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DEVELOPMENT OF A TEST BENCH FOR FRAME RUNNING (PETRA): LOAD CONDITIONS ANALYSIS AND CHARACTERIZATION

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Abstract. *This paper presents the development of a test bench to analyze the loads applied to Frame Runners, a device used in the para-athletic modality known as Frame Running (PETRA). PETRA is an adapted sport suitable for athletes with disabilities that affect mobility and balance, such as Cerebral Palsy. The device used in PETRA is a tricycle-like three-wheeled frame which allows athletes to propel themselves along the track by stepping their feet on the ground. In 2009, PETRA was taken to Brazil as an initiative of the Associação Nacional de Desportos para Deficientes (ANDE), the organization responsible for holding the events and championships in the country. In this context of promoting the sport and providing support to athletes, the Comitê Paralímpico Brasileiro (CPB) approached the authors proposing the design of an affordable and reliable Frame Runner. As PETRA is a relatively new modality, there is limited literature on the subject, which posed a challenge during the design stages as no clear load conditions were found. To overcome this challenge, the research team developed a test bench by instrumenting the structure with load cells in each one of the three wheel hubs and mounting it over an ergometric treadmill. The developed apparatus aimed to obtain data that closely resembled the real operating conditions of the equipment and provide the user with a similar feeling of use as on the track. The tests carried out on the test bench allowed the identification of the behavior and magnitude of the loads applied to the Frame Runner. The results showed that the loads have dynamic characteristics that vary depending on factors such as the user's stride technique and weight distribution on the equipment. The data obtained from the test bench will be used in the structural simulations of the new designed frames, ensuring optimal safety and performance for athletes. Additionally, the test bench can be used as a complementary tool in athletes' training routines. The research presented in this paper contributes to the development of Frame Running as a para-athletic modality and promotes the inclusion of athletes with disabilities in sports.*

Keywords: *Adapted Sports, Frame Running, PETRA, Load Analysis, Instrumentation, Biomechanics.*

1. INTRODUCTION

Frame Running, previously known as Race Running, was introduced in Denmark in 1989 as a Paralympic athletics discipline primarily targeting individuals with cerebral palsy and other mobility disabilities (Sidiqqi, 2022). Since its inception, this modality has grown in popularity and its potential inclusion in the 2024 Paralympics in Paris is currently under evaluation.

The assistive technology utilized in Frame Running resembles that of a tricycle, with the exception that it lacks pedals connected to the frame. Instead, the user generates propulsion by making contact with the ground using their feet. A trunk support system is employed to maintain the user's forward-leaning position and enables users to manipulate the handlebars for steering. The frame, typically constructed from steel or aluminum, takes on an arched tubular structure, featuring an open section at the posterior end to allow unrestricted movement of the user's lower limbs (Calve et al., 2018). The design of the equipment must adhere to category-specific regulations in terms of shape and dimensions, while also achieving a balance between stability and reduced weight, thereby ensuring the safe attainment of higher velocities (Domínguez, 2017).

The Frame Running apparatus promotes both the physical and emotional well-being of participants. Additionally, this equipment promotes greater autonomy for individuals with disabilities, facilitates inclusivity and socialization, and provides a perceptual experience of speed for those unable to engage in functional running.

In Brazil, the modality became known as PETRA and was introduced in 2009 through the Associação Nacional de Desportos para Deficientes (ANDE), and recently it has been managed by the Comitê Paralímpico Brasileiro (CPB).

Figure 1 depicts Brazilian athletes during a race in a national championship, providing a visual representation of the sport and the equipment used.

Figure 1. Brazilian PETRA athletes (ANDE, 2018).

One of the main challenges faced by coaches and para-athletes in Brazil during this implementation phase, hindering the sport's dissemination in the country, is access to equipment. Imported models are expensive, and although they may offer some size variations, it is crucial for optimal sport performance that the tricycle is adjusted according to each athlete's dimensions and characteristics (Hutzler, 2007). The most viable solution so far has been manufacturing the equipment themselves; however, these homemade solutions are not always well-designed and present issues of durability and instability, thereby jeopardizing the safety and performance of the athletes.

