

Article

The Elastic Vibration Behavior of a Springboard in Gymnastics

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Abstract

The paper presents aspects of the elastic behavior of a springboard in school gyms after contact with a basketball (0.500 kg) falling from a height of 1 m or a volunteer student jumping from 30 or 60 cm in three different areas at the end of the springboard. The results recorded obtained from three accelerometers mounted under the main plate of the springboard are presented, primarily focusing on the accelerations and vertical displacements after contact. The springboard has a special construction, the upper plate and the curved support plates being provided with two pairs of conical and cylindrical truncated helical springs, respectively. The accelerometers were placed at different points, centrally on the upper plate and on the support plates. It was found that in the dynamic process of a body falling on the springboard, the coefficient of elasticity/rigidity of the elastic system changes, presenting values of 22.14–71.12 kN/m. Normally, both accelerations and displacements are greater on the upper plate, but its vibratory motion also induces additional movements and vibrations on the two lower plates. The results may be useful both for manufacturers of such equipment and for coaches to give appropriate instructions to athletes.

Keywords: springboard; accelerometers; vertical displacements; vibration behavior



Academic Editors: Bogdan Chirita,
Rodica Sturza, Mirela
Panainte-Lehăduș and Raul D. S.
G. Campilho

Received: 19 June 2025

Revised: 28 July 2025

Accepted: 11 August 2025

Published: 14 August 2025

Citation: Dumitrescu, D.-M.; Voicu, G.; Orasanu, N.; Istrate, I.-A.; Constantin, G.-A. The Elastic Vibration Behavior of a Springboard in Gymnastics. *Processes* **2025**, *13*, 2573. <https://doi.org/10.3390/pr13082573>

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1. Introduction

Springboards are essential pieces of equipment used for performing jumping maneuvers. A springboard is a firm, spring-loaded board that gymnasts use to gain height and additional propulsion when performing jumps. It is usually made of layers of wood and spring mechanisms to provide a rebound (springback) effect.

It has been determined that the gymnast's interaction with the vaulting board is less than one second, but it provides the support upon which the vault is based. Bradshaw, 2004 [1] identified that the total contact time with the board averages 0.15 s, with the average compression and rebound time being as little as 0.08 s.

The point of contact with the board is important for jumping, but there is little research that refers to the optimal location of the feet on the springboard.

The natural progression of the sport requires the gymnast to continually increase their skill level, difficulty, and intensity, but this can lead to an increased risk of injury due to the additional physical and mental demands imposed.

Researchers in the field (Middelkoop, 2019) specify the need to investigate the effects of spring configuration and the level of compression achieved during jumping using two different plates: a plate with helical springs (conical or cylindrical) and a plate with leaf springs [2].

The correct configuration of the springboard in the gym is essential to ensure the safety and optimal performance of gymnasts. Depending on the type of equipment used, the springboard must be positioned at an optimal distance from the apparatus. The distance can vary depending on the height and speed of the gymnast. Usually, this distance is adjusted based on the gymnast's training and experience. The distance should allow the gymnast to synchronize their jumps to achieve optimal propulsion. The angle can be adjusted on some springboards to vary the height and propulsion. In addition, before jumping, the stability of the springboard is checked to ensure that it does not slip during the jump.

Coventry et al. [3] also concluded that modern springboards (with leaf springs) have a larger area of optimal impact, which allows the gymnast a greater margin of error when making contact with the springboard. When a body strikes a fixed elastic system, the force with which the body is “pushed back” depends on several factors, including the nature of the collision and the elastic properties of the system. In general, the Law of Conservation of Momentum and Hooke's Law (for a perfectly elastic system) can be applied.

There are studies to determine the reaction force of the springboard to improve take-off technique, and devices have been developed to determine the optimal parameters of the board, the repeatability of jumps, and the optimal training technique [4–7].

The springboard reacts as a dynamic system, similar to a damped mechanical oscillator, so that upon impact it starts to vibrate around the equilibrium position, the oscillations being characterized by natural frequency, amplitude, and degree of damping. The stiffness of the springboard can be different depending on its own stiffness but also on the positioning of the springs relative to its end and their stiffness. In the paper [8], the authors Zanevskyy et al. mechanically and mathematically model the springboard as a Bernoulli–Euler beam with spiral springs mounted in three rows, using Clapeyron's theorem. The experimental values of the springboard stiffness were determined using the values of the plate displacements loaded with a standard external force of 3500 N. The value of the stiffness caused by the deformations of the spiral springs decreases monotonically along the upper plate to a minimum value. The oscillatory part of the total stiffness is determined by the bending flexibility of the upper plate. In addition, the authors perform a computer simulation, and the results are compared with data obtained in experiments. They state that performance results in gymnastic jumps depend largely on the configuration parameters of the springboard and that the displacement of the upper plate depends on the stiffness of the coil springs and the stiffness of the plate. Furthermore, the position of the take-off point significantly determines the mechanical parameters of the springboard, with the theoretical model developed by the authors being useful in engineering design and sports practices of jumping.

During the contraction of the springboard, there are not only elastic forces of the springs but also damping forces of the structure. It is usually assumed that the damping force is $F_d = c \dot{x}$, where c is the damping coefficient, and $\dot{x}$ is the pressing speed. Based on the determinations on a soft and a hard plate, the authors determined the total elastic moduli of the elastic plate, which had values of 42,200 N/m and 55,200 N/m, respectively. Hao and colab [9] propose capturing the plate deformations during the jump using a high-speed camera, and after digitizing the video recording, the displacements and velocities can be obtained, which can be introduced into the total reaction force relationship of the springboard.

An analysis of the kinetic characteristics of the take-off phase of the jump and the forces that occur within the springboard is difficult to achieve due to the short time phase of contact with the springboard, which has been consistently reported to last 0.100–0.130 s. In their research, Greenwood and Newton [10] found that load cells placed under the

springboard legs could produce a maximum average peak force of 3458 N, which coincided with the maximum deformation of the springboard top plate, and the maximum average ground reaction force was 4911 N (10.3 times body mass), recorded by the platform at the moment when maximum deformation was reached.

The compression exerted on the top plate of the springboard varies from gymnast to gymnast, depending on the number of springs and the configuration of the springboard, namely the spiral spring design (conical, cylindrical, number of turns) and the leaf spring design. Middelkoop, ref. [11], shows that there is no evidence to correlate the configuration of the springboard elastic system with the gymnast's performance.

Using a Kistler strain gauge platform, Koperski et al. [12] measured and analyzed ground reaction forces and tested leg and pelvic girdle muscle strength under laboratory conditions. The speed and strength abilities of 8–12-year-old athletes were based on the evaluation of their take-off power and ground contact time. The measurement of mechanical quantities during the springboard take-off was performed using the photogrammetric method. The average result of the group was 56.2 W; the shortest ground contact time was 0.117 s, and the longest was 0.17 s. Under competition conditions, the same gymnasts achieved powers of 3228–4987 W and springboard contact times between 0.12 and 0.15 s (mean values of 0.13 s).

Using an accelerometer, Krizaj and Cuk [13] measured the acceleration of the top plate of a springboard during a gymnast's jump, which was then integrated to obtain the velocity and displacement of the springboard top plate. During the contact with it, which usually lasts around 200 ms, eight parameters were identified and evaluated: the time to reach the minimum vertical velocity, the time to the maximum compression, the time to reach the maximum negative and positive velocities, the time to the zero position, the maximum positive and negative velocities, and the maximum vertical displacement of the springboard. The maximum velocity presented values from 0.133 m/s to 1.01 m/s. The authors' conclusions show that the precision of the determinations for the evaluated parameters was 5.3%, except for the maximum positive velocity for which the average relative error was up to 15.3%.

Sano et al. [5] also monitored springboard behavior during the jumps of a 60.7 kg, 1.71 m tall gymnast using an accelerometer attached to the front side of the springboard top plate, attaching a marker to the side of the accelerometer, and video recording its movement. The vibration (acceleration) variations during contact with the plate are very similar to the signals recorded by us during experimental determinations. The two sets of acceleration data were digitally smoothed using a Butterworth low-pass filter.

The authors of the paper [14] show that upon initial contact with the springboard, almost all of the kinetic energy for Tsukahara vaults is composed of translational kinetic energy (TKE), while Yurchenko vaults are characterized by much less TKE, but the angular kinetic energy (AKE) and potential energy (PE) are much higher.

Directives for Equipment, ref. [15], include the shape and dimensions, functional properties, and color of the boards. Standardized procedures for testing boards include a drop test to analyze the deformation of the impactor, the rebound height of the impactor, and the maximum force measured during impact. The color of the carpet covering the springboard may vary depending on the type of competition and specific standards; in international gymnastics competitions, the springboard carpet is usually red or blue. These colors are preferred because they are visible and allow judges and spectators to more easily follow the athlete's movements during the jump.

In our opinion, the data presented in the analyzed works show the importance of choosing the appropriate springboards for the transfer of potential energy to gymnasts.

Accelerometer analysis and visual analysis with high-speed video cameras are two complementary methods for studying the behavior of gymnastic springboards, especially in training contexts, biomechanical research, or equipment testing.

Accelerometer analysis can provide direct measurements of accelerations and vibrations, especially vertical ones, and can highlight vibrations that occur during contact of the falling body (the gymnast) or after large impulses. The signals can be recorded and subsequently analyzed to extract natural frequencies, damping, or impact forces and can be correlated with the gymnast's position and movement.

Accelerometers can record small oscillations or deformations of the structure that are not easily visible in video camera images, being useful for evaluating the structural behavior of the springboard. It is evident that from the upper plate the vibration is subsequently transmitted to the other elements of the springboard structure, with a delay of a few milliseconds.

In our work, we investigate the behavior of a school springboard with four helical springs (arranged two by two) and an intermediate S-shaped plate under the action of a basketball falling from a height of 1 m and the weight of two volunteer students jumping from two different heights (30 and 60 cm) in three positions on its surface in order to estimate the accelerations and displacements at the moment of contact by means of three accelerometers arranged under the springboard.

2. Materials and Methods

The energy transferred to the gymnast is the elastic potential energy accumulated by the plate, which is converted into kinetic energy and then into gravitational potential energy (when the gymnast is in the air). The law of elastic deformation for the deformation force of an elastic system is given by the following relationship, [16]:

$$F_e = -k \Delta l \quad (1)$$

The deformation force is the opposite of the elastic force, where k is the elastic constant of the elastic system, and Δl is the elongation or compression of the system.

