BIOMECHANICAL ASSESSMENT OF FENCING TECHNIQUES IN MEN AND WOMEN: AN APPROACH WITH INERTIAL SENSING AND LINEAR MIXED MODELS

EVALUACIÓN BIOMECÁNICA DE TÉCNICAS DE ESGRIMA EN HOMBRES Y MUJERES: UN ENFOQUE CON SENSORES INERCIALES Y MODELOS LINEALES MIXTOS

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Impact of Biological sex on the Execution of Fencing Techniques

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Abstract

Accuracy, speed, and coordination are key factors in executing fencing techniques, and understanding these movements could enhance the effectiveness of gender-differentiated training. We sought to investigate biomechanical differences between men and women in fencing techniques using inertial sensors and their influence on sporting performance. Observational, cross-sectional, and quantitative study with 24 fencers from the Liga Vallecaucana de Esgrima (Colombia), national and international competitors. Techniques of touch to the Palestre, backhand, and arrow were performed by placing Xsens Dot inertial sensors on the biceps, forearm, quadriceps, and gastrocnemius. Linear mixed models (MixedLM) were analysed. This approach allowed for control of intra- and inter-group variability. Results were expressed as regression coefficients, standard errors, and *.-values*, enabling determination of the statistical significance of observed differences. All analysis was performed using specialised statistical software (Python), ensuring the accuracy and validity of the results. The techniques employed yielded consistent results for the Euler_X and Euler_Z variables, with sex a significant factor. Linear mixed models revealed considerable variability between groups (identified by Code), particularly in the Euler_X and Euler_Z variables.

Keywords: Fencing, inertial sensors, Linear mixed models, biomechanic.

Resumen

La precisión, la velocidad y la coordinación son factores relevantes en la ejecución de las técnicas de esgrima y la comprensión de estos movimientos podría enriquecer la adecuación del entrenamiento diferenciada por sexo. Se buscó investigar diferencias biomecánicas entre hombres y mujeres en las técnicas de esgrima mediante el uso de sensores inerciales, y su influencia en el desempeño deportivo. Estudio observacional, transversal y cuantitativo con 24 esgrimistas de la Liga Vallecaucana de Esgrima (Colombia), competidores nacionales e internacionales. Se realizaron técnicas de toque al Palestre, al fondo y a la flecha mediante la colocación de sensores inerciales Xsens Dot en el bíceps, el antebrazo, el cuádriceps y el gastrocnemio. Se analizaron modelos lineales mixtos (MixedLM). Este enfoque permitió controlar la variabilidad intragrupal e intergrupal. Los resultados se expresaron en términos de coeficientes de regresión, errores estándar y valores de ., lo que permitió determinar la significancia estadística de las diferencias observadas. Todo el análisis se realizó con software estadístico especializado (Python), lo que garantizó la precisión y la validez de los resultados. Las técnicas empleadas mostraron consistencia en los resultados para las variables Euler_X y Euler_Z, en las que el sexo fue un factor significativo. Los modelos lineales mixtos revelaron una considerable variabilidad entre grupos (identificados por Código), particularmente en las variables Euler_X y Euler_Z.

Palabras clave: Esgrima, sensores inerciales, modelos lineales mixtos, biomecánica.

Introduction

Fencing is a sport that requires a precise combination of speed, coordination, technique, and asymmetrical movements (Di Martino et al., 2024), factors that play a crucial role in athletes' performance. However, training approaches tend to be generalized without accounting for biomechanical differences between men and women. Assessing athletes' individual characteristics is essential for developing truly effective training plans, as each person has unique physical, biomechanical, and psychological characteristics (Serrato-Hernández, 2025). A generalized approach does not account for natural variation among individuals, which can limit performance and increase the risk of injury. By understanding the specific strengths and weaknesses of each fencer, such as coordination, strength, or flexibility, coaches can design programs that are more tailored to the needs of everyone, thus optimizing training efficiency. In addition, evaluating factors such as gender, age, and movement type also allows adjustments to workloads and techniques, ensuring safer, more sustained progression. In this sense, personalizing training plans not only improves athletic performance but also promotes the comprehensive and long-term development of athletes.