Following recurrent problems of breakage with one of the models used, representatives from the CPB reached out to the researchers from the Laboratório de Projetos Mecânicos Professor Henner Alberto Gomide (LPM) and the Centro Brasileiro de Referência em Inovações Tecnológicas para Esportes Paralímpicos (CINTESP.Br) to investigate the causes and develop a new design.

During this process, the authors encountered a scarcity of literature primarily due to the fact that this is a relatively recent category with limited studies focusing on engineering design aspects (Santos et al., 2021). Furthermore, certain crucial information necessary for the development of a new project was not readily available, particularly the lack of sufficient experimental data to establish clear loading conditions for the frame. Consequently, an experimental test setup was constructed to gather the required data and serve as a database for future work in this field.

2. OBJECTIVES

The overall objective of this study is to develop and validate a methodology for the experimental determination of general parameters in the PETRA category, in order to assist the authors in the optimized design of a new frame and future researches in the field. Additionally, the test setup aims to serve as a routine tool for athlete performance evaluation and training purposes. The specific objectives are:

- Evaluate the overall performance of athletes participating in PETRA;
- Identify the forces exerted on the frame, allowing for a comprehensive understanding of the structural demands;
- Analyze the techniques employed by different athletes and identify patterns that contribute to optimal performance;
- Investigate the distribution of weight among athletes during PETRA races;
- Determine the athlete’s frequency of strides;
- Contribute to the advancement and widespread of Paralympic sports.

3. DEVELOPMENT OF THE TEST BENCH

A primary concern during the development of this stage was to ensure that the experimentally obtained data closely matched the real operating conditions of the equipment. The assembly of the structure should provide the user with a similar sensation to its use on the track. To achieve this, the most important factor perceived was the restriction of degrees of freedom of the frame, aiming to ensure experimental-real-world parity and safety throughout the tests, while not affecting the measured force values captured by the load cells.

During the race, the frame is subjected to various forces with different orientations and intensities. However, the available load cells for the experiment are of the "S" type, which are specifically designed for measuring forces in the tension/compression direction. Therefore, it is necessary for the assembly of these components to guide the forces towards their ideal operating direction while avoiding the introduction of unwanted degrees of freedom to the system. By meeting these requirements, it is ensured that the load cells will not be damaged, and the obtained data will be reliable.

Monitoring the athlete's loads during track running presents challenges. Therefore, the utilization of an ergometric treadmill for simulation purposes becomes necessary. This adaptation is common in biomechanics research, offering several advantages, such as requiring less physical space, the ability to set and maintain consistent speeds across multiple sessions, and the capability to record multiple running cycles (Künzler et al., 2023).

3.1 MATERIALS

The tricycle model used in the study was provided by the CPB. It is a model manufactured in Brazil at the request of the CPB to meet the limitations of the competition regulations and aiming at a low production cost and is the most commonly used in the country. This model is mainly used to serve the sport initiation program, not being a specific competition model. The frame is manufactured from aluminum alloy and has a total mass of 3,7 kg.

Three load cells model CKS-1 from the manufacturer Kratos® were selected for use in the test bench. It has a maximum weight capacity of 200 kg with a rated output power of 2 mV/V and has an uncertainty of 0,03% of Full Scale being suitable for measurements with high precision.

The data acquisition system used to collect the signals transmitted by the load cells was the ADS1800 from Lynx®, which has a sampling rate of 24,000 data points per second, a resolution of 24 bits, and 8 measurement channels. The ADS1800 serves as a microcontroller, processing and transmitting the measurements obtained from the sensors to the computer. The computer is equipped with the AqDados software, which performs analysis and calculations on the collected data.

For the purpose of simulating the race, an EG 700.1 ergometer treadmill from the brand ECAFIX® was used. This treadmill has a usable running width of 515 mm, which is sufficient to accommodate the PETRA setup. The treadmill is controlled through the ERGO PC 1.3 software, allowing the operator to manually set the test speed with a resolution of 0,1 km/h.

3.2 CAD design

All dimensions of tubes present in the PETRA's frame were measured so that a model identical to the original was recreated in the Computer Aided Design (CAD) software SolidWorks®. Figure 2 shows the PETRA model used.

