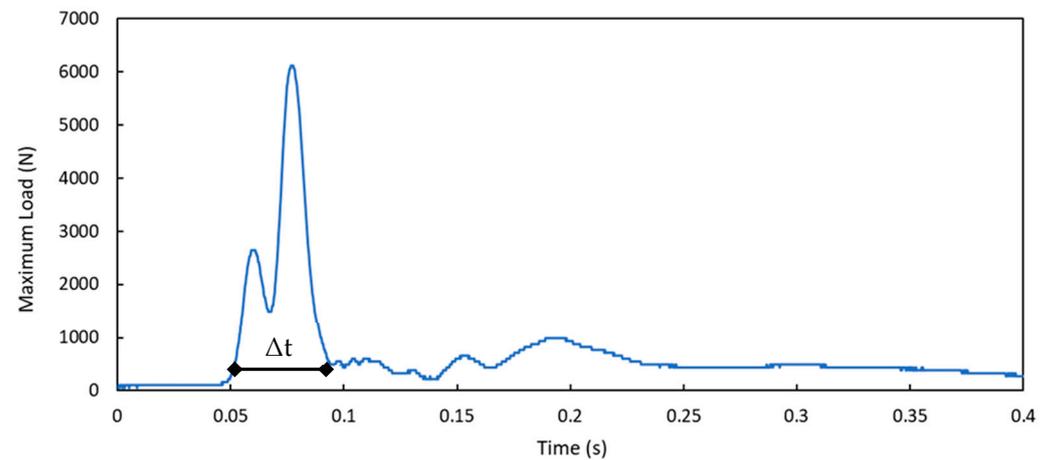


Figure 11. Maximum vertical load versus time for the specific in-house-built platform.

The mean and standard deviation ($\bar{X} \pm SD$) of the values of maximum vertical load and contact time, assessed using the commercial and the specific in-house-built platform, are presented in Table 2. Table 3 shows the values of the maximum height reached during the specific acrobatic jump analyzed, the position of the foot at the first contact with the ground at landing, and the minimum distance from the greater trochanter to the ground reached during the landing phase of the jump, independent of the type of platform used and only dependent on the gymnast's characteristics.

Table 2. Mean and standard deviation ($\bar{X} \pm SD$) for the maximum load and the contact time during landing after a specific acrobatic jump.

Gymnast	Max. Load (N) CP $\bar{X} \pm SD$	Max. Load (N) NP $\bar{X} \pm SD$	Cont. T (s) CP $\bar{X} \pm SD$	Cont. T (s) NP $\bar{X} \pm SD$
1	3647 ± 793	4092 ± 542	0.07 ± 0.01	0.07 ± 0.01
2	4451 ± 851	5363 ± 429	0.09 ± 0.01	0.08 ± 0.01
3	4283 ± 534	5178 ± 495	0.06 ± 0.01	0.06 ± 0.01
4	6287 ± 947	7041 ± 875	0.09 ± 0.01	0.08 ± 0.01
5	8213 ± 1335	9527 ± 983	0.08 ± 0.01	0.08 ± 0.01
6	6172 ± 684	7221 ± 672	0.07 ± 0.01	0.07 ± 0.01
7	6084 ± 1347	6936 ± 537	0.07 ± 0.01	0.06 ± 0.01
8	4885 ± 318	5813 ± 963	0.09 ± 0.01	0.09 ± 0.01
9	5884 ± 920	6707 ± 564	0.08 ± 0.01	0.08 ± 0.01
10	6085 ± 1553	6897 ± 581	0.09 ± 0.02	0.09 ± 0.02

CP—Commercial platform; NP—New platform; Max. Load—Maximum load; Cont. T—Contact time.

Table 3. Mean and standard deviation ($\bar{X} \pm SD$) for the maximum height, the position of the foot on landing, and the minimum distance from the greater trochanter to the ground during the landing phase (Dist.)

Gymnast	Max. Height (cm) $\bar{X} \pm SD$	Position of the Foot at the Landing	Dist. (cm) $\bar{X} \pm SD$
1	206 ± 40	Forefoot	26.35 ± 3.98
2	205 ± 40	Forefoot	46.20 ± 4.40
3	246 ± 70	Forefoot	30.12 ± 3.96
4	264 ± 50	Midfoot	30.20 ± 4.35
5	230 ± 80	Midfoot	30.70 ± 7.16
6	237 ± 40	Midfoot	37.30 ± 2.78
7	222 ± 40	Midfoot	38.90 ± 4.91
8	255 ± 80	Forefoot	40.10 ± 0.94
9	213 ± 30	Midfoot	32.20 ± 0.01
10	219 ± 60	Midfoot	39.10 ± 3.01

Figure 12 presents the maximum vertical load for each platform (CP—commercial platform; NP—new specific platform, in-house-built) by gymnast (n = 10) considering the position of the foot on landing. Table 4 shows the comparison between the maximum vertical load obtained by both platforms and the gymnast’s weight, according to Equation (1). Figure 13 shows the linear relationship between the load obtained for the two platforms.