Fencing has been studied using advanced technologies such as inertial sensors. These devices, particularly Inertial Measurement Units (IMUs), have enabled the collection of detailed, real-time kinematic data, providing a deep understanding of the complex movements involved in fencing techniques, such as lunges and thrusts (Nita &Magyar, 2023).

Despite the potential of these technologies, the application of inertial sensors in the biomechanical analysis of fencing performance has been limited. This has created a gap in understanding how intrinsic factors, such as gender, influence fencers' technical performance. The lack of specific studies examining these differences could be limiting the optimization of fencing training, given that the biomechanical demands of the sport require detailed and accurate assessment (Aresta et al., 2023), an aspect that should not only be considered in fencing but in all sports disciplines, since differences between biological sexes can be an advantage or disadvantage depending on the position from which one works (Abril, 2025), and even more so if one wishes to emphasize a physical ability that is significantly involved in the performance of the technique (Tsolakis et al., 2011).

Research into biomechanics in fencing has documented various techniques and movements, with the lunge among the most studied elements. However, most studies have focused on general analyses without addressing the influence of variables such as gender on the execution of these movements (Chen, 2017; Aresta et al., 2023). In addition, studies have shown that integrating wearable technologies into the evaluation of fencers can improve aspects such as postural control and movement effectiveness, underscoring the need for further research in this area (Nita & Magyar, 2023).

One area that has begun to receive attention is the impact of neuromuscular factors and the specific physiological characteristics of fencers on their performance, especially when comparing men and women. Recent studies have indicated that differences in body composition, muscle mass, and flexibility can influence technical execution in fencing, affecting the speed and precision of movements (Chen et al., 2017). These differences, when combined with data from advanced technologies such as IMUs, can provide a more comprehensive understanding of performance variations between genders, enabling a more personalized approach to training and athlete preparation (Pérez-Triviño, 2022).

Therefore, understanding how biomechanical differences between men and women affect fencing performance is crucial for personalizing training. Using inertial sensors, it is possible to obtain accurate, real-time data that informs more effective training strategies tailored to each sex, which could result in improved athletic performance (Aresta et al., 2023) and the recognition of athletes' identifying characteristics (Shynkaruk et al., 2020).

Fencers must maintain a high level of coordination and control in their movements, which requires a detailed understanding of the biomechanical differences between individuals. This study explores how these differences, particularly between men and women, can influence technical performance in fencing, providing an empirical basis for personalizing training programs.

The objective of this study was to investigate biomechanical differences between men and women in fencing techniques using inertial sensors and to assess how these differences may influence performance. This study aimed to provide a solid basis for personalizing fencing training, contributing to a more effective approach to athlete development.

Material and Methods

Study Design

This study was designed as an observational, cross-sectional, quantitative study to evaluate biomechanical differences between male and female fencers using Inertial Measurement Units (IMUs). Linear mixed models were used to analyze the data and control for potential confounding variables, thus providing a clear picture of how gender influences technical performance in fencing.

Context

The study was conducted at the Valle del Cauca Fencing League, a high-performance sports setting where participating fencers were actively involved in regional and national competitions. Data collection sessions took place at the league's facilities, equipped with technology suitable for real-time monitoring of movement.

Participants

The study population consisted of 24 fencers from the Valle del Cauca Fencing League, selected through non-probability sampling. Participants included both men and women aged 15 to 31. All participants had at least 2 years of training, were called in during their usual practice hours between 4 and 8 pm and were explained the test and its protocol (i.e., how it should be performed).

Variables

The dependent variables studied were Euler angles (Euler_X, Euler_Y, Euler_Z), linear accelerations (Acc_X, Acc_Y, Acc_Z), and angular velocities (Gyr_X, Gyr_Y, Gyr_Z). The main independent variable was the fencers' sex (0 = female, 1 = male).

Data Source

The data was collected using IMUs placed at strategic points on the body, such as the arms and legs. These IMUs enabled real-time capture of kinematic data as the fencers performed a series of standard movements. The data obtained was stored in Excel.

Bias

Various potential sources of bias were addressed in the study design. Selection bias was mitigated by including fencers of both genders and different skill levels. To control for measurement bias, the IMUs were calibrated before each data collection session. However, the possible influence of uncontrolled variables, such as individual differences in technique and prior experience, on the results is acknowledged.