The mechanical work performed by the deformation force of the elastic system, from the undeformed state to the state with maximum deformation, is equal to

$$L_{Fe} = -\frac{F_e \Delta l}{2} = -\frac{k \Delta l^2}{2} \quad (2)$$

The variation theorem of the elastic potential energy of an elastic body shows us that it is equal to the mechanical work performed by the elastic force, denoted with a minus sign, so that

$$\Delta E_{pe} = -L_{Fe} = \frac{k \cdot \Delta l^2}{2} \quad (3)$$

A 3SLP jumping springboard, commonly used in schools and gyms, was used for the experiments, being ideal for jumping training and coordination exercises. The springboard plates are made of densified and layered wood fibers to provide strength and, at the same time, appropriate rigidity. The top board is upholstered with polyethylene and covered with carpet, ensuring comfort and increased grip during jumping. It is mounted on two pairs of nickel-plated steel springs, providing hardness and good elasticity for improved jumping performance. These, in turn, rest on two lower curved plates, also made of laminated wood, each stiffened by a thin metal plate underneath them. The helical springs at the front have a frustoconical shape, and those in the central part have a cylindrical shape. Between the two pairs of springs there is an S-shaped curved plate (also made of

laminated wood), fixed only at the front under the upper plate. The main dimensions of the springboard are length—120 cm, width—60 cm, height—20 cm.

It is known that the jumper seeks to find the best landing position on the springboard to produce greater amplitude in the jump and greater throw distance; therefore, our tests were carried out for three positions on the upper plate approximately 25 cm apart, as specified in their works including Coventry et al. (2006) and Krizaj and Cuk (2015) [3,13], as shown in Figure 1.

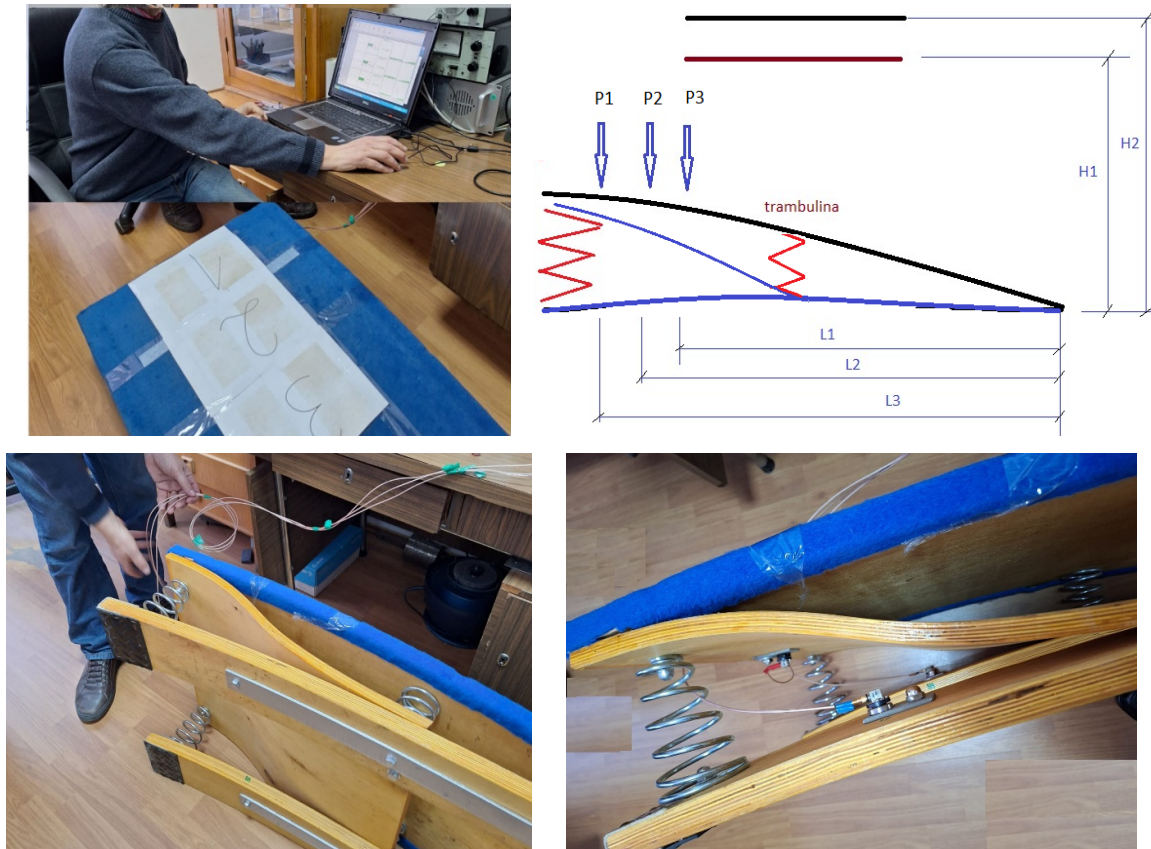


Figure 1. Longitudinal positions on the springboard from which the experimental data were taken.

Before the experiments, three CCLD piezoelectric accelerometers, type B&K 4507-B-001, TEDS, 10 mV/g, frequency range 0.1–6000 Hz, for operating temperatures -54 – $+121$ °C, $1 \text{ mV}/(\text{m}\cdot\text{s}^2)$ were fixed under the springboard plates. Under the upper plate, under the S-curved plate, in the front part (under position 1), the accelerometer A1 was attached, and at the bottom, on the lower curved plates, the accelerometers A2 and A3 were attached, as can be seen in Figure 1. The accelerometers were connected to a computer data acquisition system with an e (NI-DAQ 9233, National Instruments, Austin, TX, USA) acquisition board for vibration and noise measurement and software for signal acquisition and processing dBFA Suite 4.8.1, developed by 01dB-METRAVIB (Areva Group). The collected data were recorded and post-processed using modal analysis software (dBFA Suite 4.9). The processing of the signals recorded by the accelerometers was performed in the MATLAB program (<https://www.mathworks.com/products/matlab.html>, accessed on 18 June 2025), eliminating background noise and drifts and preserving the dynamic components of the system. Filtering was performed with a “high-pass” filter, above 2 Hz.

The experiments were carried out using both a regular basketball (dropped from a height of 1 m) and, in addition, three volunteer students of different weights of 40 kg, 58.5 kg and 68 kg who dropped from 30 cm and 60 cm, respectively, in the positions

indicated in the previous figure. Experiments were also carried out with a 2 kg gym ball dropped perpendicularly from two different heights (1 m and 1.5 m), but these are not included in the work.

The A1 accelerometer allows the measurement of vertical accelerations produced after impact, the indirect estimation of impact forces and local stiffness of the springboard, and the identification of the local vibration mode for the respective area. The use of a standard basketball dropped from 1 m produces an impact with relatively constant force, allowing repeatable testing, and helps to understand the local dynamic behavior of the springboard without the involvement of a gymnast (for safety and consistency). The graphs drawn as a result of the acceleration recordings show the maximum amplitude; the duration of the oscillations; the degree of damping and the dominant frequency, related to the mass and stiffness of the tested area; and the time until stabilization (damping of the system).

Accelerometers A2 and A3 on the lower curved plates record the transmission of vibrations from the upper impact to the supporting structure and can highlight the symmetry/asymmetry of the springboard, as well as possible differences in stiffness between the two parts; this shows the way mechanical waves propagate through the interwoven structure of the springboard, but also the way in which the impact force is dissipated or transferred into the structure. From the analysis of the acceleration graphs, it is found that there is a large and short amplitude of the vibration at the beginning on the upper plate, but there are differences in oscillation between the vibrations of the lower left–right plates due to the way the accelerometers are arranged.

This experiment is relevant for testing structural uniformity, validating a theoretical vibration model of the springboard, and possible optimization of the materials or geometry of the curved plates (for sports performance or safety). Experimental analysis of the local dynamic behavior of the springboard is useful for optimizing the materials' distribution, verifying structural safety and calibrating the elastic response uniformly across the jumping surface.

The acquisition system received the accelerations from the three accelerometers, which by integrating once and twice led to the determination of the values for the velocities the displacements of the points on the springboard where they were attached. The acquisition system was started a few seconds before the ball or the student fell; therefore, on the resulting graphs, one can see some oscillations recorded just before contact with a higher frequency. However, upon contact, one can see the change in the variation of these oscillations which become much denser, the first oscillation of which actually represents the moment of contact itself. From the analysis of the first oscillation, the contact time can be determined. The springboard plate moves downwards, and after passing through 0, the upper released plate moves above the Ox axis, the value of the displacement being given by both the weight of the falling body and the point of contact with the plate.

It can be seen (Figure 2) that accelerometer A1 records positive downward displacements (being positioned below the upper plates) and negative upward displacements, while accelerometers A2 and A3 record positive upward accelerations and deformations, being positioned above the two lower curved plates. Static tests were also performed using weights of 10, 20, 30 and 68 kg in order to determine the compression distance of the elastic system of the springboard and to determine the stiffness constants for the three possible positions of application of the pressing force (contact with the gymnast).

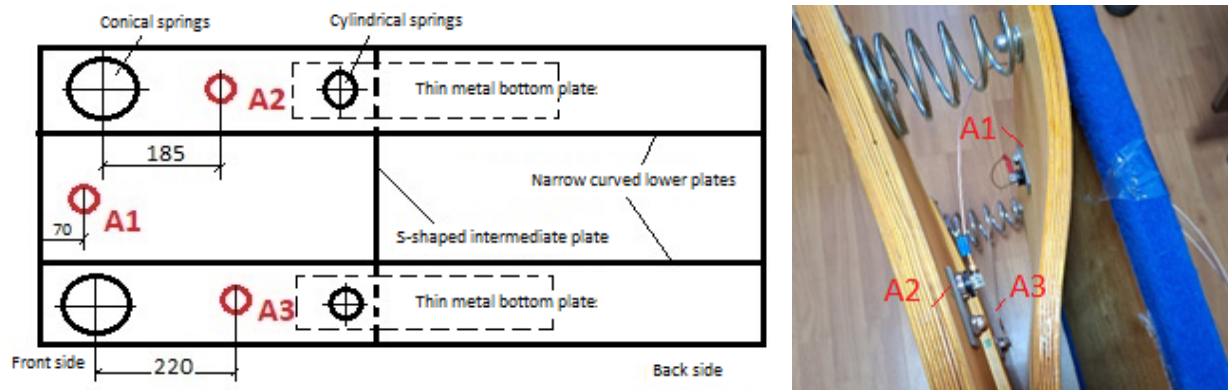


Figure 2. The mounting positions of the three accelerometers and the basic components of the springboard.

3. Results and Discussion

Accelerometers generally do not provide direct visual information about the gymnast's position or visible deformation of the springboard, and data interpretation requires signal processing (filtering, integration to obtain velocities/positions) and can be misleading if not properly mounted or calibrated. We hope, however, that our data meets the requirements. However, accelerometers are excellent for understanding the internal mechanical behavior of the springboard—deformations, vibrations, natural frequencies, and impact response.

