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Balancing acts: a case study of postural stability comparison between active and retired aerobic gymnastics athletes with inclinometer sensors

Actos de equilibrio: un estudio de caso de la comparación de la estabilidad postural entre atletas activos y retirados de gimnasia aeróbica con sensores de inclinómetro

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Abstract. Objective: This research introduces an innovative method for accurately measuring body stability in real-time using a wearable inclinometer sensor and measuring differences in the stability abilities of active and ex-aerobic gymnastics athletes in performing three stability movement tasks based on three types of balance. Methods: A total of 8 people consisting of 4 athletes (2 Males, 2 Females) age M 21 ± SD 4.4 and 4 former athletes (2 Males, 2 Females) age M 39 ± 3.3, were instructed to carry out bipedal, unipedal and tiptoe stability tests. Results: The results of the correlation test between stability components show that this wireless inclinometer instrument has high validity results. In the bipedal stability test, ex-athletes showed better abilities than active athletes, but on the other hand, for more difficult stability tasks, active athletes showed better performance. The results of the difference test in the sagittal plane show significant results in all stability schemes, and in the frontal plane, only one stability scheme shows a significant difference. Conclusion: The instrument utilized in this study demonstrates a good validity for assessing body postural stability across three balance categories. Significantly, it reveals pronounced differences between active and retired aerobic gymnastics athletes, particularly in maintaining stability, notably in the sagittal plane compared to the frontal plane.
Keywords: Angle Measurement, Postural Stability, Sports Measurements, Wearable Sensor, Wireless Inclinometer

Resumen. Objetivo: Esta investigación introduce un método innovador para medir con precisión la estabilidad corporal en tiempo real utilizando un sensor de inclinómetro portátil y para medir las diferencias en las habilidades de estabilidad de los atletas de gimnasia aeróbica activos y ex-atletas al realizar tres tareas de movimiento de estabilidad basadas en tres tipos de equilibrio. Métodos: Un total de 8 personas, compuestas por 4 atletas (2 hombres, 2 mujeres) con una edad promedio de M 21 ± DE 4.4 y 4 ex-atletas (2 hombres, 2 mujeres) con una edad promedio de M 39 ± 3.3, recibieron instrucciones para llevar a cabo pruebas de estabilidad bipedal, unipedal y de puntas de pie. Resultados: Los resultados de la prueba de correlación entre los componentes de estabilidad muestran que este instrumento de inclinómetro inalámbrico tiene resultados de alta validez. En la prueba de estabilidad bipedal, los ex-atletas mostraron mejores habilidades que los atletas activos, pero por otro lado, para tareas de estabilidad más difíciles, los atletas activos mostraron un mejor rendimiento. Los resultados de la prueba de diferencia en el plano sagital muestran resultados significativos en todos los esquemas de estabilidad, y en el plano frontal, solo un esquema de estabilidad muestra una diferencia significativa. Conclusión: El instrumento utilizado en este estudio muestra una fuerte validez para evaluar la estabilidad postural del cuerpo en tres categorías de equilibrio. Significativamente, revela diferencias pronunciadas entre los atletas de gimnasia aeróbica y los ex-atletas, especialmente en cuanto a mantener la estabilidad, notablemente en el plano sagital en comparación con el plano frontal.
Palabras clave: Medición de ángulos, Estabilidad postural, Mediciones deportivas, Sensor portátil, Inclinómetro inalámbrico

Fecha recepción: 07-05-24. Fecha de aceptación: 10-07-24
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Introduction

Balance is a component of physical skills related to maintaining balance both while still and in movement. This is important for carrying out daily activities, maintaining body posture, and preventing falls or accidents. The definition of balance itself is the act of keeping the center of gravity above the base of support, where the closer the center of gravity is to the base of support, the more stable it is (DeFrancesco & Inesta, 2012). To train overall stability, dynamic stabilization movement exercises, isometric movements, and proprioception are needed not only for the middle part but the entire trunk. Tools such as medicine balls, balance boards, foam rollers, and physio balls are highly recommended for core training and should be integrated into every program, as exercises with physio balls have been proven to be more effective than traditional floor exercises. As we age, balance and stability become impaired. If balance and stability are not addressed, both will continue to be degraded (DeFrancesco & Inesta, 2012). It is important to remember that to maintain balance, a person needs optimal interaction mechanisms between work, proprioceptive, vestibular, and visual with the external world, which is integrated by the nervous system (Zavalishina et al., 2022), even psychological factors (Jaroslaw Omorczyk et al., 2019). A weak core contributes to poor stability, and hinders proper limb movement, causing muscle imbalances in the kinetic chain (DeFrancesco & Inesta, 2012).

Several methods can be used to assess an athlete's balance such as the Single Leg Stand (Fadillah et al., 2023), Balance Error Scoring System (BESS), Star Excursion Balance Test (SEBT) (Gable & Lockard, 2023), and Balance Test on Force Plate (Je & Choi, 2022), (Istenič et al., 2015), and Flamingo Balance Test (Asan et al., 2021). The Star Excursion Balance Test is a relatively inexpensive and simple example of assessing an athlete's balance. This test requires athletic tape and a floor marked with a star pattern consisting of eight directions spaced forty-five degrees apart. Athletes are asked to place one foot in the center of the star and reach as far as possible sequentially in eight directions while maintaining balance and tapping the floor. The distance from the center of the star to the beat site is measured (Martin, 2016), Y-Balance Test (Plisky et al., 2021). Gait-force model to extract bio-mechanics information in both the dynamic state as in the gait analyzer and the steady state as in the balance scale (Li et al., 2016), the determination of postural sway quantified by tracking the trajectory of the Center Of Pressure (COP) (Williams et al., 2016), CQ-Stab 2P two-platform posturograph (Jaroslaw Omorczyk et al., 2022), center of pressure (CoP)-related parameters and surface electromyography (Rizzato et al., 2021), three-dimensional (3D) motion-capture system (Noamani et al., 2020), as well as a single lumbar inertial measurement unit (IMU) to discriminate between the three Y-Balance Test reach directions (Johnston et al., 2016), even using an iPhone (McNab et al., 2011).