Sample Size

The sample size comprised 24 fencers who met the study's inclusion criteria, representing all athletes available and eligible to participate at the time of data collection. Although this number may seem relatively small, it was considered sufficient for the exploratory purposes of the study, as it enabled the capture of possible biomechanical differences between sexes in a controlled environment with high-performance fencers.

Procedure

Each participant was equipped with IMUs before performing a series of standard fencing-specific movements. Three repetitions of each technique were performed, and each participant performed the same number of repetitions for each technique under observation. The data from each repetition were analyzed individually, without averaging, to maintain the integrity and variability of the movements in the subsequent analysis. The experimental sessions were conducted in a controlled environment to minimize the influence of external factors on the results, following the methodological standards recommended in previous biomechanics studies applied to combat sports (Castellanos-Ruíz et al., 2020).

The four Xsens Dot inertial sensors were calibrated before each session to ensure measurement accuracy and minimize instrumental errors, following protocols used in previous research (Campaniço et al., 2018). During calibration, their correct functioning was verified, and the movements generated were monitored via signals transmitted to a mobile device, ensuring proper alignment of the sensors with the body segments to be measured. In addition, the fencing piste where the tests were carried out was prepared, and a "Palestre" (fencing dummy) was installed to act as an opponent, allowing the athletes to perform the movements as if they had a real opponent. In front of the piste, a tripod with a high-resolution video camera was set up to record the athletes performing the three requested fencing techniques. These recordings allowed for subsequent complementary analysis to verify the quality and execution of the movements, in line with validation approaches used in biomechanics studies (Nykytenko et al., 2018). Each athlete was assigned a numerical identification code to keep track of the tests performed and attendance.

Before starting the tests, joint mobility exercises and a specific fencing warm-up were performed to prepare the athletes' bodies and reduce injury risk, thereby optimizing their motor performance (Kontochristopoulos & Tsolakis, 2020). They were then asked to practice the three techniques they had to perform: Technique 1, a touch to the Palestre; Technique 2, a fondo; and Technique 3, an arrow. To begin the test, the four inertial sensors were placed at strategic anatomical points: upper arm (biceps), lower arm (forearm), upper leg (quadriceps), and lower leg (gastrocnemius). These points were selected following recommendations from previous studies on kinematic analysis in combat sports, ensuring accurate capture of movements in the three spatial dimensions (Castellanos-Ruíz et al., 2020).

In the sagittal plane, using a tripod and video camera, the three techniques were recorded consecutively and in chronological order, with a single recording for each athlete. From the moment the command was given, the recording of the first technique began and continued until the third ended. After the recording was completed, the sensors were removed from the athletes' bodies. At the end of the tests, stretching exercises were performed on the lower and upper limbs, in accordance with the movements practiced, which facilitated muscle recovery and reduced accumulated fatigue (Błażkiewicz et al., 2018; Borysiuk et al., 2019). Finally, it was verified that the data was saved in the sensor software at the end of each test, and the devices used were turned off to prevent changes to data integrity.

To avoid potential biases in data collection, only data within the recording range of the three techniques were considered, eliminating those that did not correspond to the test times. In addition, quality control was performed on the database by analyzing outliers using Grubbs' tests, ensuring that the data used in the analysis were representative and reliable (Kontochristopoulos & Tsolakis, 2020). In this way, the influence of experimental errors was minimized, and the accuracy of the results obtained in the study was guaranteed.

In this study, Euler angles (Euler_X, Euler_Y, Euler_Z) were used to analyze the segmental orientation of fencers. Unlike the Cartesian reference system, which focuses on absolute positions in three-dimensional space, Euler angles enable accurate capture of relative rotation between body segments. Their application is fundamental in biomechanics because they provide a more detailed description of angular kinematics in dynamic movements (Kontochristopoulos & Tsolakis, 2020).

The values obtained by the sensors correspond to the measurement of angular orientation in specific joint segments. Each inertial sensor recorded data from its corresponding anatomical point, and the values between the four sensors were not averaged to avoid loss of information on segmental mobility. Thus, the analyzed data reflect the orientation of each body segment independently, enabling a detailed evaluation of the fencers' kinematics. This methodology enables the identification of biomechanical differences among the key joints involved in the techniques evaluated, rather than just providing a global estimate of movement.