A springboard with curved bottom plates introduces an interesting structural feature that affects the overall mechanical behavior of the system. This type of construction can influence the force distribution, the impact response, and the way the structure deforms during use. In this context, accelerometer analysis becomes even more valuable, and the comparison with high-speed video analysis remains relevant, but different. Curved plates can introduce a complex elastic behavior, with a combination of vertical and horizontal movements depending on the curvature, and the impact reaction forces can be distributed non-uniformly in the structure, influencing stability and oscillations, as the curvature can change the natural frequencies and dominant vibration directions.

Physically speaking, the errors that could occur during signal processing may also be an effect of the fact that the low-frequency filtering introduced by the first integration fails to cut the average value of the signal a_0 which produces such an effect. An acceleration signal can be of the following form:

$$s(t) = a_0 + \sum_1^N a_n \cos(2\pi nft) + \sum_1^N b_n \sin(2\pi nft) \quad (4)$$

If low frequencies are not filtered, it results in

$$v(t) = \int s(t)dt = a_0t + \frac{1}{n\omega} \sum_1^{\infty} a_n \sin(n\omega t) - \frac{1}{n\omega} \sum_1^{\infty} b_n \cos(n\omega t) + Const. \quad (5)$$

Moreover, the existence of the zero-frequency coefficient, $a_0 \neq 0$, in a signal will lead after integration to the loss of the periodic character of a signal; for this reason, this term must be eliminated from the signal.

Given the acceleration versus time graph (Figure 3), the maximum displacement can be obtained by double integration. Knowing the displacement $x_{\max}$, the coefficient of elasticity can be determined:

$$k = \frac{F_{\max}}{x_{\max}} \quad (6)$$

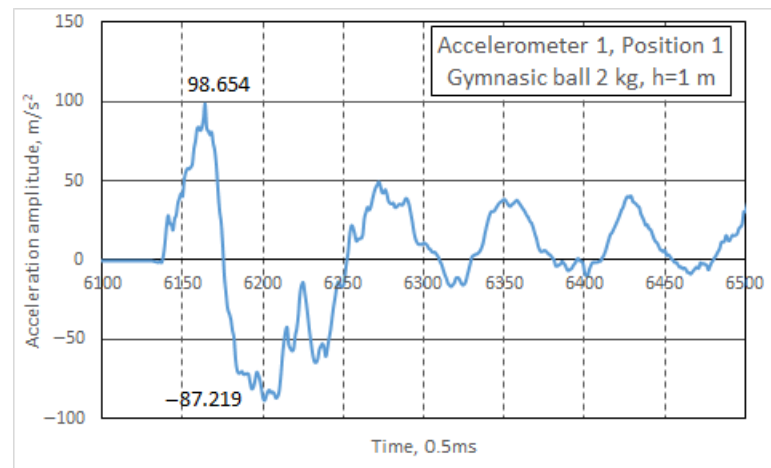


Figure 3. Variation in acceleration at the top of the springboard when a gymnastic ball falls.

If the first oscillation crosses zero at 6137 0.5 ms, then at 6176 0.5 ms, and again at 6252 0.5 ms, then the actual period of this oscillation is about 125 ms, since in a complete harmonic motion we have two zero crossings per cycle (once on the rise and once on the fall). It is observed that the oscillation is not symmetrical concerning either the Ox axis or the vertical axis passing through the central zero point (non-linear, non-harmonic oscillation).

The logarithmic decrement δ is used to find the damping ratio of an underdamped system in the time domain, being defined as the natural logarithm of the ratio of the amplitudes of two successive peaks [16,17]:

$$\delta = \frac{1}{n} \ln \frac{x(t)}{x(t+nT)} = \frac{1}{n} \ln \left(\frac{A_1}{A_{n+1}} \right) \quad (7)$$

where $x(t)$ is the amplitude value at time t , and $x(t+nT)$ is the amplitude value n periods away, n being any integer number of successive, positive peaks.

Using logarithmic decrement, the damping ratio presents the following relationship:

$$\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \quad (8)$$

The logarithmic decrement also allows the evaluation of the Q factor of the system:

$$Q = \frac{1}{2\zeta} \quad (9)$$

The damping ratio can then be used to find the natural frequency ω_n of the system vibration knowing the damped natural frequency ω_d :

$$\omega_d = \frac{2\pi}{T} \quad \omega_n = \frac{\omega_d}{\sqrt{1-\zeta^2}} \quad (10)$$

where T is the oscillation period, namely, the time between two successive amplitude peaks of the underdamped system.

To determine the compression of the springboard elastic system, tests were performed in January 2025 using different weights applied in the three positions mentioned before. As can be seen from Figure 4, the deformation of the elastic system follows a completely linear pattern, with clearly lower values for position 3 (max. 11 mm) and higher deformations for position 1 (max. 20 mm).

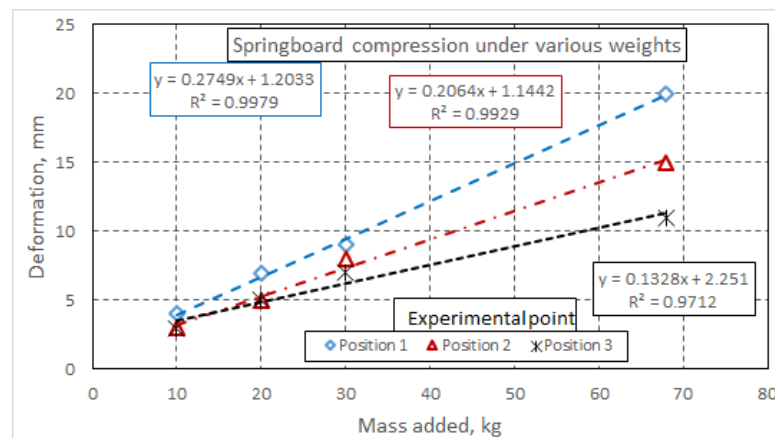


Figure 4. Static springboard deformation under different weights, for the three seating positions.

Figure 5 shows the graphs of the displacements of the elastic system for the three accelerometers during contact with the basketball (0.500 kg, circumference 720 mm) dropped vertically from a height of 1 m. As can be seen, the oscillatory behavior of the springboard is different for the three accelerometers, regardless of the position in which the ball falls. The oscillations are more pronounced, mainly, for the first accelerometer (mounted under the upper plates, immediately in front of the springboard), smaller for accelerometer A2, and much less visible for accelerometer A3, referring strictly to the contact with the ball.

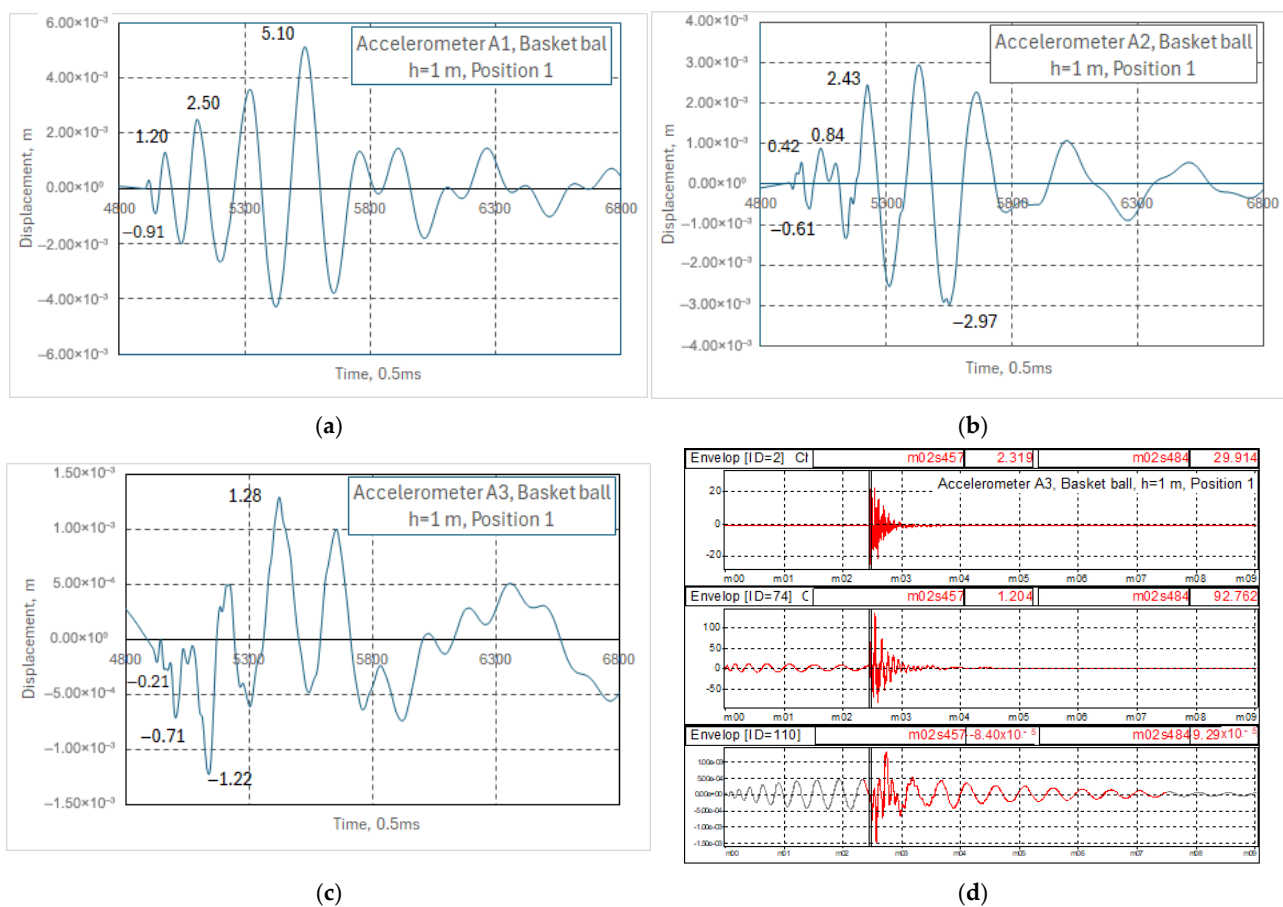


Figure 5. Oscillatory behavior of the springboard plates for contact position 1, test 1 (displacement) (a–c), and oscillatory motion for accelerometer 3 (accelerations, velocities, and displacements) after new filtering (d).

From the graphs presented below, we can see a strong impact at the beginning with large positive and negative peaks, typical of a mechanical shock.

It should be noted that the ball was not allowed to fall a second time on the springboard; it was caught and removed.

The upper plate shows an acceleration peak immediately after impact, indicating a direct reaction to the mechanical shock and subsequent oscillations with decreasing amplitudes, while the lower curved plates react with some delay time, meaning that the impact energy propagates through the structure, with one of the two accelerometers (A2 and A3) having a larger amplitude due to the mounting asymmetry and the two lower plates having the same construction.

