Kinematic variables influencing somersault turn time in medley swimmers using artificial neural networks (ANN)

Variables cinemáticas que influyen en el tiempo de giro de la voltereta en nadadores de estilos mediante redes neuronales artificiales (RNA)

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Abstract

Introduction: Efficient performance in swimming turns is a critical component of competitive success, especially in sprint and middle distance events where turn execution can significantly affect race outcomes.
Objective: Turn Time in Medley Swimmers Using Artificial Neural Networks (ANN), Examine selected kinematic and kinetic variables related to joint angles, propulsion characteristics, and centre of mass dynamics during the somersault turn in competitive youth medley swimmers. Analyze the relationships between these biomechanical variables and somersault turn time using Pearson's correlation. Determine the relative and normalized importance of the investigated kinematic variables in predicting turn time through the application of an Artificial Neural Network (ANN) model. Identify the key biomechanical determinants of turn performance, thereby providing evidence-based insights for technique optimization and training design.
Methodology: A descriptive analytical design with a biomechanical approach was employed to investigate the kinematic variables influencing somersault turn time in competitive youth male swimmers competitive medley swimmers aged 14–15 years from Smouha Sporting Club (Egypt) participated in the study. All swimmers were officially registered with the Egyptian Swimming Federation, trained regularly without prolonged interruptions, demonstrated technical proficiency in the investigated turn technique, and showed a high competitive performance level relative to their peers.
Discussions: Findings indicate that turn performance is governed by a complex nonlinear interaction among lower-limb joint angles, trunk positioning, and propulsion-related variables, rather than a single kinematic factor.
Conclusion: This supports the established understanding that swimming turns are highly coordinated, multi-phase movements in which performance emerges from the interaction of interdependent components.

Keywords

Artificial Neural Networks (ANN), biomechanics, kinematic, performance analysis, somersault turn, swimming.

Resumen

Introducción: Un rendimiento eficiente en los virajes de natación es fundamental para el éxito competitivo, especialmente en pruebas de velocidad y media distancia, donde la ejecución del viraje puede afectar significativamente los resultados de la carrera.
Objetivo: Tiempo de viraje en nadadores de combinados mediante redes neuronales artificiales (RNA). Examinar variables cinemáticas y cinéticas seleccionadas relacionadas con los ángulos articulares, las características de propulsión y la dinámica del centro de masas durante el viraje de mortal en nadadores juveniles de combinados de competición. Analizar las relaciones entre estas variables biomecánicas y el tiempo de viraje de mortal mediante la correlación de Pearson. Determinar la importancia relativa y normalizada de las variables cinemáticas investigadas para predecir el tiempo de viraje mediante la aplicación de un modelo de red neuronal artificial (RNA). Identificar los determinantes biomecánicos clave del rendimiento en los virajes, proporcionando así información basada en la evidencia para la optimización técnica y el diseño del entrenamiento. Metodología: Se empleó un diseño analítico descriptivo con un enfoque biomecánico para investigar las variables cinemáticas que influyen en el tiempo de giro de mortal en nadadores juveniles de competición. Nadadores de estilo combinado de 14 a 15 años del Smouha Sporting Club (Egipto) participaron en el estudio. Todos los nadadores estaban registrados oficialmente en la Federación Egipcia de Natación, entrenaban regularmente sin interrupciones prolongadas, demostraban dominio técnico en la técnica de giro investigada y presentaban un alto nivel de rendimiento competitivo en comparación con sus compañeros.
Discusión: Los hallazgos indican que el rendimiento en el giro se rige por una interacción no lineal compleja entre los ángulos articulares de las extremidades inferiores, la posición del tronco y las variables relacionadas con la propulsión, en lugar de un único factor cinemático.
Conclusión: Esto respalda la idea establecida de que los giros en natación son movimientos multifásicos altamente coordinados en los que el rendimiento surge de la interacción de componentes interdependientes.

Palabras clave

Redes Neuronales Artificiales (RNA), biomecánica, cinemática, análisis del rendimiento, giro mortal, natación.