Based on these reasons, the choice of Euler angles is motivated by their ability to describe the dynamics of movement in fencing more accurately, to differentiate technical patterns between the sexes, and to contribute to training optimization.

To avoid possible biases in data collection, only data within the recording range of the three techniques were considered, eliminating those that did not correspond to the test times. Castellanos-Ruíz et al. (2020) suggest that data validation using observational and technological records improves the accuracy of biomechanical analyses in fencing, enabling optimized interpretation of sports kinematics.

Data Analysis

To examine the effect of gender on each biomechanical variable, a mixed linear model was used. This statistical approach was chosen because of the hierarchical structure of the data, in which each subject could perform multiple repetitions of the fencing techniques. This creates dependencies among observations within each individual, necessitating the inclusion of a random effect associated with the participant code to control for interindividual variability. Mixed models allow us to capture both the fixed effects of sex on biomechanical variables and the variability inherent in each subject, avoiding the overestimation of statistical significance that could occur in a traditional regression analysis.

For each fencing technique considered (T1, T2, and T3), a model was adjusted for each of the dependent variables under the following formulation:

Dependent variable #Sex+(1#Code) where:

Euler angles: Euler_X, Euler_Y, Euler_Z

Accelerations: Acc_X, Acc_Y, Acc_Z

Angular velocities: Gyr_X, Gyr_Y, Gyr_Z

These are the dependent variables, each of which reflects a different aspect of movement in fencing, allowing us to evaluate how biomechanical differences between men and women manifest in orientation, acceleration, and angular velocity during the execution of techniques. Sex is the explanatory variable of interest (fixed effects factor). Code represents inter-subject variability as a random effect.

Each model was adjusted independently for each technique (T1, T2, T3) to evaluate how biomechanical differences varied between men and women. Estimates of coefficients, significance tests, and model fit statistics were obtained.

For each technique, differences in terms of accelerations, angular velocities, and Euler angles were evaluated. In each model adjustment, the statistical significance of the coefficients associated with the Sex factor was assessed to determine whether there were significant differences between men and women across the metrics analyzed. All analysis was performed using specialized statistical software (Python), ensuring the accuracy and validity of the results.

Ethical Considerations

Participants entered the study voluntarily after signing an informed consent form for adult athletes and an informed assent form for minors, with the informed consent signed by their guardians. This research was conducted in accordance with the recommendations and protocols of the Declaration of Helsinki and Resolution 8430 of 1994 of the Colombian Ministry of Health and Social Protection. This study was approved by the ethics committee of the National School of Sport under code 40.07.459 and dated December 14, 2023.

Results

In terms of gender distribution, 50% of participants were male (*n* = 12) and 50% were female (*n* = 12). This balance allowed for the observation of biomechanical differences between both sexes in an equitable manner.

As for the weapons used, most participants (50%) used a foil (*n* = 12), followed by a saber (33.3%, *n* = 8) and a sword (16.7%, *n* = 4). This indicates a diversity of styles within the sample, which is relevant, given that each weapon type could involve specific technical and biomechanical variations (Table 1).

In addition, the socioeconomic status of participants was represented by different strata, with greater representation in strata 3, 4, and 5 (each with 29.2% of participants, *n* = 7), while strata 1 and 2, the lowest economically, were less represented (4.2% and 8.3%, respectively).

Table 1

Distribution of Athletes With Respect to Qualitative Variables

Qualitative Variable	Category	Frequency	Percentage
Biological sex	Female	12	50
	Male	12	50
Weapon	Foil	12	50
	Épée	4	16,7
	Sabre	8	33,3
Socio-economic stratum	1	1	4,2
	2	2	8,3
	3	7	29,2
	4	7	29,2
	5	7	29,2

The fencers' age ranged from 15 to 31 years, with a mean of 23.2 years and a standard deviation of 6.5 years. In terms of experience in the sport, participants had been training for between 2 and 15 years, with a mean of 5.5 years and a standard deviation of 3.85 years (Table 2).