For example, if the ball falls at position 1, from 1 m, the moment of impact is recorded at 4905 0.5 ms (half a millisecond—the recording system being started earlier), with a maximum positive displacement (the accelerometer A1 being mounted under the plate) at the upper plate of +5.10 mm (all values written on the graphs are correlated with the measurement units written on the vertical axis) after 0.319 s and five oscillations. Meanwhile, at accelerometer A2, the maximum displacement is recorded at 5550 0.5 ms, with a negative value of −2.97 mm (i.e., 0.323 s after impact), and at accelerometer A3, the value is 5425 0.5 ms, with a positive value, of +1.28 mm (i.e., 0.260 s after impact moment).

The oscillation period recorded at accelerometer A1 (considered between the first two positive peaks) is 0.066 s, and at A2 and A3 (mounted on the lower plates), these values are 0.018 s and 0.065 s, respectively.

Thus, the delays between the maximum values of displacement recorded by the three accelerometers for the fall of the basketball from 1 m to position 1 from the moment of impact were 0.319 s for accelerometer A1, 0.323 s for accelerometer A2, and 0.260 s for accelerometer A3, respectively, highlighting the fact that the transmission of the oscillation signal from the upper plate to the lower plates via the coil springs occurs randomly, but with certain delays. It can also be observed that in the interval of 250 ms (moments 5000–5500 0.5 ms), the springboard plates generally make 2–2.5 oscillations, which is minimal, in our opinion.

In general, numerical integration introduces some low frequencies; these errors are difficult to correct, especially since in an elastic system, there are oscillations naturally even without excitation. However, we can notice the oscillation of the upper plate, which is more pronounced, compared to the oscillations of the two narrow lower plates which present a minimal curvature, being much more rigid, because they constitute the base of the elastic system of the springboard, with the upper plate being articulated at the rear end to these two plates.

In this regard, we also present the acceleration variations for the elastic system of the springboard for position 1, when the basketball falls from 1 m, in Figure 6.

From the analysis of the acceleration spectra, it is observed that, in general, the acceleration levels for the lower plates (A2 and A3) are lower than those recorded for the upper plate at A1, even if anomalous peaks still appear at the two accelerometers mounted on the lower plates. At the same times, the acceleration values at the curved support plates are much lower compared to those recorded at the upper plate, but there are certainly interferences.

The acceleration signals show more obvious damping at the upper plate, while at the lower plates, the oscillations are more frequent and more uneven, including due to the complex elastic system of the springboard and the longitudinally asymmetric arrangement of the accelerometers A2 and A3.

In the case of displacements, a high peak value on the upper plate means an elastic structure, capable of absorbing and returning energy (which is ideal in gymnastics), and

small displacements of the lower plates suggest a rigorous support structure and reduced energy transfer.

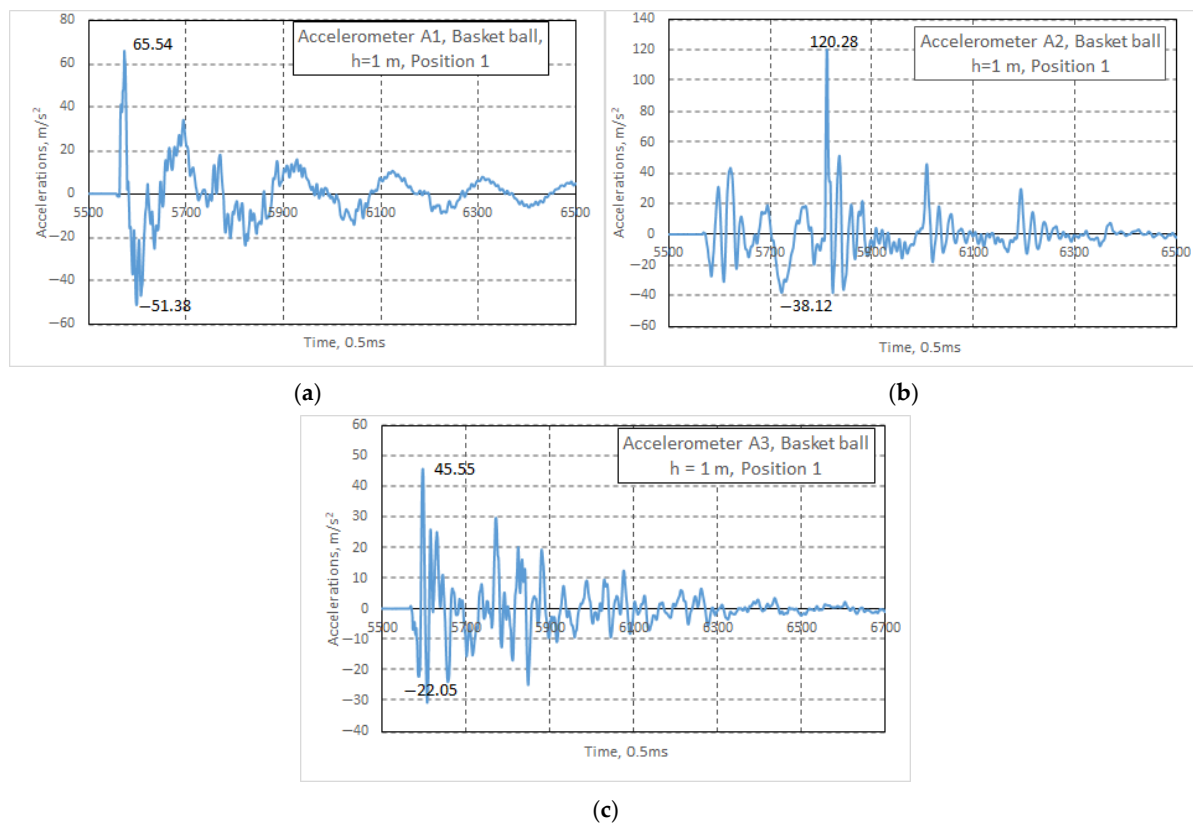


Figure 6. Accelerations of springboard elastic system during basketball ball fall, position 1.

The upper plate, being the direct impact zone, presents a signal typical of a suddenly excited mechanical system, and the oscillation frequency corresponds approximately to the local natural frequency of the upper plate; its damping level is not very high due to the additional existence of the intermediate helical springs.

The displacement vs. time signal presents a maximum value immediately after the impact, returning to the equilibrium position in an oscillating manner. Obviously, the helical springs in the springboard composition provide elasticity to the system (the upper plate), which deforms under the shock and then returns.

For these moments, the curved plate on which the accelerometer A2 is mounted has a deformation of 0.59 mm after passing “0”, and for the other moments, the deformation decreases to −0.70 mm, then increases to 2.05 mm and then reaches −3.00 mm (as shown in Figure 7b). We believe that we can observe here, at these first moments of contact, a small deformation of the ball, which we cannot quantify. For the accelerometer A3 mounted on the other lower curved plate, for the three moments specified above, the plate displacements are of the order of −0.28 mm, +0.49 mm and −1.01 mm respectively.

The same phenomenon can be observed at position 2 of contact of the basketball with the springboard, but the displacement values are slightly smaller (Figure 5). Here, too, disturbances are introduced from the other accelerometer attachment points, the contact with the springboard causing a disturbance to the other two accelerometers (A2 and A3), which may indicate even greater vibrations after being touched by the disturbing object (the gymnast or basketball, in our case).

Figure 7 shows the oscillations recorded by the accelerometers mounted on the springboard for the fall of the basketball from 1 m for position 2. Here, too, the delays from one

accelerometer to another are observed, as can be seen by analyzing the data in the figure and previously processed using the MS Excel program. If the first oscillation is recorded at accelerometer A1 at time 11,799 0.5 ms (as -1.06 mm), for the other two accelerometers, the movements begin at time 11,814 0.5 ms for A2 ($+0.59$ mm) and 11,857 0.5 ms for A3 (-2.87 mm). The delays are therefore 7.5 ms from A1 to A2 and 29 ms from A1 to A3 (from the upper plate to the lower plate).

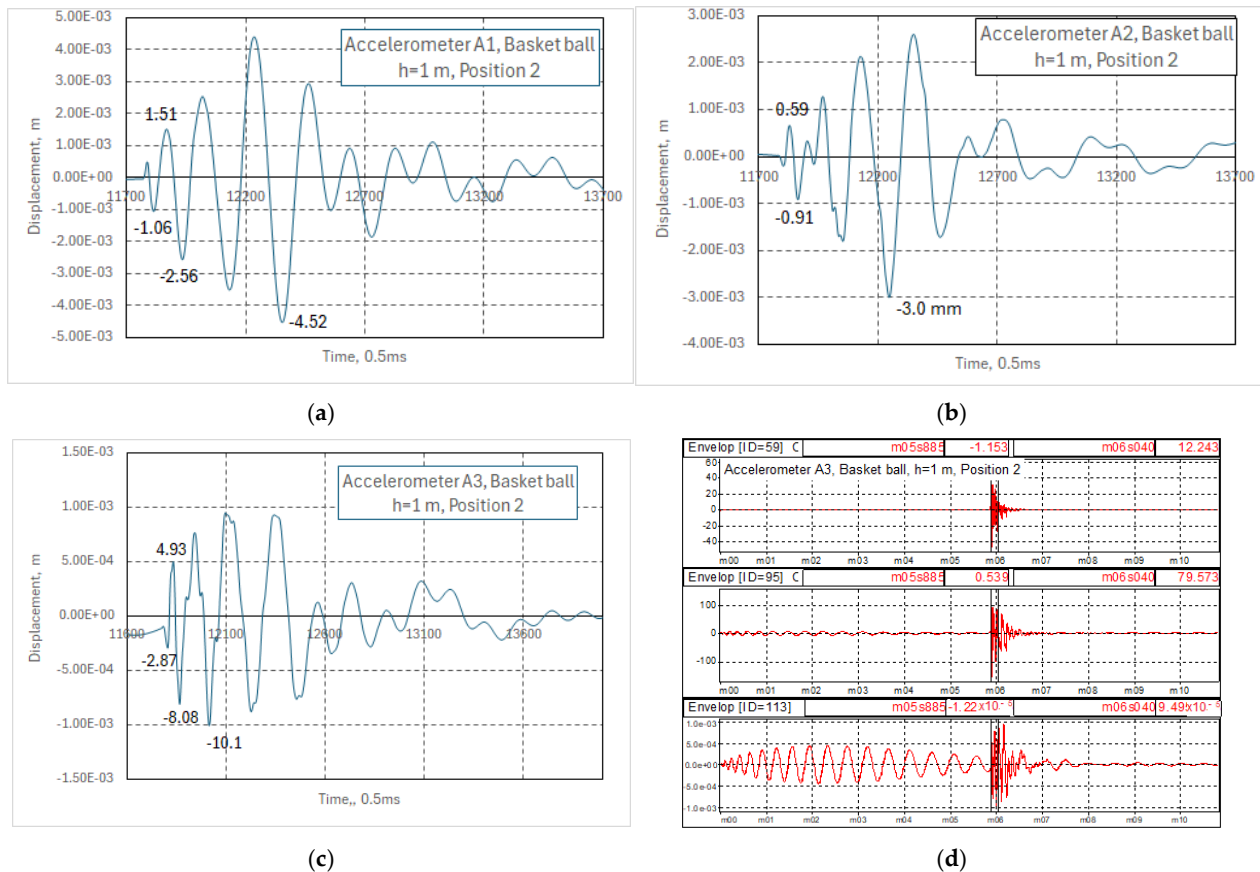


Figure 7. Oscillatory behavior of springboard plates for contact position 2–2 (a–c), and oscillatory motion for accelerometer 3 (accelerations, velocities, and displacements) after new filtering (d).