Introduction

Efficient performance in swimming turns is a critical component of competitive success, especially in sprint and middle distance events where turn execution can significantly affect race outcomes (Pereira et al., 2015; Veiga & Roig, 2016). The turn phase is a complex sequence involving an approach, rotation, wall contact, push-off, and glide, where minor variations in technique can lead to substantial gains or losses in time (David et al., 2022). Consequently, the biomechanics of swimming turns have become a major focus of research, aiming to identify the kinematic and kinetic determinants of elite performance.

Biomechanical studies of the flip (somersault) turn have identified multiple determinants of performance. For instance, 3D kinematic and kinetic analyses have shown that variables such as wall contact time (WCT), push-off force and impulse, and the velocity of the center of mass (CM) during the push-off and glide phases are integral to total turn performance (Pereira et al., 2015; Weimar et al., 2019).. Additionally, effective push off mechanics—especially producing high perpendicular force and velocity shortly after wall contact—have been shown to significantly influence early post turn speed and transition performance. (South & Tor, 2019).

The characteristics of wall contact time (WCT) and body positioning at the wall also play pivotal roles. For example, optimization of wall contact duration and tuck index (a measure of how closely the swimmer's body is drawn toward the wall) has been linked with shorter turn times, emphasizing the interaction between posture, push off mechanics, and velocity at the exit from the wall (David et al., 2022).

However, while kinetic and kinematic elements have been extensively examined, there is still no consensus regarding the relative contribution of each individual variable, such as joint angles, resultant velocity, and impulse, to overall turn performance.

Some research highlights that no single parameter strongly predicts performance, advocating instead for a holistic approach that considers multiple interacting factors (Blanksby et al., 1998). This complexity is further supported by comprehensive biomechanical analyses in varied turning contexts. Studies on transitions (e.g., backstroke to breaststroke) reveal that combinations of push-off forces, gliding distances, and drag characteristics explain a large proportion of variability in turn time, underscoring the multifaceted nature of turn mechanics (Toussaint et al., 2002). This lack of clarity creates a significant challenge for coaches who need to prioritize technical feedback for athlete development.

Given the interactive and dynamic nature of turn biomechanics, traditional linear statistical methods (e.g., correlation, multiple regression) may be insufficient to fully elucidate the underlying mechanisms that determine performance. Such methods often assume linear relationships and independence among predictors, assumptions that are frequently violated in complex, coordinated motor skills like the swimming turn (Glazier, 2010). The performance outcome is not a simple sum of its parts but an emergent property of a complex, nonlinear system (Bartlett et al., 2007). This methodological limitation represents a critical gap in the literature, as it may obscure the true nature of the relationships between biomechanical variables and performance.

To overcome this limitation, integrative analytical approaches, including advanced modeling techniques such as Artificial Neural Networks (ANN), are necessary. ANNs are powerful computational models capable of identifying and ranking the most influential factors affecting turn time by modeling complex, nonlinear interactions between variables (Maszczyk et al., 2016). By learning from the data, ANNs can uncover hidden patterns and determine the "importance" of each input variable without assuming a linear relationship, thus providing a more nuanced and accurate understanding of performance determinants (Carvalho et al., 2024). The application of ANNs offers a novel solution to the problem of identifying the hierarchical importance of kinematic variables in swimming turns.

Research Problem

Although previous studies have established that kinematic and kinetic variables influence swimming turn performance, the relative importance of these variables remains unclear, particularly in youth competitive medley swimmers. Most existing literature focuses on adult or elite populations, limiting the generalizability of findings to younger athletes whose biomechanics and training adaptations may differ substantially (Lloyd et al., 2015).

Moreover, research predominantly utilizes linear statistical analyses, which may not capture the non-linear interrelationships and combined effects of multiple biomechanical factors. This gap suggests the need for comprehensive analyses that integrate conventional statistical methods with advanced modeling techniques capable of handling complex predictor interactions to provide a clearer, more actionable hierarchy of performance determinants.