Figure 2. Frame Runner CAD model

Next, the wheels were decoupled so that only the frame remained suspended over the treadmill. All dimensions of the treadmill were measured to reconstruct its base in CAD and serve as a reference for proper positioning of the supports. Figure 3 illustrates the overall assembly of the test setup. The balloons indicate the load cells: 1- Rear Right; 2- Rear Left; and 3- Front. This numbering system will be used throughout the article.

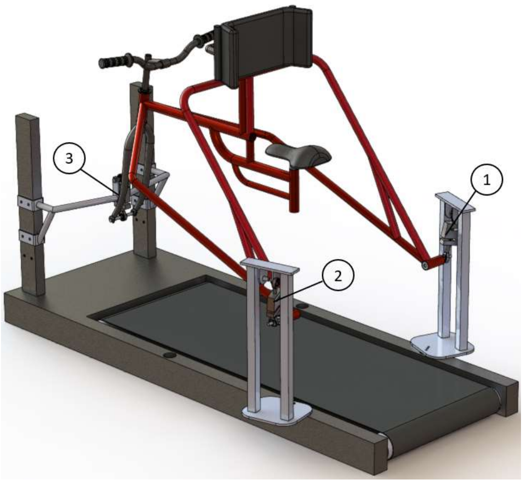

Figure 3. Test bench CAD assembly

To ensure that all forces captured by the load cells are accurately directed in their intended working direction, they are mounted on the structure and base using two spherical rod ends. In this configuration, the spherical rod ends self-adjust to compensate for any undesired force orientations. Another critical consideration is to ensure that the assembly maintains stability to guarantee safety during the tests and foster user confidence in the equipment. Therefore, it was decided to mount the load cells in the traction direction and with a slight inclination to guarantee that the PETRA was suspended in a stable manner with minimal clearance. Figure 4 provides a detailed view of the assembly of the load cells on the front support (left) and rear support (right).

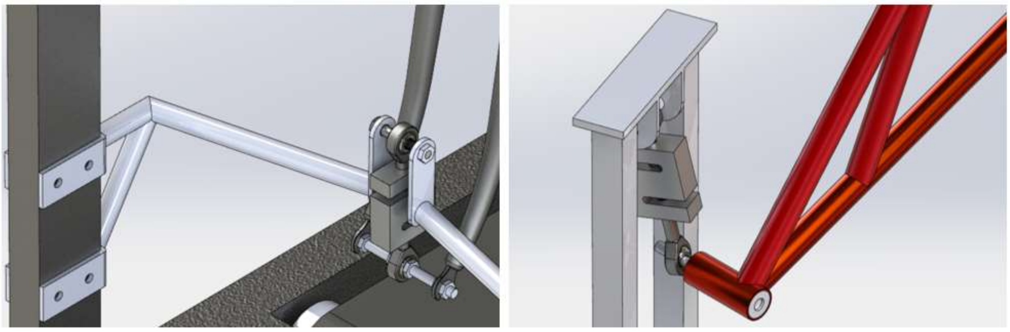

Figure 4. Assembly of the load cells on the front support (left) and rear support (right)

3.3 FEA Analysis

Once the design of all equipment components was finalized, structural simulations of the front and rear supports were conducted to ensure proper sizing and capability to withstand forces during testing, thereby ensuring participant safety. The geometries were exported to the Finite Element Analysis (FEA) software, ANSYS® Workbench, where the simulations were performed. The specified material was 1020 carbon steel and its mechanical properties can be found in the Table 1 bellow.

Table 1. Material's mechanical properties (Callister, 2008)

Properties	1020 carbon steel
Density	7,85 g/cm³
Modulus of Elasticity	207 GPa
Poisson's Ratio	0,30
Yield Strength	350 MPa
Ultimate Tensile Strength	420 MPa

The boundary conditions imposed were the fixation of the supports at the points where they are bolted to the treadmill base. As for the simulated loading condition, a downward vertical force of 1000 N was applied at the location where the load cell is attached. This value was selected to ensure that each support could individually withstand the weight of the user. The simulations were performed, and the model's mesh was refined until convergence of results was achieved. The mesh used was of the tetrahedral type, as this element type allows for good geometry filling with minimal computational processing (WANG et al., 2004), and its size was determined through convergence analysis, using the Skewness parameter as a measure of mesh quality. According to the user guide of the ANSYS® software, values less than 0.5 indicate a good mesh quality, so it was established that the maximum skewness value of the mesh would not exceed this limit.