We might think that the displacements recorded by the accelerometers for the lower plates must be much smaller compared to the displacement of the upper plate, and this is visible for the accelerometer A2 (mounted on one of the two support plates); however, for the accelerometer A3 (for both tests performed), the displacement recorded is larger, which would mean that there may be some transverse oscillations that the authors did not quantify. However, this phenomenon only occurs for positions 1 and 2; for position 3 (i.e., 60–65 cm from the end of the springboard), the displacements recorded are in descending order.

The accelerations recorded for position 2 have very varied maximum values (Figure 8) from one accelerometer to another, with some relatively large jumps at accelerometers A2 and A3. For accelerometer A1, the phenomena are generally those expected if we refer to the mode of variation of the oscillations and values.

Figure 9 shows the oscillations recorded by the accelerometers mounted on the springboard, for the fall of the basketball from 1 m, for position 3. Here, too, we observe more frequent oscillations at the moment of contact at accelerometer A1 (Figure 9a) and less frequent oscillations at accelerometer A2 (Figure 9b). At accelerometer A3 (Figure 9c), they are barely noticeable, overlapping the other oscillations of higher frequency and amplitude. Here, the first oscillation at accelerometer A1 is recorded at time 8155 0.5 ms (with a dis-

placement of -0.92 mm). For the other two accelerometers, the displacements begin at time 8160 0.5 ms for A2 (-0.53 mm) and 8162 0.5 ms for A3 (-0.09 mm). The delays here are lower than in the previous cases, being 2.5 ms from A1 to A2 and 3.5 ms from A1 to A3 (from the upper plate to the lower plate).

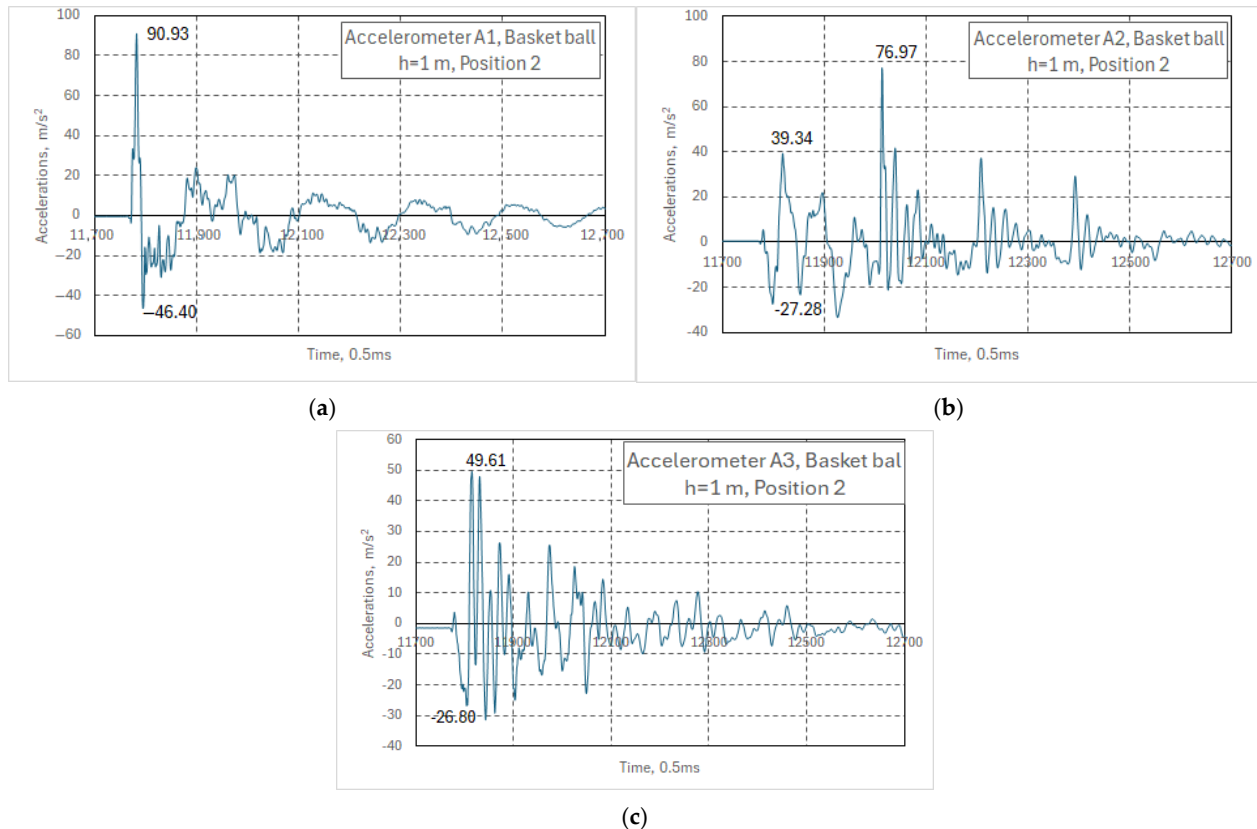


Figure 8. Accelerations of springboard elastic system at basketball ball fall, position 2.

We can also again conclude that the number of oscillations recorded for the three plates of the springboard is about 2–2.5 oscillations in an interval of 250 ms, with larger amplitudes at accelerometer A1 (which records the oscillations of the upper plate) that can increase excessively at accelerometer A3 after a time interval of several tens of milliseconds.

The rules seem to hold true regarding the level of accelerations, however, with higher values being recorded for the upper plate and relatively lower values being recorded for the two lower plates (as can be seen in Figure 10).

For the second set of the same tests, no significant differences were recorded compared to the first series of tests, although there were differences. Thus, the contact of the ball with the springboard plate was on average between 0.032–0.056 s, the differences in the oscillation amplitude being about 10% for accelerometer A1 and below this value for accelerometers A2 and A3 (for test 2 compared to test 1). The same number of oscillations were recorded within 0.25 s for both sets of tests for all three accelerometers and for each of the three positions in which the basketball fell (i.e., 2–2.2 oscillations).

The tests with the two volunteer students began with jumps from a height of 35 cm. The volunteers then jumped immediately next to the springboard, and there were also two rows of tests. The first athlete had a mass of 40 kg, and the second one 58.5 kg.

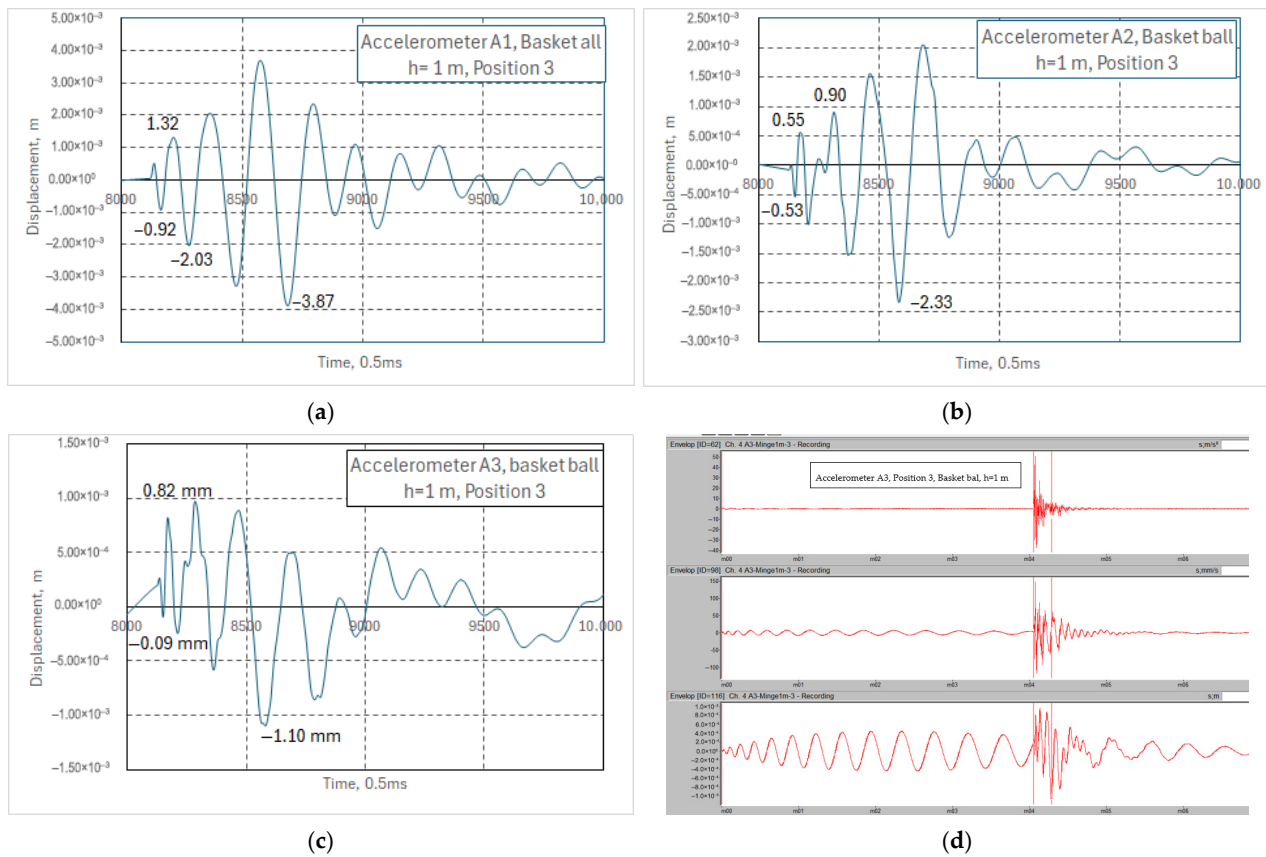


Figure 9. Oscillatory behavior of springboard plates for contact position 3 (a–c) and oscillatory motion for accelerometer 3 (accelerations, velocities, displacements) after new filtering (d).