Study Objectives

To address the identified gaps, the present study aimed to:

1. Examine selected kinematic and kinetic variables related to joint angles, propulsion characteristics, and centre of mass dynamics during the somersault turn in competitive youth swimmers.
2. Analyze the relationships between these biomechanical variables and somersault turn time using Pearson's correlation.
3. Determine the relative and normalized importance of the investigated kinematic variables in predicting turn time through the application of a nonlinear Artificial Neural Network (ANN) model.
4. Identify the key biomechanical determinants of turn performance, thereby providing evidence based insights for technique optimization and training design for youth medley swimmers.

Method

Study Design

A descriptive analytical design with a biomechanical approach was employed to investigate the kinematic variables influencing somersault turn time in competitive youth medley swimmers.

Participants

Competitive male medley swimmers aged 14–15 years (Mean ± SD: age 14.5 ± 0.5 years; height 163.22 ± 12.00 cm; body mass 48.89 ± 11.01 kg) from Smouha Sporting Club (Egypt) were recruited for this study. All participants were registered with the Egyptian Swimming Federation, trained systematically without prolonged interruptions, and demonstrated advanced technical proficiency in the turn technique under investigation, in addition to maintaining a high competitive standard within their age group. Ethical approval for the study was obtained from the Research Ethics Committee of the Faculty of Sport Sciences for Men, Alexandria University, prior to the commencement of the study.

Experimental Setting and Data Collection

All experimental procedures were conducted at an Olympic-sized swimming pool under standardized environmental and testing conditions to minimize external variability.

Basic Physical Characteristics

Prior to biomechanical testing, the following basic physical characteristics were assessed:

- Body mass (kg), measured using a calibrated medical scale
- Standing height (cm), measured using a standardized anthropometer
- Body mass index (BMI), calculated as body mass divided by height squared ($kg{\cdot}m^{-2}$)

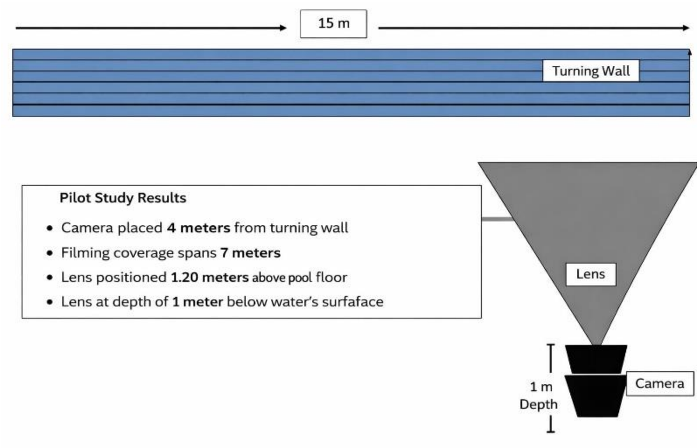
Instrumentation and Equipment

Underwater motion analysis was performed using a high-speed digital video camera (Sony HDR-AS10/AS15) operating at 240 $frames{\cdot}s^{-1}$. The camera was mounted in a waterproof housing and positioned perpendicular to the sagittal plane of motion using a fixed underwater support to ensure consistent image acquisition of the turning and push-off phases.

A rigid calibration object (2 m in length) was placed within the camera's field of view to establish spatial scaling. Calibration was performed prior to data collection to reduce measurement error.

Visual reference markers were used to identify anatomical landmarks relevant to lower-limb and trunk kinematics, enabling accurate determination of joint angles and linear kinematic variables throughout the somersault turn.