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The results of the static simulation for the rear support (Figure 5) showed low values of displacement and stress. A maximum displacement of 0,0380 mm with a maximum equivalent von-Mises stress of 19,2 MPa.

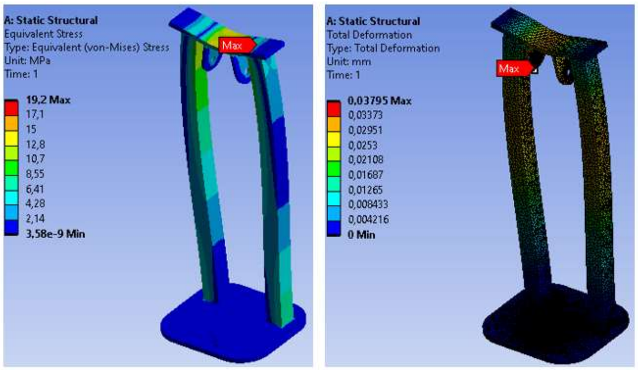

Figure 5. Equivalent von-Mises stress (left) and total deformation (right) simulations results for the rear support

For the front support, the simulations resulted in low values as well (Figure 6). A maximum displacement of 0,1965 mm with a maximum equivalent von-Mises stress of 48,9 MPa. Consequently, both supports exhibited resistance with stress levels well below the material's yield strength, confirming their structural integrity and safety for testing.

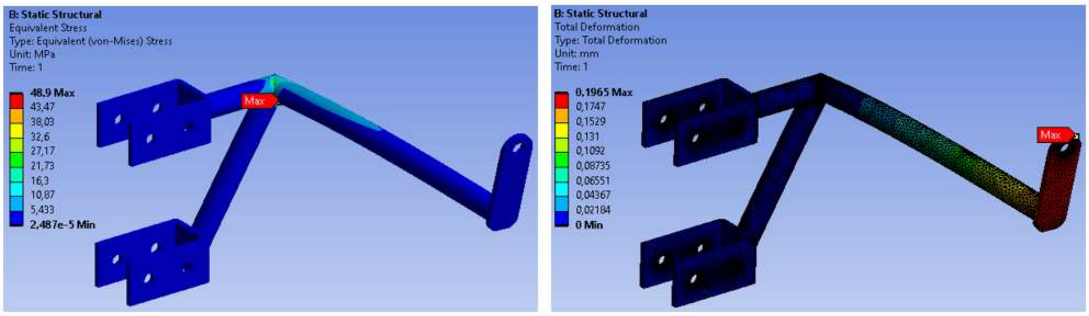

Figure 6. Equivalent von-Mises stress (left) and total deformation (right) simulations results for the front support

Only static simulations were conducted, and dynamic simulation for fatigue life assessment of the components was not performed at this initial stage. The prototype is currently in the concept validation phase, and one of the objectives is to experimentally confirm the level and behavior of the load on the structure. Once the methodology has been validated, the supports will undergo further adjustments, and dynamic analysis will be carried out to account for the cyclic nature of the loadings.

4. METHODOLOGY

In this initial proof-of-concept phase of the test setup, the experiments were conducted with the participation of two volunteers from the research team. In Figure 7, one of the researchers involved in the study is positioned at the test setup to conduct the experiments.