One of the field tests commonly used to assess body balance is the One Leg Standing Test (OLST). The test is carried out by standing on one leg, the sample is instructed to stand on one leg as long as possible, keeping the standing leg straight, the other leg bent, and the arm at his side. The individual performing the test should be trained to stop the test when the athlete's arm moves away from his or her side, the supporting leg moves across the floor, or the raised leg touches the floor. The result measured is the length of time the athlete remains balanced on each leg (Martin, 2016). OLST itself can be done with eyes open (Seichi et al., 2014), and eyes closed (Johnston et al., 2016) depending on the purpose of the activity and the balance situation in the actual world, or both eyes open and closed as conducted on the Unipodal Test for Static Body Stability (TUPECE) (Díaz Escobar et al., 2021). A test to measure the ability to stand on one leg using an innovative tool has also been carried out by (Tanaka et al., 2023) by focusing on upper body mass and segment control in maintaining body balance, as well (Zaghlul et al., 2023) who performed stability tests using one leg on the Lafayette Stability platform. The use of easy-to-use sensors will be very beneficial for everyday life and has the potential to function as a balance aid in everyday life, which can be used indoors and outdoors (Ma et al., 2016).

The use of sensors in measuring the body of athletes is an urgent need following current developments and technology (Espinosa et al., 2019). This is very rational because the components and sensors measuring various variables of the human body's abilities are now sophisticated and starting to be affordable. However, the use of inclinometer sensors to measure balance in real-time is not widely used at present. In various articles published in the last 10 years, personal balance tests are still carried out manually with a specific time or average time as a measure, such as in the OLST which aims to indicate both static and dynamic balance. The use of sensors to measure body balance is still limited to several previous studies such as comparing body and trunk sway kinematic data calculated based on sensors with data from force platforms (Bertolotti et al., 2016).

Inclinometers have been used in many studies related to abilities and studies of the human body and joint movement, such as in research on lower locomotor joint movement. (Francia et al., 2022) which is limited to the sagittal axis, the use of an inclinometer to measure ankle joint mobility (Francia et al., 2020), Range of motion (ROM) assessment (Cejudo et al., 2020), body posture (Barwais et al., 2013), standing and sitting time activities (Contardo Ayala et al., 2022), to measure the angle between the tibial shaft and the vertical (Bennell et al., 1998), quadriceps muscle flexibility using maximal knee flexion angle (Bender et al., 2019), knee joint angle (Jakobsen et al., 2013), upper arm elevation, upper back, head, and neck forward flexion postures (Cid et al., 2020), shoulder flexion and scaption range of motion (Dejaco et al., 2023), spending time in standing position (Diniz et al., 2016), and to measure joint position sense (JPS), and the strength ratio of external and internal rotators (ER/IR) in handball athletes (Pinheiro et al., 2020). Of all the uses of inclinometers, none has specifically recorded a person's balance ability over a certain period, to then observe the balance condition. This research aims to reveal the usefulness and validity of a time-based inclinometer for measuring body balance in real-time, combined with OLST which has been widely used in various scientific studies. OLST itself has become an instrument that is often used to determine a person's balance ability both while still and in motion (Kobayashi et al., 2023). The center of mass is defined as the fulcrum (axis, fulcrum) around which an object will be in equilibrium under the influence of gravity (Middleditch, 2001). If we refer to this definition, time is not an important variable in determining whether a person has good balance, but rather how a person tries to keep his body weight centered on the center of gravity of his body, and as much as possible not to change his position accordingly. to the three-dimensional corners of his body. This is different from the body stability instrument in the traditional OLST test which uses units of time as its measurement standard.

Stability research within the scope of gymnastics has been carried out by (Opala-Berdzik et al., 2021) where gymnastics training contributes positively to the body's postural sway becoming more stable, for senior gymnasts visual control does not have much influence in maintaining stability when standing (Puszczałowska-Lizis & Omorczyk, 2019), a physical education curriculum that focuses on gymnastics can accelerate the development of movement abilities compared to a regular physical education curriculum. It is characterized by greater improvement in stabilization and object control skills (Rudd et al., 2017). Gymnastics training causes positive stimulation of the systems involved in increasing stability and improving kinesthetic awareness, spatial coordination, and postural rigidity (Jaime-Gil et al., 2021). In the Aerobic Gymnastics branch, the skill of standing on one leg and tiptoe is one of the basics of many difficult standing element "C" movements such as Turns, Illusion, Balance, and Vertical Split. In executing the difficulty of turns, athletes must focus their entire body weight on a narrow pivot point, usually the tip of one foot, while performing a horizontal rotational movement. This requires optimal core stability and overall body control.