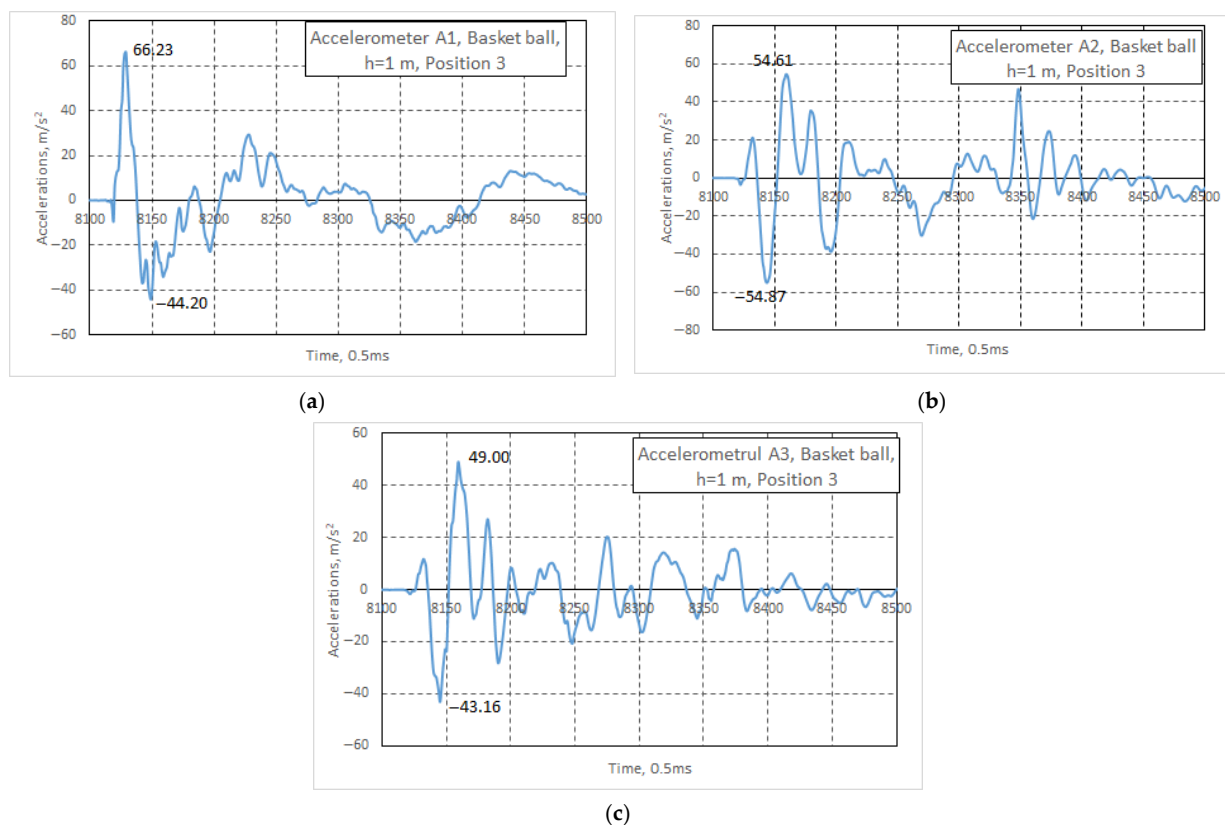


Figure 10. Accelerations of the springboard elastic system at basketball ball fall, position 3.

In the tests with the 40 kg athlete (Figure 11), the first moment at which the maximum displacement was recorded was at 500 0.5 ms, with an amplitude of +0.58 cm, the amplitude value at the next maximum being −1.81 cm (at 615 0.5 ms). However, after the release, the amplitude of the upper plate reached 2.86 cm (at the time 799 0.5 ms). The same variation of the oscillation was observed in test 2, with the first maximum at +0.66 cm, −1.44 cm, and +2.02 cm, respectively. In the interval of 250 ms, less than one oscillation of the springboard occurred.

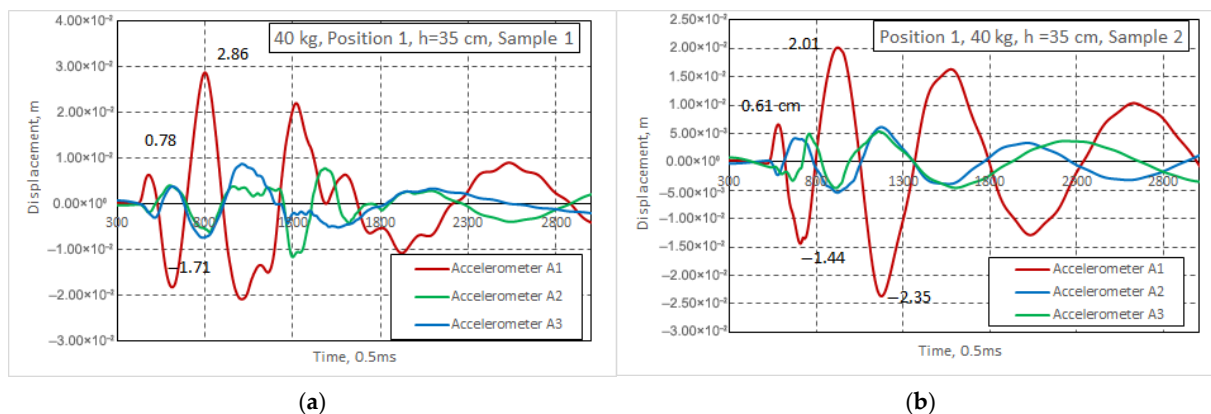


Figure 11. Springboard oscillation amplitudes for position 1 with the 40 kg student, $h = 35$ cm.

As can be seen from Figure 11, only for accelerometer A3 are the differences from sample 1 to sample 2 slightly different; however, the oscillation mode is similar. Due to the positioning of the accelerometers, it is observed that for A1, the first maximum is above the Ox axis, while for accelerometers A2 and A3, the first maximum moment is below the Ox axis for both samples.

Analyzing the first set of samples, we observe that the transmission of the oscillation to the accelerometers A1 and A2 is almost instantaneous, with only a small signal delay of about 0.01 ms at accelerometer A3. It should be noted, however, that the maximum amplitude of the oscillation is recorded much later after the gymnast's contact with the springboard, at approximately +2.86 cm and 0.150 ms after the first maximum at accelerometer A1. There is a 0.420 ms delay in recording the maximum at accelerometer A2 and about a 250 ms delay from the first maximum for accelerometer A3 (about 8.72 mm).

If we analyze Figure 12, regarding the displacements recorded for jumping position 2 relative to the end of the springboard, we can observe, as for position 1, the variation in the displacements at the moment of contact between the gymnast and the springboard is positive for the upper plate and negative for the lower plates, with values of approximately +4.6 mm for accelerometer A1 (at the upper plate), −1.79 mm at the lower left plate (accelerometer A2), and 3.15 mm at the lower right plate (accelerometer A3), respectively.

Here, too, it is observed that the oscillation for accelerometers A1 and A2 shows relatively similar moments to the maximum amplitudes, while for accelerometer A3, the signal has a delay of approximately 20 ms. Moreover, the maximum amplitudes are recorded after approximately 250 ms for accelerometers A1 and A2 (3.59 mm for A1 and 1.69 mm for A2, respectively), while the maximum amplitude for accelerometer A3 is recorded a little earlier, at 242 ms, with a displacement amplitude value of 1.31 mm. It is also observed that the position of the amplitude maximum is different from one accelerometer to another, precisely due to the way the accelerometers are arranged; however, the value of this maximum tends to decrease from A1 to A2 or from A1 to A3.

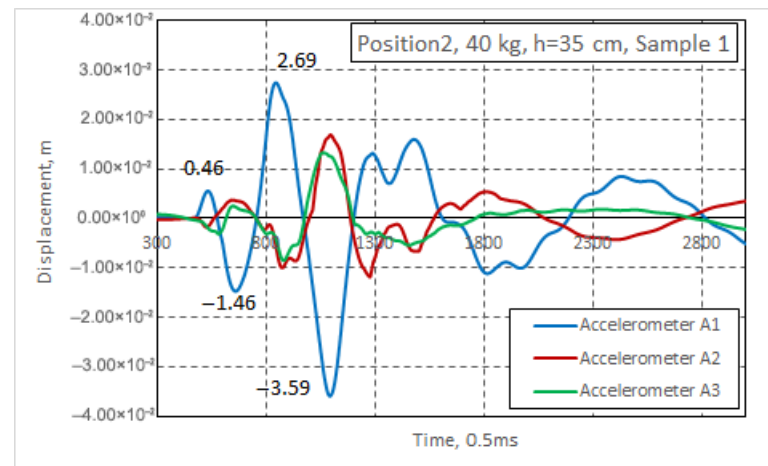


Figure 12. Springboard oscillation amplitudes for position 2 with the 40 kg student, $h = 35$ cm.

The variation trend in the springboard oscillations and the position of the maximum amplitude of the displacements are also preserved for position 3, when the 40 kg gymnast jumps from $h = 35$ cm (Figure 13); a maximum of 8.07 mm is recorded at 689 0.5 ms, and a maximum of -18.7 mm is recorded at 767 0.5 ms for the upper plate.

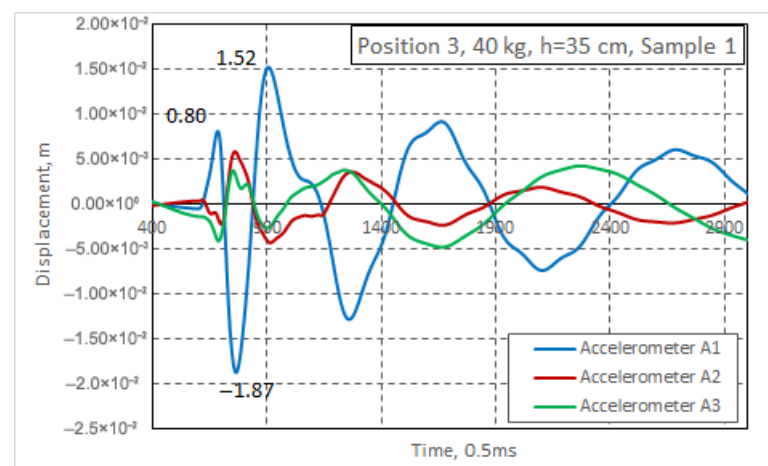


Figure 13. Springboard oscillation amplitudes for position 3 with the 40 kg student, $h = 35$ cm.