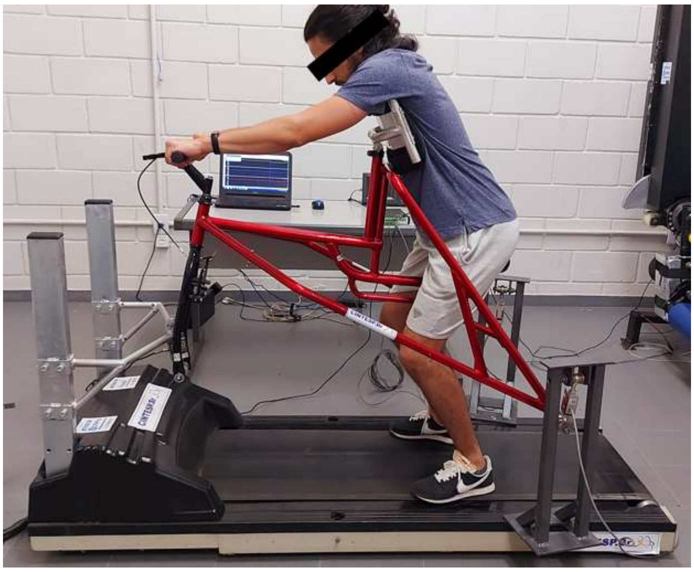

Figure 7. Participant positioned on the treadmill for test execution

Three different velocities were selected for analysis: 6 km/h, 10 km/h, and 14 km/h. For each velocity, three separate trials were performed. Prior to the testing, participants underwent a brief warm-up period to prepare for the running sessions. During each trial, the participants initiated the running motion and maintained a steady pace. It was recorded data with the duration of 15-second for each run. During this time, various parameters were recorded, including force exerted on the load cells and the speed of the treadmill. Following the completion of each trial a short rest period was provided to prevent fatigue and to ensure reliability.

4.1 Treadmill calibration

Calibration of the ergometer treadmill was conducted to ensure that the tests were performed at the correct speeds. For this purpose, a piece of tape was affixed to the treadmill, and the total time for each lap was recorded. With knowledge of the total length of the treadmill surface being 3 meters, the actual velocity could be calculated. Table 2 presents the calibration data obtained for the three speeds. It can be observed that the highest relative error found was 4,51%, a value considered small and not significantly affecting the experiment.

Table 2. Treadmill calibration

	6 km/h		**10 km/h**		**14 km/h**	
	Δt [s]	**v [km/h]**	**Δt [s]**	**v [km/h]**	**Δt [s]**	**v [km/h]**
1	1,87	5,78	1,13	9,56	0,81	13,42
2	1,88	5,76	1,10	9,82	0,81	13,33
3	1,88	5,74	1,17	9,23	0,82	13,17
4	1,89	5,71	1,13	9,56	0,79	13,67
5	1,83	5,9	1,13	9,60	0,82	13,25
Mean	1,87	5,78	1,13	9,55	0,81	13,37
	Error	3,68%	**Error**	4,47%	**Error**	4,51%

4.2 Load cell angle correction

As previously mentioned, the load cells were mounted with a slight inclination. Therefore, since the vertical component of force is of primary interest, it was necessary to perform the decomposition of the force vector. Figure 8 illustrates this step. The α-angle measured in the front was 5,50º and in the rear was 11,25º.

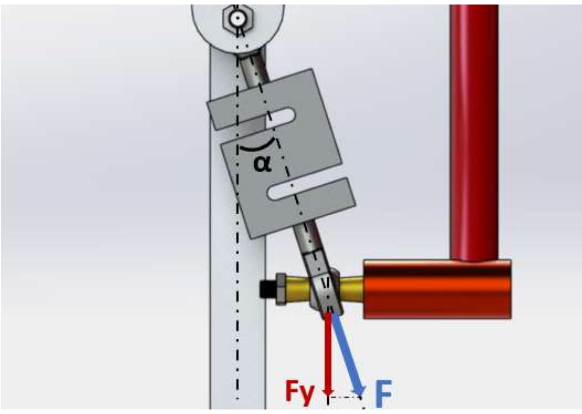

Figure 8. Schematic depicting the decomposition of the force vector into its vertical component

During the tests, small variations in the angular position of the load cells were observed due to the assembly with the spherical-end fittings. However, for the purpose of this article, it will be assumed that the angular position is fixed. In future work, further investigation will be necessary to address and mitigate the effects of these variations completely.

5. RESULTS AND DISCUSSION

The tests were conducted as mentioned in the methodology section and the data was collected. Figure 9 is a print from the AqDados software plot for the load values obtained by each one of the load cells during the 15 seconds of one of the trials (Participant B – 10 km/h) to serve as an exemplification. In the graph it can be observed a periodic pattern that repeated in every trial. From the data of all trials it was analyzed the load range and its correlation with the stride frequency.