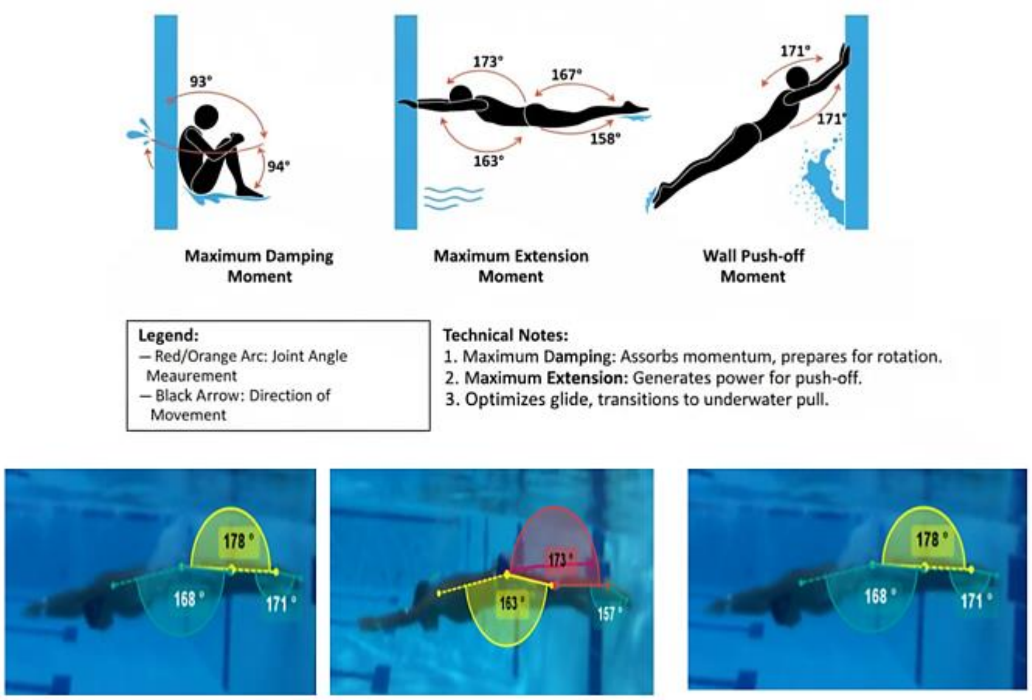
Figure 1. Pilot Study Results



Motion Capture

For kinematic analysis, the camera was fixed with predetermined field, height, and dimensions based on a preliminary study. A 2 m ruler was placed at the center of the movement field to establish scale. Swimmers wore dark swimsuits, and phosphorescent X-shaped markers were placed on anatomical joint points (shoulder, elbow, wrist, hip, knee, ankle). The experiment was conducted in a 25 m pool; after warming up, participants performed repeated rotations until correct execution was achieved.

Figure 2. Phases of the Somersault Turn in Individual Medley Swimming



Video Processing and Motion Analysis

Raw video recordings were corrected for lens distortion using Defishr. Video segmentation was performed using Camtasia Studio 8.6.0, and kinematic analysis was conducted using Kinovea (version 0.8.25) to digitize anatomical landmarks and calculate joint angles, velocities, accelerations, and temporal variables.

Kinematic Variables

The following kinematic variables were extracted and included in the analysis:

- Knee angle at maximum flexion during the absorption phase.
- Thigh angle at maximum extension.
- Trunk angle relative to the ground at maximum extension.
- Trunk tilt angle at take-off relative to the horizontal.
- Propulsive (extension) distance.
- Propulsive (extension) phase velocity.
- Resultant center of mass velocity at wall release.
- Resultant linear momentum of the center of mass at wall release.
- Maximum acceleration during wall push-off.
- Time to reach maximum acceleration.
- Maximum push-off force at wall release.
- Somersault turn time.

Statistical Analysis

Statistical analyses were carried out using SPSS (Version 25). Descriptive statistics (mean, standard deviation, skewness, and kurtosis) were calculated for all variables, and data normality was assessed using the Kolmogorov–Smirnov test.Pearson’s correlation coefficient was used to examine the relationships between the kinematic variables and somersault turn time,In addition, a three-layer Artificial Neural Network (ANN) with a single hidden layer and one output neuron was implemented to determine the relative importance of the investigated kinematic variables in predicting somersault turn time. The dataset was divided into 55.6% for training and 44.4% for testing, and statistical significance was set at $p \leq 0.05$.