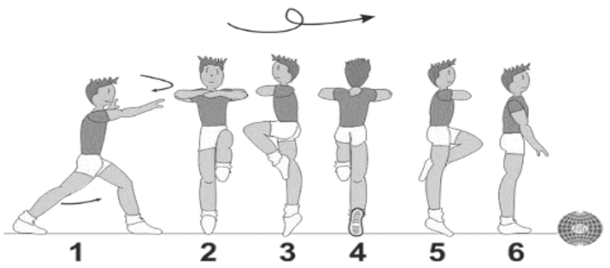

Figure 1. The Turn Difficulty (FIG, 2020)

Similarly, in the illusion movement, the pivot point remains on one foot, but the body rotates in the sagittal plane, either forward or backward. For the balance movement, the athlete's center of gravity is on one foot while rotating and maintaining the other leg as close to the body as possible. The vertical split movement also demands superior body stability to perform a vertical split position perfectly. This study aims to present a novel approach for real-time measurement of body stability using a wearable inclinometer sensor. It also examines the differences in stability capabilities between active and former aerobic gymnastics athletes as they perform three stability movement tasks based on three types of balance.

Methods

A total of 8 people consisting of 4 athletes (2 Male, 2 Female) age M 21 ± SD 4.4 and 4 former athletes (2 Male, 2 Female) age M 39 ± 3.3, were instructed to carry out the Bipedal test which represents a stable balance condition, OLST which represents normal balance conditions and Tiptoe which represents labile balance conditions. The sensor itself consists of two parts, namely the sensor hardware part in the form of a device measuring 42.8mm long, 36.1mm wide, and 15mm thick, which is attached to the test participant's body by attaching it to the bottom of the test participant's sternum using a flexible and adjustable rubber strap. with the test taker's body size so that it fits well and reduces the potential for it to shift out of place during the test. Each testee carries out the test for ± 10 seconds for each variation. During the test, the sensor hardware installed on the testee's body provides real-time data on the testee's movements from three-dimensional angles of the body axis during the test, which are recorded every 0.1 seconds via Bluetooth to be recorded on the software installed on the computer and become test results.

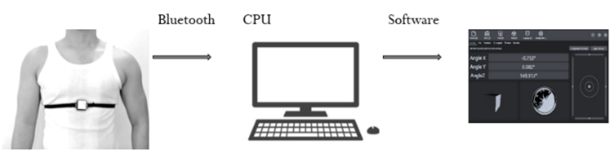

Figure 2. Stability recording flow via wireless inclinometer

We recorded the X-axis to represent the Sagittal plane and the Y-axis to represent the frontal plane of the bodies of the samples. The frontal axis is defined along the mediolateral direction; the sagittal axis is defined along the anteroposterior direction.

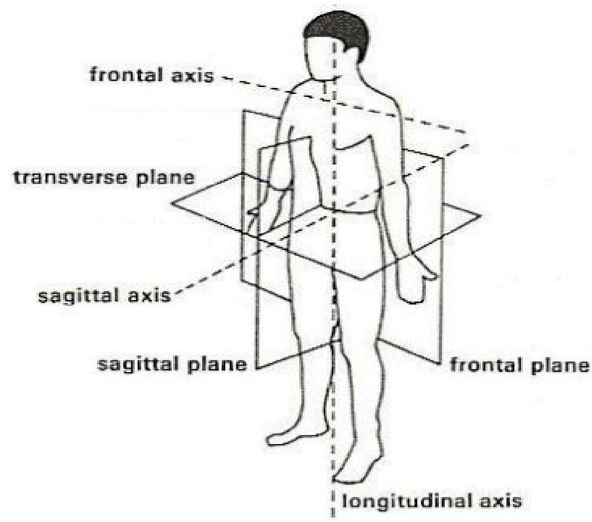

Figure 3. Body Planes and Axis (Sato et al., 2010)

These results are processed using statistical software to obtain descriptive and inferential statistical results.

Table 1.
Anthropometric Descriptives

	Status	Weight	Height	Age	BMI
N	Active	4	4	4	4
	Ex	4	4	4	4
Mean	Active	53.3	159	21	21
	Ex	67.3	165	39	25
SD	Active	7.8	6.29	4.4	2.1
	Ex	8.34	8.66	3.3	0.6
Min	Active	42	150	15	19
	Ex	57	155	37	24
Max	Active	60	165	25	23
	Ex	75	173	44	25

Results

Table 2.
Descriptive Data

	Status	Bi-X	Bi-Y	Uni-X	Uni-Y	X-Tip	Y-Tip
N	Active	286	286	286	286	286	286
	Ex	286	286	286	286	286	286
Mean	Active	2.42	,316	,317	,192	.71	-1.86
	Ex	1.53	-.032	,523	.0627	,962	-19.8
SEM	Active	,285	.0639	,198	,044	.15	,258
	Ex	.24	.0116	.108	.0257	,633	2.03
SD	Active	4.82	1.08	3.35	,745	2.53	4.36
	Ex	4.05	0.197	1.82	,435	10.7	34.3

The table provides a detailed description of the characteristics of two groups, namely the group who are still active in sports (Active) and the group of former athletes (Ex-athletes). By using several measured variables, we can understand the differences between these two groups. First, our attention is drawn to the same number of data (N) for

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both groups, namely 286, indicating a balance in the number of respondents observed. Then, we look at the average (Mean) of the observed variables. In the Active group, the Bi-X mean was 2.42, while the Bi-Y mean was 0.316. Meanwhile, in the Ex-athlete group, the average Bi-X was 1.53 and the average Bi-Y was -0.032. This indicates a difference in score tendencies between the two groups, with the Active group having a higher mean score compared to the Ex-athlete group. Then, we look at the Standard Deviation (SD), which measures how far the data is spread out from the mean. The Ex-athlete group had higher SD in some variables such as Tip-X and Tip-Y, indicating greater variation in their data compared to the Active group. This may indicate a greater degree of diversity in experiences or characteristics observed within the group of former athletes. Next, we look at the Standard Error of the Mean (SEM), which provides an estimate of how accurately the sample mean represents the population. The Active and Ex-athlete groups had varying SEM, indicating different levels of mean estimation accuracy between the two groups.