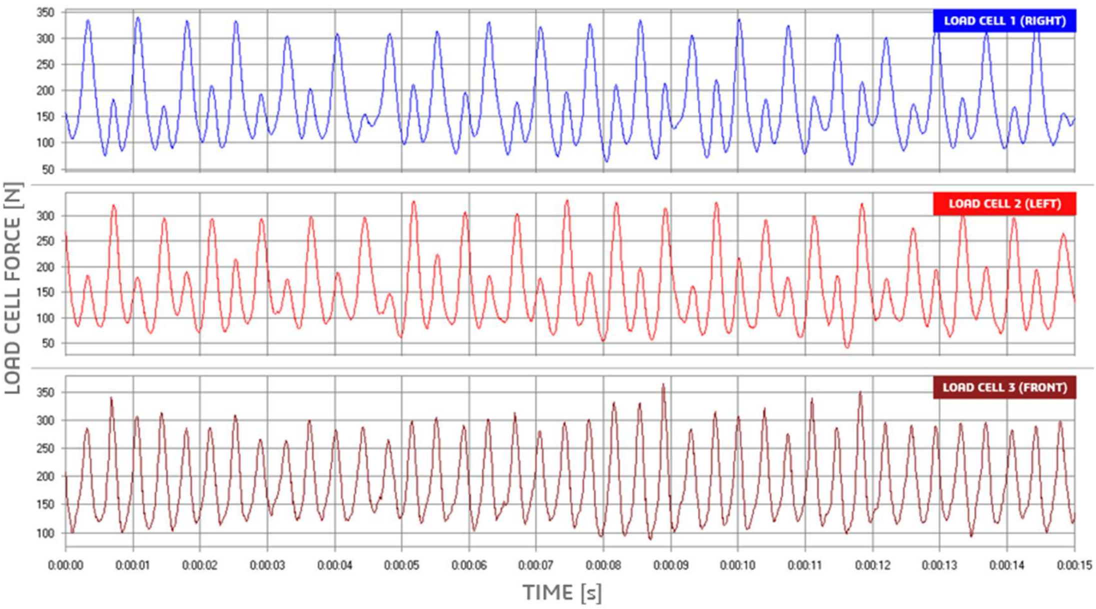

Figure 9. Load cells readings during one of the test trials (Participant B – 10 km/h)

5.1 Load Analysis

The raw data collected by the data acquisition system were processed and converted into a text file for export to MatLab®, where further calculations and analyses were conducted. To gain an understanding of the force levels, the mean values were calculated for each trial, followed by the overall mean of the three trials for each speed. Additionally, the maximum force observed for each speed was recorded. Experimental results were organized for each velocity: 6 km/h (Table 3), 10 km/h (Table 4), and 14 km/h (Table 5).

Table 3. Experimental results for 6 km/h

		Rear Right			Rear Left			Front		
		Load cell forces [N]			Load cell forces [N]			Load cell forces [N]		
Participant	**trial**	**mean**	**MEAN**	**MAX**	**mean**	**MEAN**	**MAX**	**mean**	**MEAN**	**MAX**
A	1	141,72	118,75±16,36	360,10	92,22	75,98±12,74	293,32	154,88	143,50±8,08	319,26
	2	109,70			61,09			136,99		
	3	104,83			74,63			138,62		
B	1	163,21	163,36±7,16	344,65	149,07	148,81±5,00	317,40	189,74	188,24±3,59	333,56
	2	154,66			142,56			183,29		
	3	172,20			154,80			191,70		

Table 4. Experimental results for 10 km/h

		Rear Right			Rear Left			Front		
		Load cell forces [N]			Load cell forces [N]			Load cell forces [N]		
Participant	**trial**	**mean**	**MEAN**	**MAX**	**mean**	**MEAN**	**MAX**	**mean**	**MEAN**	**MAX**
A	1	105,24	106,35±5,87	256,30	71,91	76,28±4,01	212,29	142,47	139,33±2,32	253,62
	2	114,04			81,60			136,94		
	3	99,78			75,33			138,58		
B	1	167,73	166,92±0,77	367,02	152,39	150,45±1,52	338,47	188,19	186,80±1,02	363,87
	2	167,14			148,69			186,41		
	3	165,88			150,27			185,79		