Results

This section presents the results of the statistical analysis, beginning with descriptive statistics for the participant cohort and the measured kinematic variables. Subsequently, the results of the Pearson correlation analysis are provided to illustrate the linear relationships with turn time. Finally, the output of the Artificial Neural Network (ANN) model is presented, which ranks the variables based on their nonlinear contribution to predicting turn time, directly addressing the core research objective of identifying the hierarchical importance of these factors.

Descriptive Statistics

Table 1. Descriptive Statistics of the Basic Variables Under Investigation for the Study Group

Variables	Minimum	Maximum	Mean	Std. Deviation	Skewness	Kurtosis	Kolmogorov-Smirnova	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Sig.
Weight	37.00	65.00	48.89	11.01	0.45	-1.42	0.17	.200*
height	149.00	186.00	163.22	12.00	0.51	0.18	0.18	.200*
BMI	15.59	22.23	18.14	2.11	0.90	0.28	0.21	.200*

It is evident from Table (1) which presents the statistical description of the study sample in the basic variables under investigation that the data of the total sample are moderate, non-scattered, and characterized by a normal distribution. The skewness values range between 0.45 to 0.90), which are close to zero, confirming the normality and stability of the sample data. This is further supported by the Kolmogorov–Smirnov test, where all variables were non-significant (p > .05), indicating that they follow a normal distribution and are therefore suitable for parametric statistical analyses.

Table 2. Descriptive Statistics of the Kinematic Variables and somersault turn time Under Investigation for the Study Group

Variables	Minimum	Maximum	Mean	Std. Deviation	Skewness	Kurtosis	Kolmogorov-Smirnova	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Sig.
Knee angle at maximum flexion (absorption phase)	48.00	74.00	61.67	9.18	-0.06	-1.53	0.16	.200*
Thigh angle at maximum extension	159.00	178.00	169.67	5.87	-0.37	-0.05	0.12	.200*
Trunk angle relative to the ground at maximum extension	4.00	21.00	12.44	6.29	0.13	-1.77	0.20	.200*
Trunk tilt angle at take-off relative to the horizontal	5.00	22.00	11.33	5.87	0.78	-0.44	0.19	.200*
Propulsive (extension) distance	0.40	0.71	0.54	0.10	0.59	-0.36	0.16	.200*
Propulsive (extension) phase velocity	1.12	2.51	1.46	0.44	0.73	4.19	0.25	0.10
Resultant center of mass velocity at wall release	2.01	3.40	2.72	0.44	0.09	-0.37	0.16	.200*
Resultant linear momentum of the center of mass at wall release	45.57	163.07	75.22	38.87	1.08	2.87	0.28	0.045
Maximum acceleration during wall push-off	4.25	7.40	6.25	0.97	-0.47	1.24	0.22	.200*
Time to reach maximum acceleration	0.34	0.51	0.45	0.06	-1.00	-0.16	0.24	0.15
Maximum push-off force at wall release	195.72	472.18	315.14	102.13	0.41	-1.62	0.21	.200*
somersault turn time	1.33	1.94	1.64	0.21	-0.14	-1.27	0.15	.200*

It is evident from Table (2), which presents the statistical description of the study sample in the kinematic variables and turn time under investigation, that the data for the entire sample are moderate, non-scattered, and characterized by a normal distribution. The skewness values range between (-1.00 to 1.08), which are close to zero, confirming the normality and stability of the sample data. This finding is further supported by the Kolmogorov–Smirnov test, where most variables recorded non-significant values (p > .05), indicating that they follow a normal distribution and are therefore appropriate for the use of parametric statistical methods.

Table 3. The Relationship Between Kinematic Variables and Turn Time Under Investigation for the Study Group