Table 3.
Correlation between stability variables

Correlation Matrix			
Bi-Y - Bi-X	Kendall's Tau B	,083	**
	p-value	,003	
Uni-X - Bi-X	Kendall's Tau B	.51	***
	p-value	< .001	
Uni-Y - Bi-X	Kendall's Tau B	,078	**
	p-value	,005	
Tip-X - Bi-X	Kendall's Tau B	.12	***
	p-value	< .001	
Y-Tip - Bi-X	Kendall's Tau B	-.288	***
	p-value	< .001	
Uni-X - Bi-Y	Kendall's Tau B	,039	
	p-value	,162	
Uni-Y - Bi-Y	Kendall's Tau B	,174	***
	p-value	< .001	
Tip-X - Bi-X	Kendall's Tau B	-0.12	***
	p-value	< .001	
Tip-Y - Bi-Y	Kendall's Tau B	-.026	
	p-value	,361	
Uni-Y - Uni-Y	Kendall's Tau B	,183	***
	p-value	< .001	
Tip-X - Uni-Y	Kendall's Tau B	,084	**
	p-value	,003	
Y-Tip - Uni-Y	Kendall's Tau B	-.225	***
	p-value	< .001	
Y-Tip - X-Tip	Kendall's Tau B	-.298	***
	p-value	< .001	

Note. * p < .05, ** p < .01, *** p < .001

According to the correlation table above, the Uni-X and Bi-X show a Kendall's Tau B coefficient of .51 with a very low p-value, less than .001, indicating a moderate relationship between these two variables. The correlation between the Uni-Y and Bi-Y has a Kendall's Tau B coefficient of .174 with a very low p-value, less than .001, indicating a weak relationship between these two variables. The correlation between the Tip-X and Bi-X variables has a Kendall's Tau B coefficient of .12 with a very low p-value, less than .001, indicating a weak relationship between these two variables. The correlation between the Tip-Y and Bi-X shows a Kendall's Tau B coefficient of -.288 with a very low p-value, less than .001, indicating a weak negative relationship between these two variables.

The correlation between the Uni-Y and Uni-Y shows a Kendall's Tau B coefficient of 0.183 with a very low p-value, less than 0.001, indicating a weak positive relationship between these two variables. The correlation between the Tip-Y and Uni-Y has a Kendall's Tau B coefficient of -0.225 with a very low p-value, less than 0.001, indicating a weak negative relationship between these two variables. The correlation between the Tip-Y and Tip-X shows a Kendall's Tau B coefficient of -0.298 with a very low p-value, less than 0.001, indicating a weak negative relationship between these two variables.

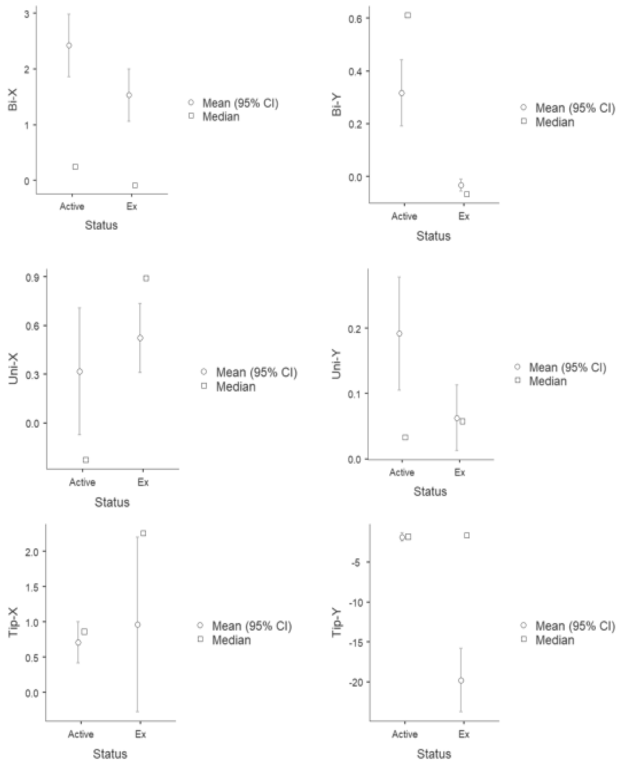
Meanwhile, a correlation is seen between the Bi-Y and Bi-X showing a Kendall's Tau B coefficient of .083 with a p-value of .003, indicating a weak positive relationship between these two variables, and the correlation results shown between the Uni-X and Bi-Y show a Kendall's Tau B coefficient of .039 with a p-value of .162, indicating a weak and insignificant positive relationship between these two variables. In addition, the correlation between the Tip-X and Uni-Y shows a Kendall's Tau B coefficient of .084 with a p-value of .003, indicating a weak significant relationship between these two variables, and the correlation between the Tip-Y and Bi-Y shows the Kendall's Tau B coefficient of -.026 with a p-value of .361, indicating an insignificant relationship between these two variables.