Table 5. Experimental results for 14 km/h

		Rear Right			Rear Left			Front		
		Load cell forces [N]			Load cell forces [N]			Load cell forces [N]		
Participant	**trial**	**mean**	**MEAN**	**MAX**	**mean**	**MEAN**	**MAX**	**mean**	**MEAN**	**MAX**
A	1	145,10	135,03±7,14	255,48	102,02	97,83±5,89	236,37	158,23	151,55±5,37	332,41
	2	129,33			89,49			145,08		
	3	130,66			101,97			151,55		
B	1	139,06	130,76±7,29	391,38	122,27	114,69±6,58	349,12	163,35	157,82±5,08	380,39
	2	121,29			106,22			151,08		
	3	131,93			115,57			159,04		

As expected, test results with participant B, who had a higher body weight, generated higher force levels compared to participant A. Additionally, both participants exhibited a load imbalance, with load cell 1 (rear right) receiving more force than load cell 2 (rear left). It is important to note that special care was taken to ensure the equipment was properly aligned during the setup and testing processes. These measures minimized the impact of assembly factors on load distribution, and any remaining imbalance may be attributed to differences in running form, gait mechanics, or individual biomechanical factors between the participants. Low to moderate asymmetry is a natural phenomenon in recreationally trained runners during treadmill graded exercise testing (Olivier et al., 2022)

Interestingly, for both participants, the standard deviation of the mean forces was smaller during tests with intermediate speeds (Table 4). This observation suggests that running at intermediate speeds may result in more consistent force exertion on the PETRA equipment compared to running at higher or lower speeds.

However, the study faced challenges in establishing a direct relationship between speed and forces due to the strong dependency on individual user characteristics and the highly dynamic nature of running. While it was anticipated that increasing the speed would result in higher force values due to the greater impact forces, this relationship was not uniformly observed for all participants. Some tests showed increased forces at higher speeds, while others did not exhibit a significant correlation between speed and force levels.

5.2 Stride frequency

The data obtained from the force measurements exhibited a clear periodic pattern, indicating a cyclic behavior in the running motion. To illustrates this, Figure 10 is a zoomed-in plot of the forces signals from the previously mentioned Figure 9 where it was sectioned the distinctive moments of each stride. Upon closer examination, it was observed that the valleys in the force signal of the central load cell coincided with the moment of each footstrike, indicating the occurrence of a stride. Subsequently, a higher force peak was observed in the load cell on the opposite side of the foot that performed the stride, suggesting that the participant shifted their body weight to the opposite side during the running motion.

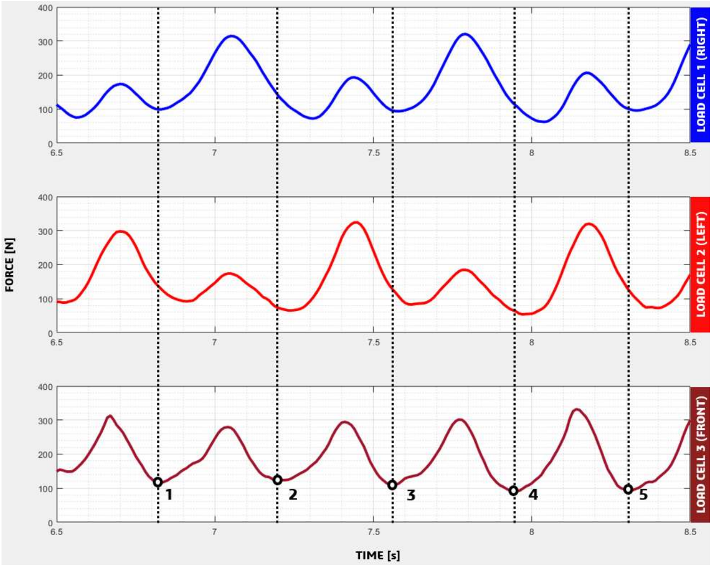

Figure 10. Periodic stride pattern analysis from one of the test trials (Participant B – 10 km/h)

To further investigate the stride frequency during the tests, the force data was subjected to a frequency analysis using Fast Fourier Transform (FFT). This procedure decomposes the force signal into its frequency components, allowing us to identify the dominant frequencies (Inman, 2007) and relate them to the stride frequency. The FFT analysis revealed peaks in the frequency spectrum, which corresponded to the stride frequency at each running speed (Figure 11).