Variables	Knee angle at maximum flexion (absorption phase)	Thigh angle at maximum extension	Trunk angle relative to the ground at maximum extension	Trunk tilt angle at take-off relative to the horizontal	Propulsive (extension) distance	Propulsive (extension) phase velocity	Resultant center of mass velocity at wall release	Resultant linear momentum of the center of mass at wall release	Maximum acceleration on during wall push-off	Time to reach maximum acceleration	Maximum push-off force at wall release	somersault turn time
Knee angle at maximum flexion (absorption phase)	1											
Thigh angle at maximum extension	0.016	1										
	0.967											
Trunk angle relative to the ground	0.163	-0.832**	1									
	0.675	0.005										

at maximum extension												
Trunk tilt angle at take-off relative to the horizontal	-0.070	-0.797*	0.865**	1								
	0.859	0.010	0.003									
Propulsive (extension) distance	0.126	0.258	-0.301	-0.361	1							
	0.747	0.502	0.432	0.340								
Propulsive (extension) phase velocity	0.594	-0.058	0.045	-0.046	0.785*	1						
	0.091	0.881	0.908	0.907	0.012							
Resultant center of mass velocity at wall release	0.119	0.195	-0.162	-0.165	0.829**	0.739*	1					
	0.761	0.615	0.676	0.672	0.006	0.023						
Resultant linear momentum of the center of mass at wall release	0.644	0.177	-0.147	-0.289	0.799**	0.955**	0.745*	1				
	0.061	0.650	0.705	0.450	0.010	0.000	0.021					
Maximum acceleration during wall push-off	0.299	0.340	-0.355	-0.184	0.517	0.612	0.621	0.573	1			
	0.434	0.371	0.349	0.636	0.154	0.080	0.074	0.107				
Time to reach maximum acceleration	-0.663	-0.307	0.254	0.265	-0.187	-0.501	-0.080	-0.527	-0.660	1		
	0.052	0.421	0.510	0.490	0.629	0.169	0.839	0.145	0.053			
Maximum push-off force at wall release	0.573	0.549	-0.491	-0.529	0.679*	0.756*	0.711*	0.872**	0.771*	-0.647	1	
	0.107	0.126	0.180	0.143	0.044	0.018	0.032	0.002	0.015	0.060		
somersault turn time	-0.319	0.714*	-0.694*	-0.753*	0.113	-0.398	-0.219	-0.217	-0.148	0.056	0.005	1
	0.402	0.031	0.038	0.019	0.771	0.289	0.571	0.574	0.703	0.887	0.990	

Table (3) illustrates the relationship between kinematic variables and somersault turn time for the study sample ,The Pearson correlation coefficients indicate that some variables are significantly associated with turn time, while others show no significant relationship. For instance, thigh angle at maximum extension showed a strong positive and significant correlation with turn time (r = 0.714, p = 0.031), indicating that larger thigh extension angles are associated with longer turn times. Similarly, trunk angle relative to the ground at maximum extension and trunk tilt angle at take-off relative to the horizontal demonstrated strong negative and significant correlations with turn time (r = -0.694, p = 0.038 and r = -0.753, p = 0.019, respectively), suggesting that smaller angles are associated with faster turn times, highlighting the importance of trunk positioning during take-off for optimal performance. Other variables, including knee angle at maximum flexion during the absorption phase, propulsive distance, propulsive phase velocity, resultant center of mass velocity at wall release, resultant linear momentum at wall release, maximum acceleration during wall push-off, time to reach maximum acceleration, and maximum push-off force at wall release, did not show significant correlations with turn time (p > 0.05). This suggests that these variables may have less influence on turn time within the current sample, or that the small sample size (n = 50) was insufficient to detect their statistical effect.

Artificial Neural Network (ANN) Analysis

The results of the ANN analysis are presented to identify the relative importance of each kinematic variable in predicting somersault turn time. Figure 1 illustrates the architecture of the trained neural network model.

Figure 3. Illustrates the Artificial Neural Network Resulting from the Interaction of Kinematic Variables Under Investigation Affecting somersault turn time