Table 4
Independent Samples T-Test

Components		Statistics	p	Effect Size
Bi-X	Mann-Whitney U	34134	< .001	.1654
Bi-Y	Mann-Whitney U	11055	< .001	.7297
Uni-X	Mann-Whitney U	34784	,002	.1495
Uni-Y	Mann-Whitney U	40359	,785	.0132
X-Tip	Mann-Whitney U	33188	< .001	.1885
Y-Tip	Mann-Whitney U	38132	,162	.0676

Note. H_a μ Active ≠ μ Ex

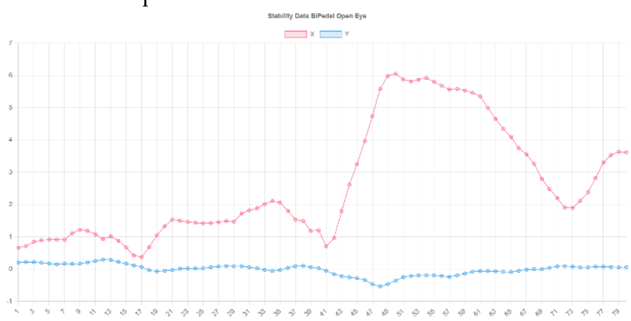
The following is an analysis that we can take from the table of differences between samples above. There was a significant difference between the Active and Ex-athlete groups in the Bi-X (U = 34134, p < .001). The effect size calculated using rank biserial correlation is .1654. The difference between the Active and Ex-athlete groups in the Bi-Y was also significant (U = 11055, p < .001), with an effect size of .7297. Significance was also found in the Tip-X, showing a difference between the Active and Ex-athlete groups (U = 33188, p < .001), with an effect size of .1885, significant difference between the Active and Ex-athlete groups in the Uni-X (U = 34784, p = .002), with an effect size of .1495. On the other hand, there was no significant difference between the Active and Ex-athlete groups in the Uni-Y (U = 40359, p = .785), with an effect size of .0132. The difference between the Active and Ex-athlete groups in the Tip-Y was also not significant (U = 38132, p = .162), with an effect size of .0676.



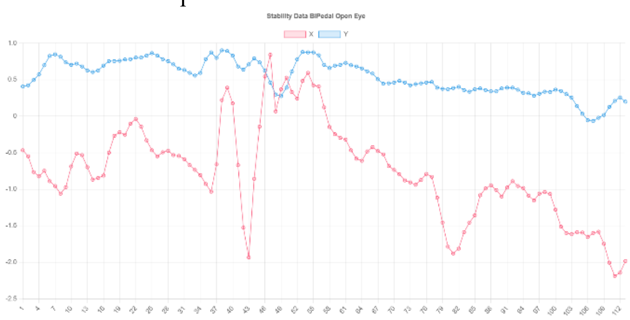
Figures 1-6. Difference Test between Athlete and Ex-Athlete samples based on stability scheme

Below we can see the results of observing the stability movement of the samples via the inclinometer sensor recorded graph.