Table 2

Distribution of Athletes With Respect to Quantitative Variables

Quantitative Variable	Minimum	Maximum	Media	Standard deviation
Age	15	31	23,2	6,5
Years training in their sport	2	15	5,5	3,856

For the T1, T2, and T3 techniques, biomechanical differences between men and women were evaluated using mixed linear models for dependent variables related to Euler angles, accelerations, and angular velocities.Los ángulos de Euler (Euler_X, Euler_Y, Euler_Z) reflejan la orientación del cuerpo durante la ejecución de las técnicas. Se analizaron las diferencias en estas variables en función del sexo.

The acceleration variables (Acc_X, Acc_Y, Acc_Z) describe the variations in speed on each axis and their relationship to biomechanical performance.

The angular velocities (Gyr_X, Gyr_Y, Gyr_Z) indicate how quickly the orientation of the body changes on each axis.

Technique 1

Euler Angles

Euler_X: A significant effect of gender on Euler_X was found (β = -1139.95, p = 0.017). The negative coefficient indicates that Euler_X values were lower in female participants than in male participants. This suggests differences in inclination or angular positioning in the T1 technique.

Euler_Y: No significant differences were found between sexes for Euler_Y (β = 218.67, p = 0.411), indicating that orientation on this axis is not affected by the sex factor.

Euler_Z: No significant differences were observed in Euler_Z (β = -301.48, p = 0.419), suggesting that movement on this axis behaves similarly in men and women.

Acceleration Variables

Acc_X: No significant effect of gender was found on Acc_X (β = -199.36, p = 0.442), suggesting that acceleration on this axis is comparable between men and women.

Acc_Y: A negative coefficient was obtained for Acc_Y (β = -712.40), but it did not reach significance (*p* = 0.128), indicating that, although there is a tendency for differences in acceleration on this axis, it cannot be statistically concluded that sex has a significant impact.

Acc_Z: No significant differences were observed in Acc_Z (β = 203.14, *p* = 0.569), indicating a similarity in vertical acceleration between sexes.

Angular Velocities

Gyr_X: A trend toward differences in Gyr_X (β = -181.67) was observed, but it was not statistically significant (*p* = 0.095). This suggests that there may be differences in angular velocity on this axis, although no definitive conclusions can be drawn.

Gyr_Y: No significant differences were found in Gyr_Y (β = -11.95, *p* = 0.919), indicating that angular velocity on this axis is similar between sexes.

Gyr_Z: A negative coefficient was observed in Gyr_Z (β = -136.07), with a trend toward significance (*p* = 0.099), suggesting that there may be differences in angular velocity on this axis, although it did not reach the conventional statistical threshold. A tendency toward differences between sexes that could be relevant from a biomechanical point of view.

Technique 2

Euler Angles

Euler_X: A significant effect of gender on Euler_X was found (β = -1023.32, *p* = 0.045). This result indicates that women have lower values than men for this parameter, suggesting differences in angular inclination during the execution of the technique.

Euler_Y: No significant differences were found between sexes for Euler_Y (β = 61.86, *p* = 0.697), suggesting that orientation on this axis is not affected by the sex factor.

Euler_Z: A statistically significant difference was found in Euler_Z (β = -358.76, *p* = 0.001), indicating that the inclination values on this axis are lower in women compared to men.

Acceleration Variables

Acc_X: No significant effect of gender on Acc_X was found (β = -40.73, *p* = 0.871), indicating that acceleration on this axis is comparable between men and women.

Acc_Y: Although a negative coefficient was obtained for Acc_Y (β = -528.54), it was not statistically significant (*p* = 0.278), indicating that it cannot be concluded that sex has an impact on this axis.

Acc_Z: No significant differences were observed in Acc_Z (β = 19.34, *p* = 0.953), indicating that vertical acceleration is similar between men and women.

Angular Velocities

Gyr_X: No significant differences were found in Gyr_X (p not provided in the image).

Gyr_Y: No significant effect of sex on Gyr_Y was found (β = -5.76, *p* = 0.956), indicating that the angular velocity on this axis is similar between men and women.

Gyr_Z: No significant differences were found in Gyr_Z (β = -10.65, *p* = 0.891), suggesting that this parameter does not vary between sexes.

Technique 3

Euler Angles

Euler_X: A significant effect of gender on Euler_X was found (β = -869.55, p = 0.040). This indicates that women have values 869.55 units lower than men in this parameter, suggesting differences in angular inclination during the execution of the technique.