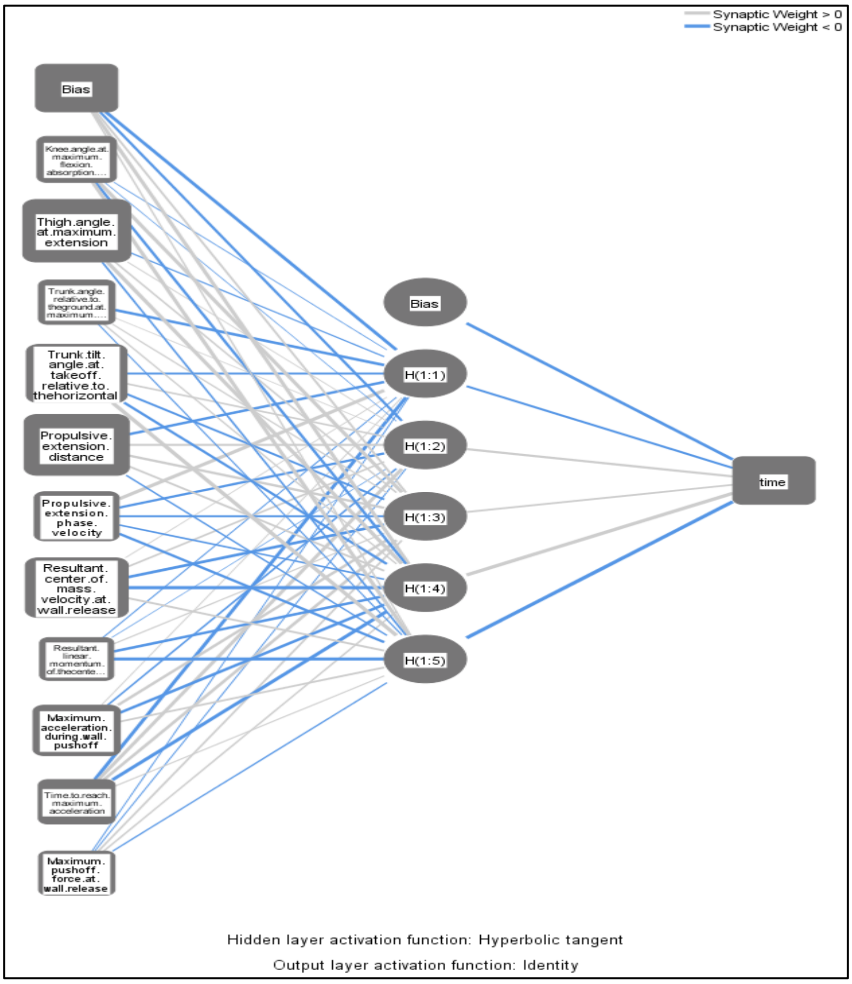


Table 4. Statistically Significant Independent Variables Ranked Descendingly According to Their Degree and Percentage of Importance

Statistically Significant Independent Variables	Importance	Normalized Importance
Thigh angle at maximum extension	0.147	100.0%
Propulsive (extension) distance	0.139	94.6%
Resultant center of mass velocity at wall release	0.133	90.2%
Trunk tilt angle at take-off relative to the horizontal	0.126	86.1%
Maximum acceleration during wall push-off	0.088	59.6%
Propulsive (extension) phase velocity	0.081	54.9%
Knee angle at maximum flexion (absorption phase)	0.066	44.6%
Time to reach maximum acceleration	0.058	39.1%
Trunk angle relative to the ground at maximum extension	0.057	38.9%
Maximum push-off force at wall release	0.056	38.3%
Resultant linear momentum of the center of mass at wall release	0.050	34.1%