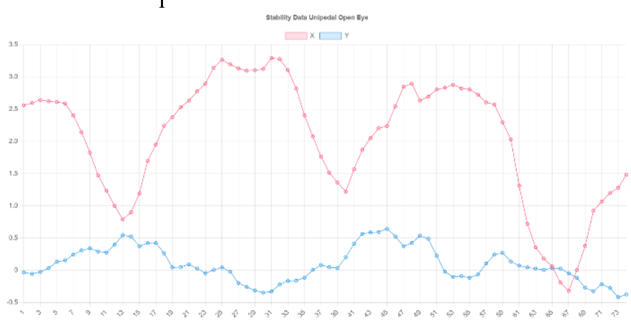
Ex.1 Male Bipedal



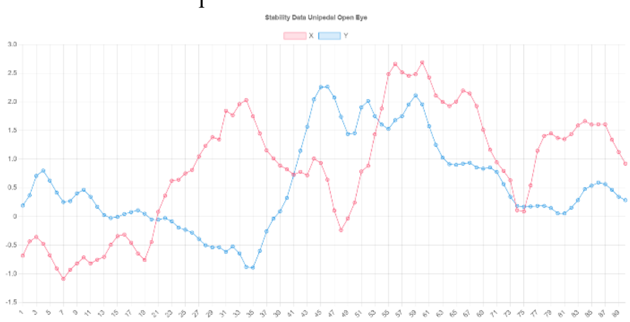
Active 1 Male Bipedal



Ex 1 Male Unipedal

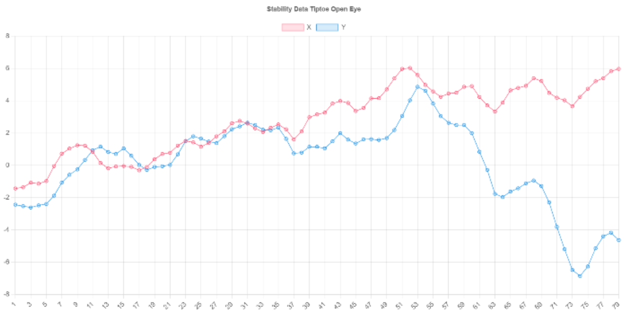


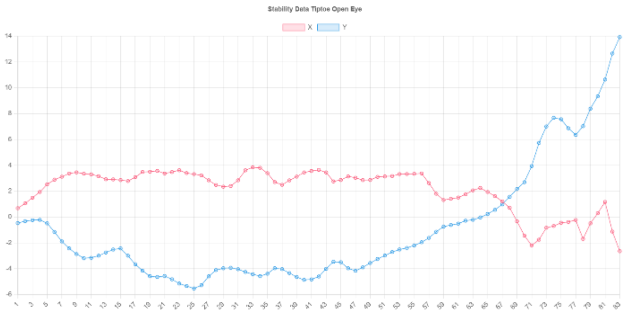
Active 1 Male Unipedal



Ex 1 Male Tiptoe

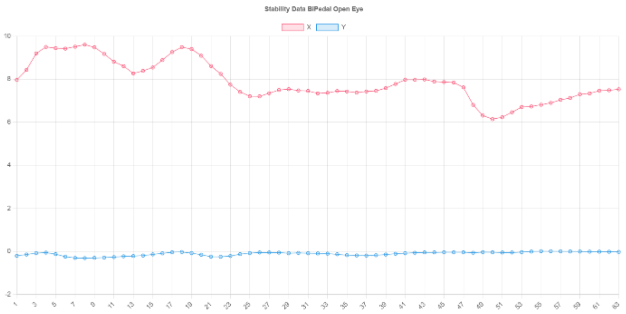
Active 1 Male Tiptoe

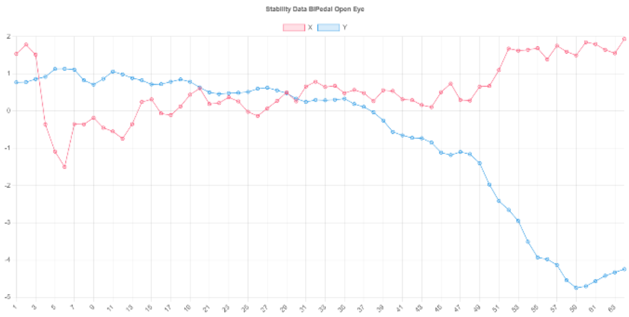




Ex 2 Male Bipedal

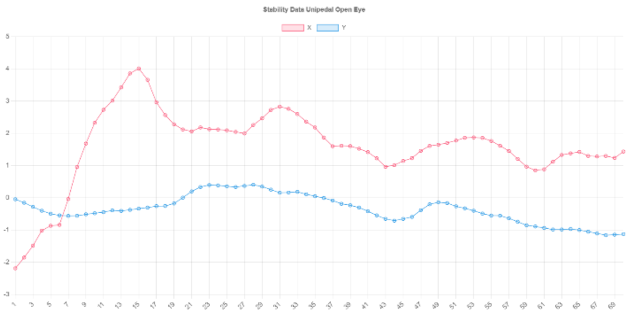
Active 2 Male Bipedal

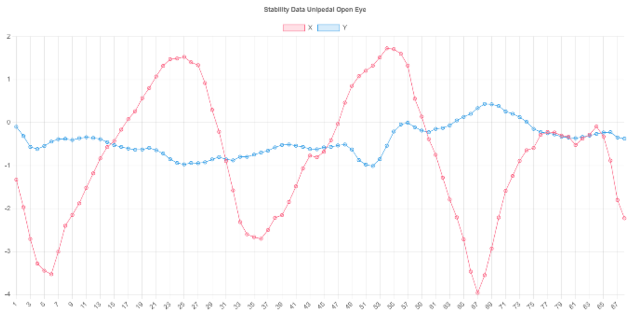




Ex 2 Male Unipedal

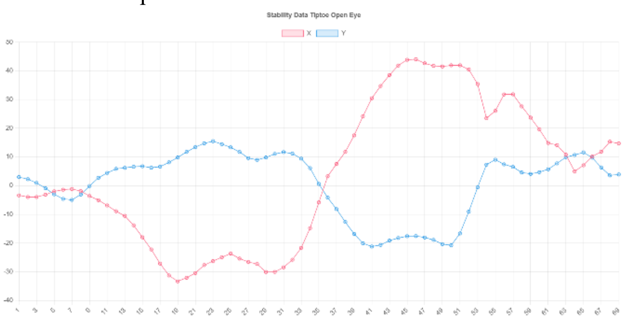
Active 2 Male Unipedal

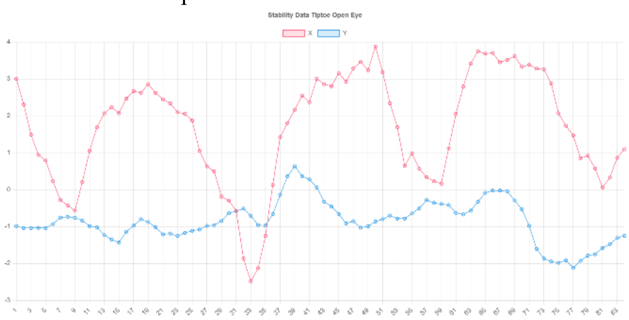




Ex 2 Male Tiptoe

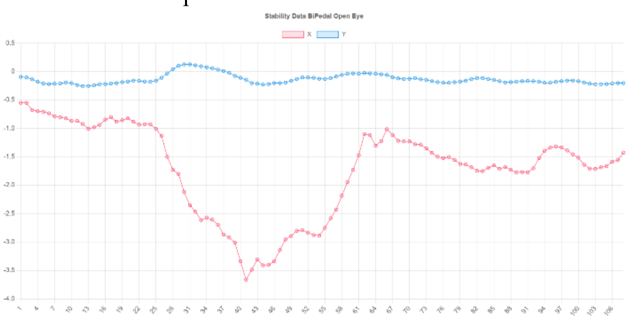