For accelerometers A2 and A3, the maximum values are in opposing positions to A1, i.e., -0.22 cm (at time 702 0.5 ms) and 0.58 cm (at time 764 ms) for accelerometer A2 and -4.06 mm (at time 682 0.5 ms) and $+3.74$ mm (at time 756 0.5 ms) for accelerometer A3. From one maximum to another (for the first two maxima) for the upper plate, 39 ms passed. Values of 31 ms and 33 ms were recorded for the lower plates, with the second maximum also being the highest value of the recorded amplitudes.

For the same fall height ($h = 35$ cm), in the case of the 58.5 kg gymnast, the oscillation variation graphs presented in Figure 14 were recorded at the three accelerometers, in position 1. The same displacement profile as for the 40 kg gymnast was recorded in this case. Thus, the first maximum has a positive value at the A1 accelerometer and negative values at the A2 and A3 accelerometers, with values of $+5.77$ mm at A1, -2.44 mm at A2, and 4.27 mm at A3. The maximum was recorded after 60 ms at A1 with a value of -1.87 mm, $+4.64$ mm also after 60 ms at A2, and $+6.11$ mm after only 34 ms at A3 (compared to A1). The maximum values recorded are 22.4 mm at accelerometer A1 after approximately 100 ms from the other maximum peak, 5.80 mm at A2, and 6.11 mm at A3 (these being the values mentioned previously). The period of the first complete oscillation is, therefore,

approximately 125–130 ms for all three accelerometers, as can be verified by the graphs in Figure 14.

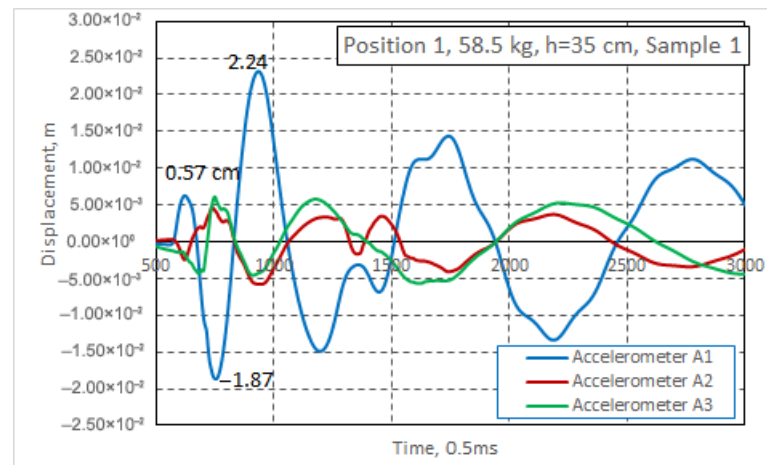


Figure 14. Springboard oscillation amplitudes for position 1 with the 58.5 kg student, $h = 35$ cm.

If we further analyze only the determinations for position 1, at all three accelerometers (Figures 14 and 15a,b), for the 58.5 kg gymnast, we observe that the highest values of the oscillation amplitude are recorded when they jump at position 2, with maxima of 5.77 mm, 7.20 mm, and 3.75 mm (from A1, A2, and A3, respectively) for the first maximum; -1.87 cm, -1.42 cm, and -1.61 cm (for the second maximum); and $+2.24$ cm, $+2.61$ cm, and $+2.39$ cm for the third peak (at A1, A2, and A3, respectively). The period of the first oscillation is 130 ms at accelerometer A1, 142 ms at A2, and 145 ms for A3; the difference between these values is not significant.

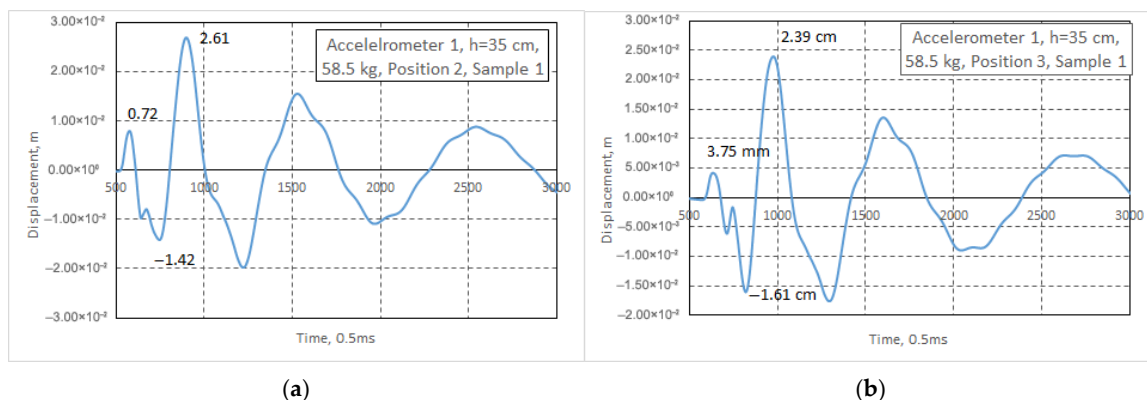


Figure 15. Springboard oscillation amplitudes for positions 2 and 3 with the 58.5 kg student, $h = 35$ cm.

When selectively analyzing the vibrational accelerations from the 35 cm jump for the 58.5 kg student for a time interval of 500 ms (Figure 16), very random oscillations are observed; for this reason, we integrated twice to determine the displacements and maxima of the oscillation amplitudes, especially for the period of the first oscillation immediately after contact with the springboard and the beginning of the oscillation of the component plates. It is worth noting that higher values are recorded for the A1 accelerometer, as expected, as it is mounted under the upper plate, which is the one that gives the gymnast the impulse to jump as high or as far.

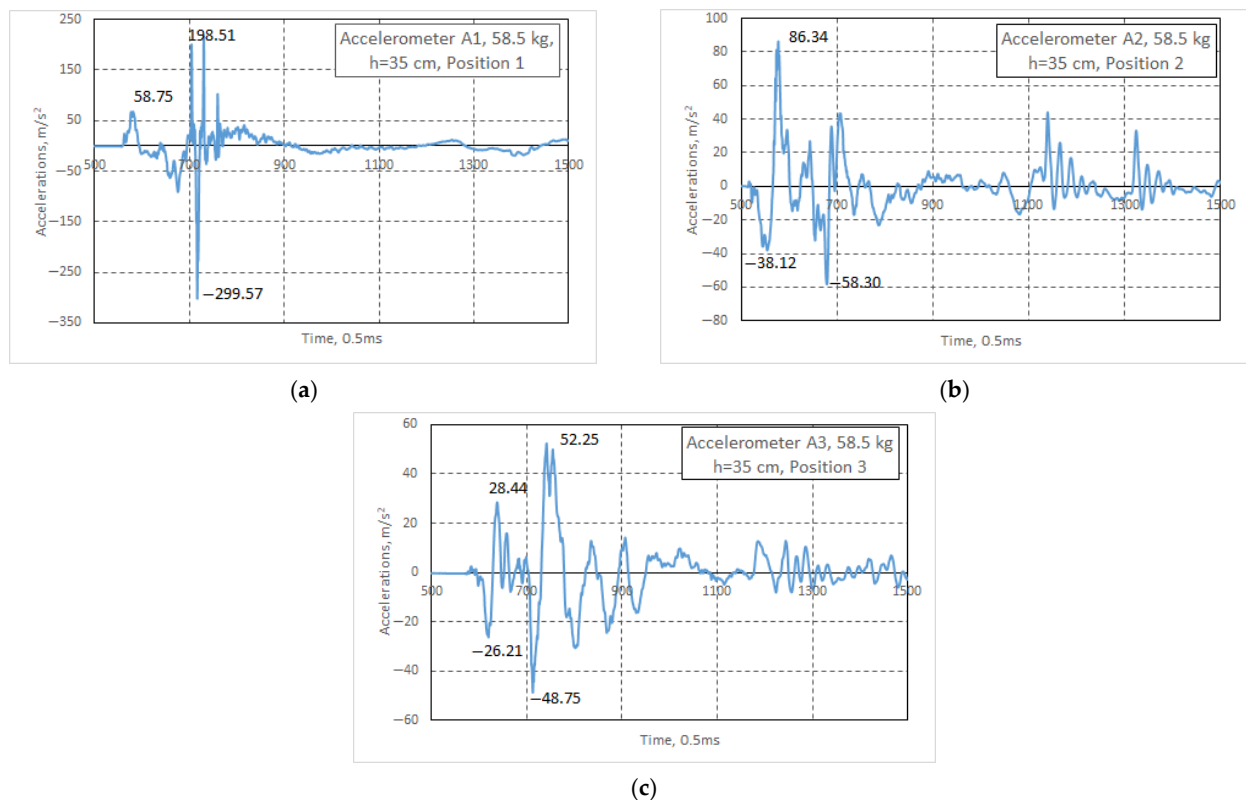


Figure 16. Springboard acceleration variation for positions 1, 2, and 3 with the 58.5 kg student, $h = 35$ cm (selective).

Analyzing the oscillation graphs of the springboard for jumps from 60 cm, for the 40 kg gymnast (Figure 17), the same mode of oscillations induced in the springboard plates is again observed, with maxima starting from +1.62 cm for accelerometer A1, −3.36 mm for A2, and −6.10 mm for A3. The second peak of the oscillation amplitude is also the point at which the maximum amplitude is recorded for the upper plate (−2.87 cm for accelerometer A1, +8.29 mm for accelerometer A2, and +6.85 mm for accelerometer A3). We also found the period of the first oscillation to be about 115 ms for the upper plate and about 103 ms for accelerometers A2 and A3.

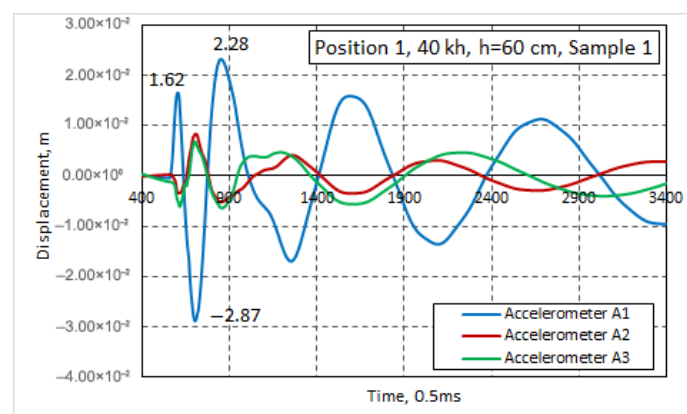


Figure 17. Springboard oscillation amplitudes for positions 1, 2, and 3 with the 40 kg student, $h = 60$ cm.