Euler_Y: No significant differences were found between sexes for Euler_Y (β = 88.67, p = 0.509), indicating that orientation on this axis is not affected by the sex factor.

Euler_Z: A negative coefficient was obtained in Euler_Z (β = -351.95, p = 0.064), with a tendency toward significance, but without reaching the 5% threshold. This suggests that women may have lower values on this axis, although the result is not conclusive.

Acceleration Variables

Acc_X: No significant effect of gender on Acc_X was found (β = -258.88, p = 0.283), indicating that acceleration on this axis is comparable between men and women.

Acc_Y: A negative coefficient was obtained for Acc_Y (β = -270.45, p = 0.424), but without reaching statistical significance, indicating that sex does not have a clear impact on acceleration on this axis.

Acc_Z: No significant differences were observed in Acc_Z (β = -82.31, p = 0.708), indicating a similarity in vertical acceleration between sexes.

Angular Velocities

Gyr_X: No significant differences were found in Gyr_X (β = -51.07, p = 0.666), indicating that the angular velocity on this axis is similar between sexes.

Gyr_Y: No significant effect of sex was found on Gyr_Y (β = 92.58, p = 0.357), indicating that the angular velocity on this axis does not vary significantly between men and women.

Gyr_Z: No significant differences were found in Gyr_Z (β = -19.12, p = 0.812), suggesting that this parameter does not vary between sexes.

Discussion

The results obtained in this study indicate that gender significantly influences orientation measures, particularly the Euler angles (Euler_X and Euler_Z), in the analyzed fencing techniques. Across the three techniques studied, men tended to show lower Euler_X values than women, suggesting that men may adopt more closed postures or less rotation in certain movements. This difference in Euler_X was significant in all techniques ($p< 0.05$), reinforcing the consistency of this finding. In contrast, differences in linear accelerations (Acc_Y) and angular velocities (Gyr_X, Gyr_Y, Gyr_Z) did not show a clear influence of sex, except in some specific cases that did not reach statistical significance. This suggests that, while body orientation during movement may vary between men and women, the forces generated and angular velocities during the execution of fencing techniques do not show marked differences between the sexes.

Previous studies have examined biomechanical differences in fencing by gender. Nikolov et al. (2024) found that elite fencers exhibited more fluid and optimized execution compared to less experienced fencers, suggesting that some of the differences in segmental orientation observed in this study may be related to the level of experience and not exclusively to gender. This reinforces the idea that the biomechanics of fencing are influenced by adaptation to training and optimization of movement patterns over time.

The research by Akbaş et al. (2024) provides additional relevant context by demonstrating that the base of support influences early postural adjustments and COM (Center of Mass) acceleration in fencing. A wider BOS (Base of Support) was found to be associated with a smaller amplitude of COP displacement and greater COM acceleration at foot takeoff. This finding is key to interpreting the differences observed in Euler angles in this study, as it could indicate that the initial position of fencers influences the kinematics of their movements, which could explain why men, with more closed postures, exhibit lower Euler_X values.

The study by Guan et al. (2018) provides crucial biomechanical information on the determinants of speed in fencing. Elite fencers were found to achieve significantly higher horizontal center of gravity velocities and greater ground reaction forces in the rear leg compared to intermediate-level fencers. These findings suggest that optimization of force moment and rear knee joint power are key determinants in the biomechanics of the lunge, which may be related to the differences in segmental orientation observed in this study (Nykytenko et al., 2018).

Additionally, the study by Magnani and Defrasne Ait-Said (2021) introduces the concept of "motion scheme" as a flexible structure for representing the geometric evolution of fencers' movements during combat. Their analysis of the distance between fencers and the importance of footwork provides a basis for interpreting how the differences in orientation and kinematics observed in this study may be linked to the tactics and biomechanics of attacks.

The study by Sorel et al. (2019) evaluated accuracy and reaction time in fencing under conditions of uncertainty. Their findings revealed that accuracy and success decrease significantly under uncertain and moving conditions compared to fixed conditions. In addition, reaction and movement times were also affected by the experimental conditions. This is highly relevant to this study, as it suggests that differences in Euler angles may be related to strategies for adapting to combat conditions. The prioritization of accuracy over speed observed by Sorel et al. (2019) may help explain why biomechanical differences in segmental orientation may influence the tactical effectiveness of men and women in fencing (Gutiérrez-Dávila et al., 2019; Kriventsova et al., 2021).