Active 2 Male Tiptoe

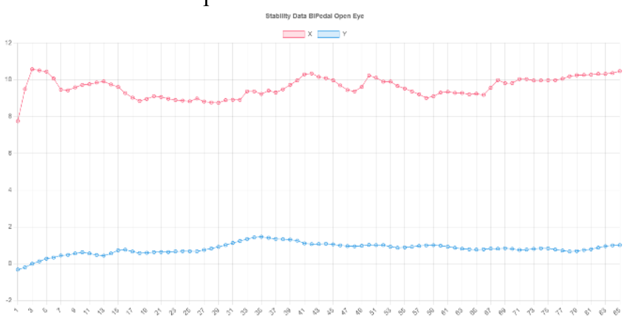




Ex 1 Female – Bipedal

Active 1 Female Bipedal





Ex 1 Female Unipedal

Active 1 Female Unipedal

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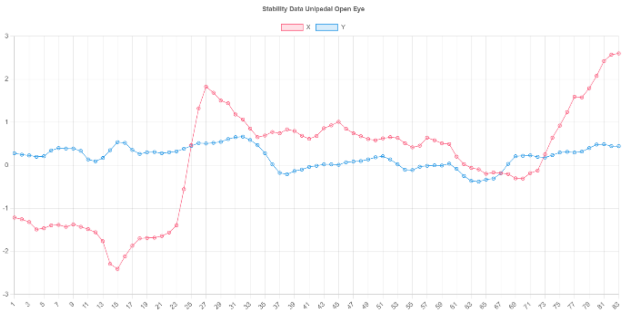
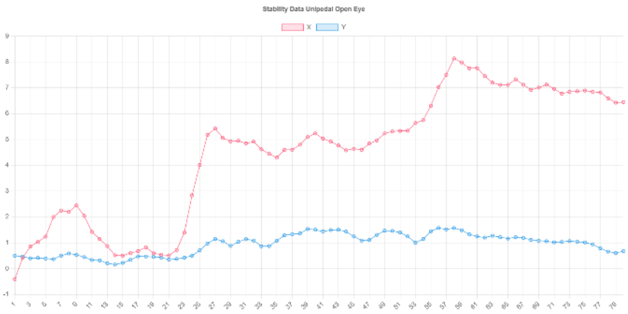
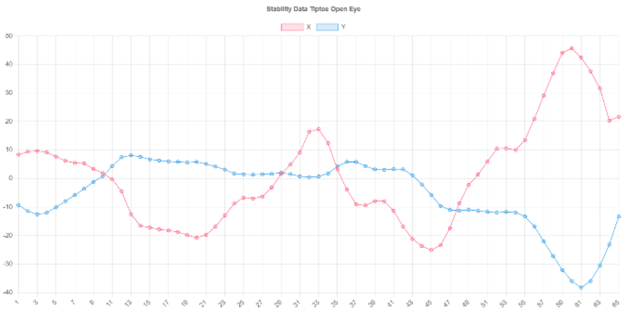
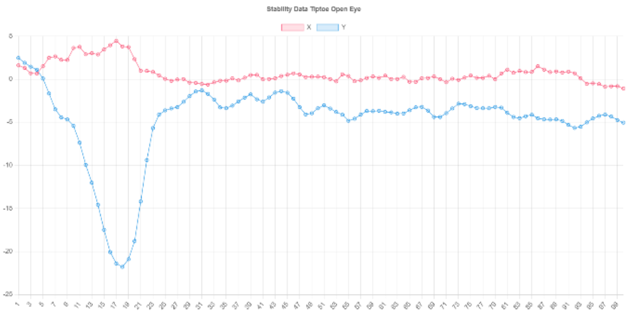




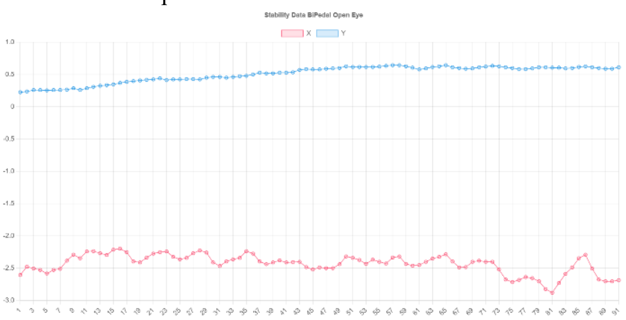
Ex 1 Female Tip toe



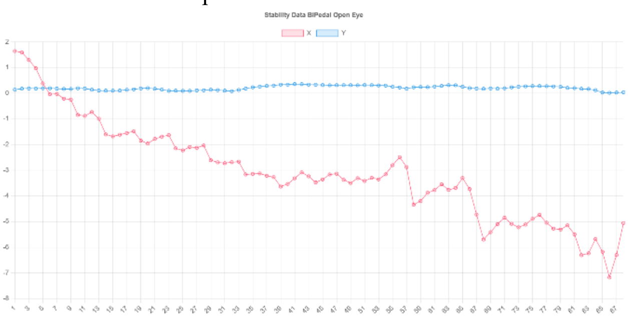
Active 1 Female Tiptoe



Ex 2 Female Bipedal



Active 2 Female Bipedal



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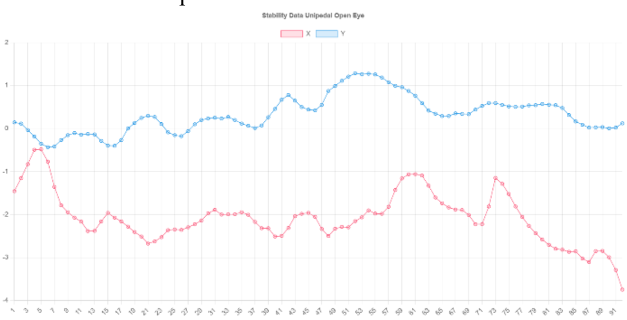