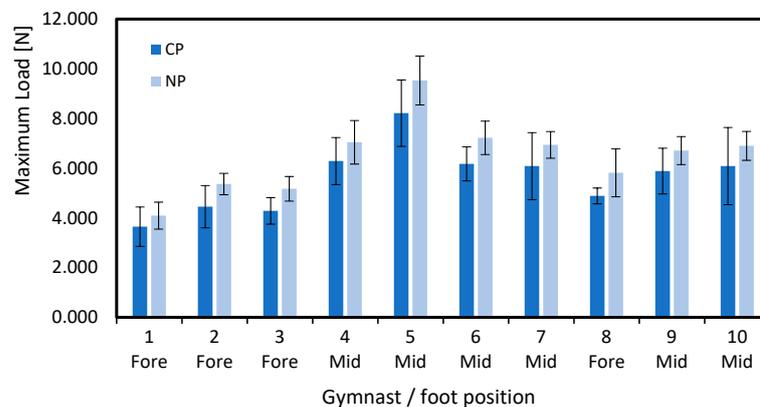
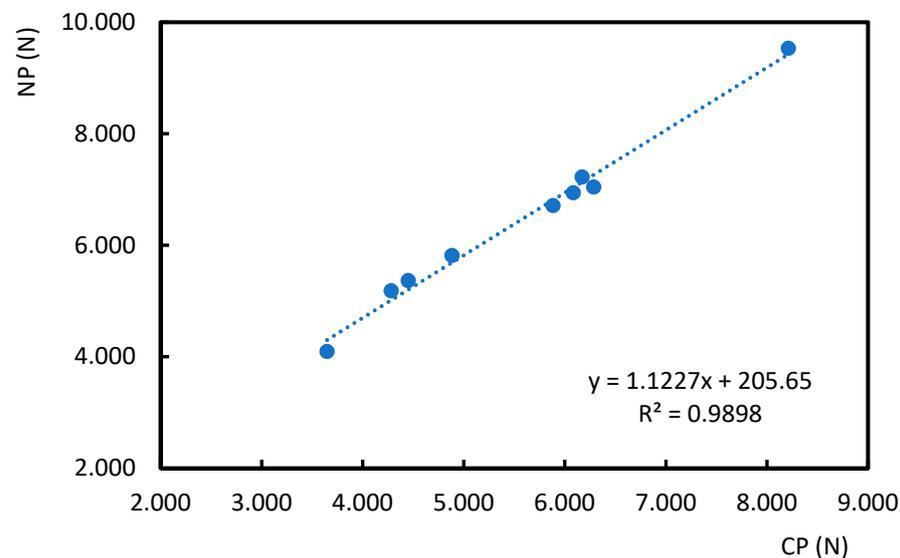


Figure 12. Maximum vertical load and the foot position on landing.

Table 4. Ratio (Equation (1)) for both platforms.

Gymnast	Ratio CP	Ratio NP
1	11.99	13.46
2	10.85	13.08
3	13.31	16.09
4	18.26	20.45
5	13.68	15.87
6	16.38	19.17
7	15.43	17.59
8	11.53	13.72
9	14.63	16.68
10	10.73	12.16

CP—Commercial platform; NP—New platform.

**Figure 13.** Linear relationship between the two platforms.

4. Discussion

The purpose of this study was to build a platform with a similar surface to that used in training practice to allow measuring the forces performed in a high jump. This way, all the results could be compared with the results obtained on the commercial platform to validate the new platform.

By comparing Figures 10 and 11, it can be observed that the curves show the same behavior, the maximum vertical loads are very similar, and the contact times are almost the same.

From Table 2, it is possible to verify that the maximum vertical loads obtained with the specific platform are always higher than those evaluated with the commercial one. Also, the standard deviation of the maximum load value obtained for the new platform is much lower than the corresponding load for the commercial force platform.

As can be seen in Figure 12, 60% of the athletes land with the midfoot and the other 40% with the forefoot. Comparing the maximum load transmitted in both cases, it can be seen that the load transmitted when athletes land with the midfoot is around 33.5% higher than that evaluated when the landing is performed with the forefoot.