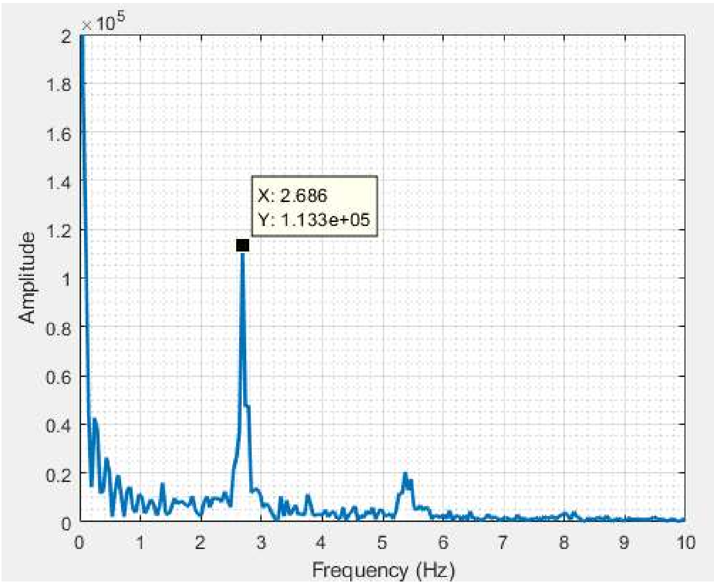

Figure 11. Frequency spectrum of load cell force signal (Participant B – 10 km/h)

The values of frequency were extracted from the frequency spectrum of each trial's force signals. The average frequency and standard deviation were then calculated for each running speed. The obtained results were compiled to create Table 6.

Table 6. Experimental results for strides frequencies

		6 km/h [steps/s]		**10 km/h [steps/s]**		**14 km/h [steps/s]**	
Participant	**trial**	**frequency**	**mean**	**frequency**	**mean**	**frequency**	**mean**
A	1	2,539	2,669±0,122	2,979	2,963±0,023	3,125	3,158±0,046
	2	2,637		2,979		3,223	
	3	2,832		2,930		3,125	

	1	2,539		2,783		3,271	
B	2	2,490	2,458±0,083	2,832	2,767±0,061	3,516	3,369±0,106
	3	2,344		2,686		3,320	

As expected, the stride frequency increased with higher running speeds, indicating that participants adjusted their cadence to maintain a consistent gait rhythm at different velocities. Notably, the low value of the standard deviation indicated the consistency of the participants to maintain a steady rhythm to sustain the same velocity.

6. CONCLUSIONS

Overall, this study represents a promising first step in analyzing loads during PETRA exercises. While still a proof-of-concept stage, the methodology showed great potential for characterizing structural efforts and the load conditions will aid the optimization design of the equipment. The analysis of force distribution offered valuable insights into the biomechanics aspects of Frame Running. It was observed clear relationships between force patterns and stride frequency, providing a valuable tool for understanding gait mechanics and performance evaluation.

It is essential to acknowledge the challenges encountered in characterizing the forces involved in PETRA sports. The significant dependency on individual characteristics and the dynamic nature of running present obstacles in precisely quantifying force distribution. Although the participants in the study did not present cerebral palsy-related pathologies, further investigation with athletes from the specific category is needed to better understand the sport's unique demands.

The research's results also demonstrate the feasibility of implementing force analysis in routine training to identify areas for performance improvement in athletes. As PETRA sports continue to gain popularity, this methodology may serve as a valuable resource for coaches and athletes seeking to optimize their training programs and enhance overall performance.

7. ACKNOWLEDGEMENTS

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