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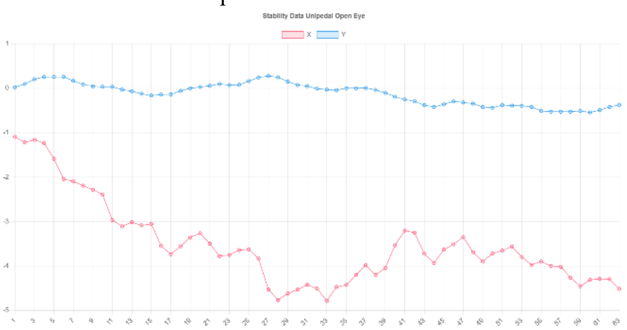
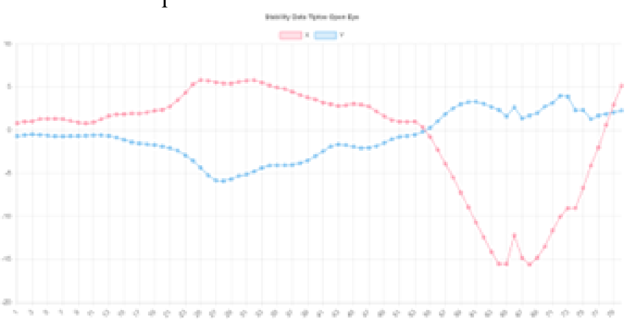
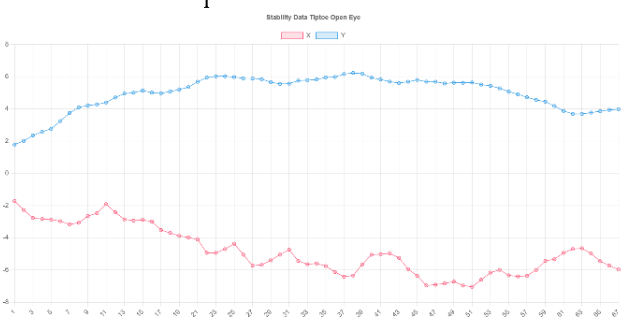


Ex 2 Female Tiptoe



Active 2 Female Tiptoe



Discussion

From all the component correlations between axes as a basis for the validity of the instrument, we can conclude that this device is valid for measuring body tilt in a state of moderate level, where 11 correlations are significant in a low to moderate level and 2 correlations that are not showing significant results. If we look at the stability performance of the sample's body in the three balance scenarios, the differences in the sample's movement fluctuations increase as the movement challenge increases with a reduction in the body's footing area, from two feet, one foot on the ground and one foot on tiptoe. Aligned with (Jaroslaw Omorczyk et al., 2022) where the higher the body position will affect a person's stability ability. From the overall difference test in angle If you look at the X and Y angle bipedal test plot graph, it can be seen that ex-athletes display better stability abilities, this supports the results obtained in other previous studies. (Jarosław Omorczyk et al., 2018). The X-angle Unipedal stability test demonstrated that athletes exhibited enhanced stability, particularly in the proprioceptive system of the soles of the feet and ankles, when standing and moving on soft surfaces. This improvement can be attributed to specialized and general exercises aimed at strengthening the muscles that support the body, as well as increasing vestibular tolerance to rapid changes in movement. Regular training in a variety of sports further amplifies these benefits, leading to better overall proprioceptive and vestibular function. Consistent engagement in diverse sports is essential for optimizing body stability and postural control (Andreeva et al., 2021), jumping and hoping activities (Anugrah et al., 2024), and core stability exercise (Zulhasniati et al., 2024), (Yılmaz et al., 2023).

Overall, the samples exhibited better stability in the frontal plane compared to maintaining their stability in the sagittal plane. This observation suggests that the subjects have a more developed control or greater ease in managing balance and movements in the frontal plane, possibly due to the different muscular demands or biomechanical strategies required for stability in each plane. Further analysis could provide insights into specific factors contributing to this difference in stability between the two planes.

Conclusion

The use of an inclinometer sensor will become a very effective instrument in measuring the body's static balance ability in real time with a good level of measurements. The results of measuring body stability using this inclinometer sensor, which is also based on body tilt analysis, are very useful, especially in the sport of gymnastics which uses body tilt angle as one of the main factors in assessing the performance of athletes who are performing various movements of difficulty. Bipedal stability test results shown by samples of former athletes showed better performance than active athletes, but on the other hand samples of active athletes showed better stability in unipedal and tiptoe conditions. The significant difference in test results is dominated by the difference in the X angle which represents the sagittal plane compared to the difference test in the Y angle which represents the frontal plane, this indicates that the sample's body's ability to maintain body stability in the front-back direction is more difficult than in the side direction. This study has several limitations, including a limited sample size and the focus on only one type of sport, aerobic gymnastics. Future studies with larger sample sizes and longer study periods are needed to validate the measurement tools and to uncover differences in postural stability abilities across more diverse samples. Expanding the research to include athletes from various sports disciplines will provide a more comprehensive understanding of postural stability and its contributing factors. Such studies would also help in refining the measurement techniques and ensuring their applicability across different athletic populations.

Acknowledgment

The authors would like to express their utmost gratitude to Dr. Hadi Nasbey as the advisor in the field of applied physics and Dr. Ari Septian as the advisor in the field of mathematics in this research, as well as to the Indonesian Agency for the Assessment and Application of Technology (BPPT) and the Educational Fund Management Institution (LPDP) as our sponsors who have provided funding for conducting this research and for publishing this article.

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