The same oscillation variation pattern can also be observed for the 40 kg gymnast's jumps from 35 (Figure 11) and 60 cm (Figure 17), but with obviously higher amplitude peak values. Thus, for accelerometer A1, if the first maximum has a value of 0.58 cm for the

jump from $h = 35$ cm, for the jump from 60 cm, the same peak has a value of 1.62 cm. The second peak of the oscillation maximum has a value of -1.81 cm for the jump from 35 cm, while for the jump from 60 cm, it has a value of -2.87 cm; the oscillation amplitude values then decrease over time.

The same happens for accelerometer A2, also in position 1, with amplitude peaks of -1.76 mm for height $h = 35$ cm (Figure 11) and -3.36 mm for $h = 60$ cm (Figure 17). The second peaks are $+4.09$ mm for $h = 35$ cm and 8.29 mm for $h = 60$ mm. It should be noted, however, that the maxima of the first oscillation differ from the jump from $h = 35$ cm to $h = 60$ cm, these values being $+2.86$ cm and -2.87 cm, respectively, for accelerometer A1. Meanwhile, for accelerometer A2, the maximum of the first oscillation was -6.13 mm for $h = 35$ cm and $+8.29$ mm for $h = 60$ cm. We believe, again, that the oscillation of the first plate (the upper one) induces additional oscillations of values that may differ from those expected.

For the A3 accelerometer, the same mode of variation of the oscillations of the elastic system of the springboard can be observed if we carefully analyze Figures 11 and 17, the first maximum being recorded at -2.97 mm for $h = 35$ cm and -6.10 mm for $h = 60$ cm for the same gymnast (40 kg). The maximum of the oscillation amplitudes is recorded at the next oscillation for both the 35 cm and 60 cm jump. The second amplitude peak had a value of 6.24 mm for $h = 35$ cm and 6.85 mm for the 60 cm jump.

Looking at Figure 18, we can observe the variation in the accelerations, velocities, and displacements of the springboard at the A1 accelerometer for the 40 kg gymnast's jump from 60 cm above the springboard, as well as the values of the characteristic points immediately after contact with the upper plate. However, small, insignificant delays are noted from accelerations to velocities and then displacements in terms of the moment of recording the characteristic moments. Thus, if the moment of the first acceleration maximum is at 578 0.5 ms ($+224.1$ m/s²), the same peak is recorded at the moment of 586 0.5 ms for the springboard speed (1.29 m/s) and at the moment of 604 0.5 ms for displacements; delays may result from the processing of the experimental data, although there was rigor in the processing of these data. The maximum amplitude moment deviations for the first peak are about 1.3% for velocities vs. accelerations and 5.2% for displacements vs. accelerations.

The same phenomenon is observed for the second amplitude peak at the 617 0.5 ms moment for accelerations (-199.5 m/s²), at 625–638 0.5 ms for velocities (1.38–1.56 m/s), and at the 703 0.5 ms moment (with a peak of 2.87 cm) for displacements. By calculating the percentage errors, we can say that they are within the limits of 2% for velocities vs. accelerations and the maximum of 12% for displacements vs. accelerations for the second peak. The variation mode is found, however, to be preserved for all three characteristic magnitudes of the oscillation.

Based on the graphs in Figure 18, the local equivalent stiffness can be estimated. Because the trampoline has a stiffness function, its oscillation is non-harmonic. Using the well-known relations $F = m \cdot a$ and $F = k \cdot x$ from the displacement graph, the equivalent stiffness k_{eq} can be estimated for the first period of the oscillation. Using experimental modal identification, the fundamental eigenfrequency (f_1) can be obtained by calculating the distance between the peaks in the displacement graph or Fourier analysis; the damping and the eigenmode of vibration may also be calculated.

$$k_{eq} = (2\pi f_1)^2 m_{ef} \quad (11)$$

where m_{ef} is the effective mass that imparts the movement, possibly adjusted by a factor. From the displacement graph, the period of the first oscillation can be estimated at about 0.058 ms, so that the oscillation frequency is $1/T \cong 17.33$ Hz. This eventually results in a

local equivalent stiffness of about 474,260 N/m. In the same way, the stiffness coefficients can be estimated for the other tests performed.

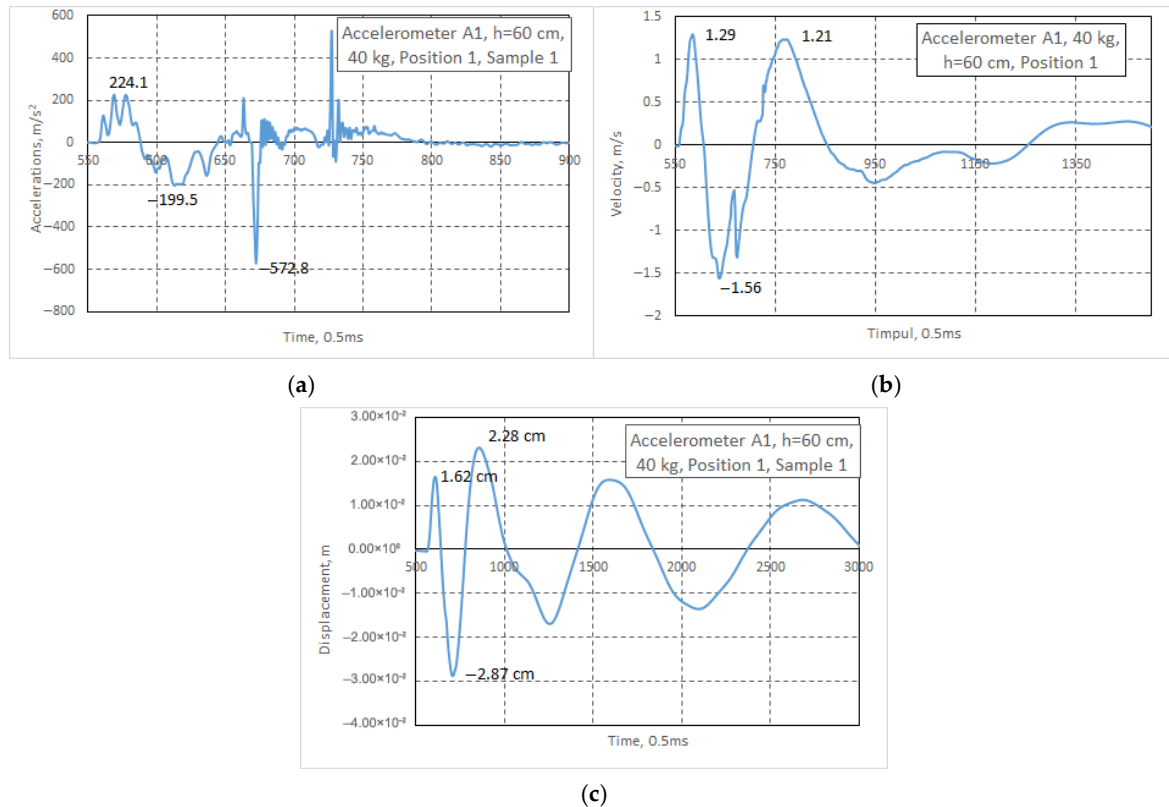


Figure 18. Springboard oscillation amplitudes (accelerations, velocities, and displacements) with the 40 kg student, $h = 60$ cm.

If we use relations (7) and (8), then for the graph in Figure 5a, a damping ratio $\zeta = 0.114$ is found at the main board of the springboard, using as input data the amplitudes of the maximum peak and the first positive peak of the oscillation amplitude, while for one of the lower plates (where the accelerometer A2 is positioned), the damping ratio is $\zeta = 0.167$, and for the other lower plate (where A3 is positioned), the damping ratio is $\zeta = 135$ when the basketball falls from a height of 1 m with the springboard in position 1.

For position 2, when the basketball falls from $h = 1$ m, the oscillation frequency at all three accelerometers is 13.33 Hz, and the damping coefficients are $\zeta = 0.060$ for A1, $\zeta = 0.088$ for A2, and $\zeta = 0.093$ for A3.

We observe a higher damping ratio at the lower plates, but it is not necessarily a rule. Random values are obtained for stiffness and damping ratio including for gymnasts' jumps, with the system being non-linear; however, as we have previously stated, all parameters can fall within certain ranges of values. Locally and for certain fixed moments, the values presented in this paper can be taken into account.

Finally, it can be said that the potential energy in the compression of the springboard is transformed into the kinetic energy of the gymnast, but the authors' intention was not to analyze the behavior of the gymnast but of the springboard, which acts as an elastic system (analogous to a spring), and for more in-depth calculations, the conservation of energy between the moment of maximum compression and the moment of the gymnast's release can be used.

4. Conclusions

In addition to other observations and suggestions resulting from the study of the specialized literature, by knowing the behavior of the elastic system of the springboard, interesting and important information can be obtained that can be used by gymnasts' coaches in order to achieve better jumping performance. The use of accelerometers under the springboard plates allowed us to obtain results about its behavior when a basketball of 0.500 kg and a circumference of 0.72 m falls in three positions along the length of the upper plate; we also obtained results regarding two gymnasts of different weights, who jumped from two different heights. It is expected that gymnasts will mainly use position 2 indicated in the paper (for safety reasons), and therefore, the authors insist on continuing experiments for this position.

It goes without saying that the coil springs (end and intermediate) are the ones that mainly ensure the elasticity of the trampoline and, together with the lower curved plates (which complete this elasticity), give the jumper the desired impulse, which the jumper obtains after several attempts in training.

It is also true that the accelerometers mounted on the lower curved support plates do not immediately provide information about the elasticity of the trampoline, which is ensured by the oscillations of the upper plate. However, upon further analysis, they can provide information about the behavior of the entire assembly (springboard) during the jump.

It was also found that in the dynamic process of a body falling on a springboard, the elasticity/stiffness coefficient of the elastic system changes, presenting values of over 22.14–71.12 kN/m, with values about three times higher for the first landing position on the springboard. These results may also be useful to manufacturers of such sports equipment for the creation of springboards with improved performance.

Author Contributions: Conceptualization, G.V. and N.O.; methodology, D.-M.D. and G.V.; software, G.V. and I.-A.I.; validation, G.V., N.O. and G.-A.C.; formal analysis, G.V.; investigation, D.-M.D. and N.O.; resources, D.-M.D.; data curation, G.V. and N.O.; writing—original draft preparation, D.-M.D. and N.O.; writing—review and editing, G.V. and G.-A.C.; visualization, I.-A.I.; supervision, G.V.; project administration, G.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding. The work is carried out, documented and edited during the doctoral internship of the first author, who is a doctoral student at the Politehnica University of Bucharest.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: For the preparation of this study, the authors used the Mechanical Vibrations laboratory of the Mechanics Department of the National University of Science and Technology Politehnica, Bucharest. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

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