From Figure 13, it can be observed that there is a linear relationship between the loads obtained for both platforms. Also, the scatter of the maximum force values assessed with the new platform is much lower than the values measured with the commercial system. In

fact, the dispersion is 10.6% for the new platform and 15.5% for the commercial one. This can be justified by the fact that the piezoelectric platform can induce some errors in the evaluation of static loads. In the case of a jump, as the contact time is very small, the load can be considered almost static. However, the biggest difference between the platforms, around 21%, was determined for gymnast number 2, and the smallest, around 12%, for gymnast number 4. These differences can be justified by the building principles associated with each platform. In the case of the commercial platform, the force is applied to a piezoelectric crystal, and the electric charge is captured at the crystal surface and converted into a voltage signal by a charge amplifier. The new in-house-built platform is strain gauge-based, in which the load is applied to a spring body, capturing changes in electrical resistance, and causing compression or stretching of the attached strain gauges and, therefore, a change in their electrical resistance. Also, the contact surface is different. The commercial one is metallic, and the new one is made of plywood, meaning the rigidity of the platforms is quite different, which explains the different forces exerted on the platforms. As previously mentioned, the new platform has a surface close to the practicable surface normally used by acrobatic gymnasts and is, therefore, more suitable for this study and analysis in these sports.

According to Table 3, it is possible to verify that only four gymnasts performed the landing with the forefoot. Observing Figure 12, it can be concluded that gymnasts who initiate the jump landing on the forefoot exert significantly lower maximum loads ($p < 0.05$) than those in the group performing the landing on the midfoot, regardless of body weight. No statistical correlation was observed between the maximum load and the maximum height ($p = 0.442$), the maximum load and the contact time ($p = 0.060$), and the maximum load and the distance from the greater trochanter to the ground ($p = 0.683$). On the other hand, a significant correlation was observed between the maximum load and the gymnast's weight ($p = 0.001$).

During landing, the ground impact applies forces and moments of force that accelerate hip, knee, and ankle flexion (dorsiflexion), giving rise to kinetic energy to be absorbed by the body [32]. Analyzing together Figure 12 and Table 4, it can be observed that landing on the forefoot induces ratio values of less than 13 times body weight. Regarding the landing on the midfoot, for all gymnasts except for gymnast number 10, this value was greater than 13 times body weight. These values suggest a lower maximum load is exerted when performing a forefoot landing. Landing must be made by the forefoot to allow the kinetic energy to be absorbed gradually up to the maximum flexion of the knee joints. When the landing is on the midfoot, the greatest absorption of kinetic energy occurs in the foot, which can lead to an imbalance in the gymnast, increasing the tension in the bone structures of the foot. According to Teng et al. [37], forefoot landings are better for load absorption but are associated with smaller knee flex angles at initial contact, which can cause injuries, namely in the foot, ankle, and/or knee.

Repeated landings and the loads absorbed during these landings contribute to the serious injuries suffered by many gymnasts; it is therefore important to assess these loads so that coaches are aware of the high loads their gymnasts are exposed to during landings, in order to promote training strategies in terms of landing technique to reduce these loads [7]. Thus, it is important to develop a platform, perfectly adapted to acrobatic gymnastics, which can give coaches and athletes the maximum load values reached during landings. Norcross et al. [38] carried out a study to evaluate the relationship between the energy absorption of the lower limbs and biomechanical factors, having concluded that injuries are influenced both by the magnitude and the moment of energy absorption by the lower limbs during landings.

This platform is designed to replicate training equipment, enabling gymnasts to analyze jumps and improve their performance while minimizing the risk of injuries.

The development of a platform that represents the same landing conditions improves the performance of athletes. As this is a prototype platform, it can be improved in terms of acquisition frequency, coupled with software that analyzes the jumps made during training.

5. Conclusions

The landings on the forefoot allowed for obtaining lower vertical load values, suggesting these to be more advantageous in terms of injury prevention. Body weight was a determinant in the load exerted on the ground during landing, since the greater the body weight of the gymnast, the greater the maximum vertical load reached. It is important to identify and measure other parameters that influence the occurrence of injuries in this type of jump, like the type of landing on the ground, the flexion of the knee, or the form of foot support. To prevent injuries related to landing, such as ankle sprains, Achilles tendonitis, plantar fasciitis, and calcaneal fractures, it will be important to sensitize gymnasts to perform their landings starting on the forefoot.

The specific platform proved to be more suitable for gymnastic use, compared to the industrial one. The upper area, which gave the gymnasts a larger landing zone, allowed them to have a safer landing zone and provided more valid jumps for analysis. In addition, the use of plywood in the construction of the platform allowed the gymnasts to have more cushioned and comfortable landings during the rehearsals. The standard deviations considering the maximum loads obtained with the specific platform are small when compared to the commercial one. The specific platform allows us to characterize the athletes' jumps in order to improve their performance and to analyze the landing form, ensuring that the landing is correct and avoiding injuries. To adapt to this specific platform, it is important to develop software that shows gymnasts in real time the forces involved in the jump. They can adjust the jump for better performance and lower values of force, thus reducing injuries. Commercial platforms, despite having different dimensions, may not be the most suitable for this modality, due to the maximum position, in terms of width, of the athletes during landing. That is why this study will be of added value to acrobatic gymnastics athletes as well as coaches.

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