On the other hand, Michaelsen and Cleland (2019) analyzed the kinematic determinants of success in scoring the flick, a specific movement in foil fencing, finding that variability in technical execution significantly affects the success rate. Although the flick was not evaluated in the present study, this finding is relevant as it suggests that differences in segmental orientation may depend not only on gender but also on individual experience and the technique used by each fencer.

The study by Fei & Zhao (2022) highlights the influence of neuromuscular fatigue on fencers' biomechanics. Their findings indicate that fatigue can significantly alter movement patterns and affect postural stability, which is relevant for understanding how biomechanical differences between sexes may be influenced by neuromuscular endurance capacity.These findings reinforce the need to design personalized training programs that account not only for biomechanical differences between sexes but also for each athlete's individual strategies for optimizing technical execution.

Conclusions

Significant differences were identified in the orientation angles (Euler_X and Euler_Z) between men and women in the three fencing techniques evaluated. These findings suggest that posture and body alignment may vary by gender, which could influence stability and movement control during technique execution. From an applied perspective, these results indicate the need to consider adjustments to postural training and angular alignment to improve combat performance.

The absence of significant differences in acceleration variables (Acc_X, Acc_Y, Acc_Z) and angular velocities (Gyr_X, Gyr_Y, Gyr_Z) suggests that speed of movement and reaction capacity are similar between the sexes. This supports the applicability of standardized biomechanical performance metrics to assess speed and agility in fencers, ensuring equitable criteria for both groups.

The consistency of the findings across the three techniques evaluated suggests that differences in body orientation are not specific to any technique but rather represent a general biomechanical pattern in fencing. This validates the methodological approach used in this study and reinforces the need to integrate postural analysis as a key criterion in training planning.

Coaches can use these results to develop specific programs that optimize posture and angular alignment by gender, which could translate into greater technique efficiency and a reduced risk of injury. Strategies focused on improving stability and postural control could benefit fencers' performance by enabling them to better adapt to the demands of combat.

Study Limitations

This study has certain limitations that should be acknowledged. First, although the results are significant, the sample size and specificity of the population studied (fencers of a specific age range and competitive level) limit the generalizability of the findings. Additionally, the lack of significant differences in linear accelerations and angular velocities could be due to intra-subject variability or to the accuracy of the measurements captured by the IMUs, suggesting the need to consider additional tools for biomechanical analysis. Furthermore, this study does not address other factors that could influence the results, such as differences in experience, individual technique, or physical condition at the time of testing.

Future Research

For future research, it would be valuable to expand the sample to include a more diverse set of fencers in terms of age, skill level, and competitive experience. It would also be interesting to investigate how these biomechanical differences translate into competition performance, possibly combining video analysis and sensor data to correlate these measures with specific tournament results. Furthermore, exploring how specific training interventions aimed at improving orientation and posture according to gender may influence long-term performance could offer valuable practical insights for coaches and athletes. Finally, the incorporation of advanced technologies such as 3D motion analysis or motion capture systems could provide a deeper understanding of biomechanical differences and their impact on fencing performance.

Ethics Committee Statement

The study was conducted in accordance with the Declaration of Helsinki and Resolution 8430 of 1994 of the Ministry of Health and Social Protection for research involving human subjects. It was also approved by the Ethics Committee of the National School of Sport (registration code 40.07.459, date of approval December 14, 2023).

Conflict of Interest

The authors declare no conflict of interest.

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Authors' Contribution

Conceptualization; Methodology: ALHE, NCCM, JGCH, ICRP; Software: JGCH; Validation; Formal Analysis, Data Curation; Writing – Original Draft; Writing – Review & Editing: ALHE, NCCM, JGCH, DFOA, ICRP; Visualization: ICRP; Supervision; Project Administration: JGCH, ICRP; All authors have read and agree with the published version of the manuscript.

Data Availability Statement

Data available upon request to the corresponding author at isabelcrojasp@gmail.com/isabel.rojas@endeporte.edu.co

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