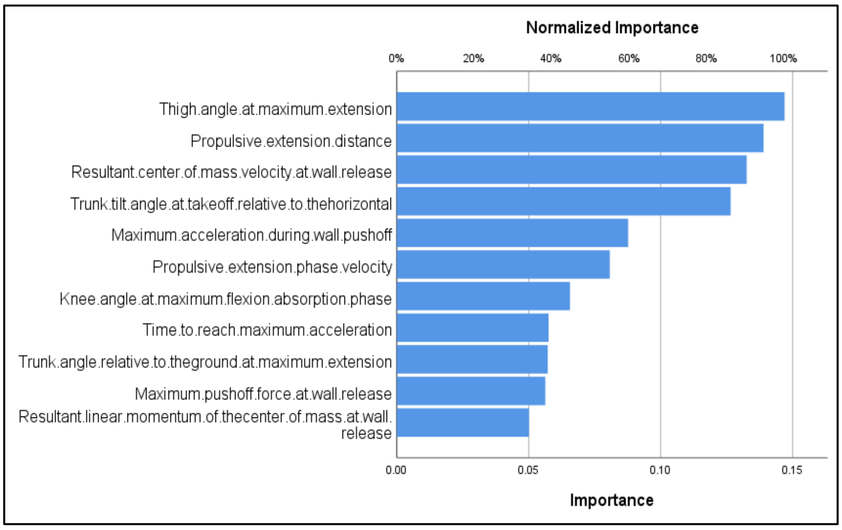
Table (4) presents the ranking of statistically significant independent variables according to their absolute and relative importance in explaining performance during the turn for the study sample. The results indicate that the thigh angle at maximum extension occupies the top position, representing 100% of the normalized importance, highlighting its critical role in determining the effectiveness of turn time and overall rotational performance.

Following this, propulsive (extension) distance (94.6%) and resultant center of mass velocity at wall release (90.2%) emphasize that the ability to generate effective movement and high speed during push-off is directly associated with shorter turn time and improved performance.

The trunk tilt angle at take-off relative to the horizontal ranks fourth (86.1%), indicating the importance of body positioning during take-off for achieving a fast and efficient rotation.

Other variables, including maximum acceleration during wall push-off, propulsive phase velocity, knee angle at maximum flexion (absorption phase), time to reach maximum acceleration, trunk angle relative to the ground at maximum extension, maximum push-off force at wall release, and resultant linear momentum of the center of mass at wall release, displayed varying levels of relative importance (ranging from 34.1% to 59.6%), suggesting that they have a lesser but still notable influence on performance compared to the top-ranked variables.

Figure 4. Ranking of Statistically Significant Independent Variables According to Their Percentage of Importance



Discussion

The present study aimed to investigate the kinematic variables influencing somersault turn time in competitive youth medley swimmers using both traditional correlation statistics and Artificial Neural Network (ANN) modeling. By addressing the limitations of linear analysis, this study sought to resolve the ambiguity regarding the relative importance of biomechanical factors. The findings indicate that turn performance is governed by a complex nonlinear interaction among lower-limb joint angles, trunk positioning, and propulsion-related variables, rather than a single kinematic factor. This supports the established understanding that swimming turns are highly coordinated, multi-phase movements in which performance emerges from the interaction of interdependent components (Veiga & Roig, 2016; González-Ravé et al., 2025).

Influence of Thigh Angle at Maximum Extension

Thigh angle at maximum extension was identified as the most influential variable in turn performance. Pearson correlation revealed a significant positive association with somersault turn time, and the ANN analysis ranked it first with 100% normalized importance. This suggests that a greater angle of thigh extension at the end of the push-off is associated with a slower turn. Effective wall push-off requires coordinated hip, knee, and ankle extension to maximize propulsion and allow a rapid transition into a streamlined position. Excessive thigh extension may disrupt the optimal force–time profile or delay the alignment of the trunk into a streamlined, low-drag position, thereby increasing hydrodynamic resistance immediately post-wall release (Toussaint et al., 2002). This aligns with recent findings suggesting that elite swimmers prioritize rapid body realignment over achieving maximal joint extension to facilitate efficient force transfer and minimize exit drag (South & Tor, 2019). This emphasizes the importance of technique-focused interventions that teach young medley swimmers to balance propulsive force generation with efficient body positioning.

Role of Trunk Angle and Trunk Tilt at Take-Off

Significant negative correlations were observed between somersault turn time and both trunk angle relative to the ground and trunk tilt at take-off. Swimmers with better trunk alignment—closer to horizontal—achieved shorter turn times. This aligns with fundamental hydrodynamic principles: a misaligned body increases frontal area and form drag during the critical underwater glide phase (Conceição et al., 2025). Veiga et al. (2014) reported that trunk orientation at wall exit critically affects post-turn velocity. The ANN modeling further emphasized trunk tilt as a highly important factor (86.1%), reinforcing its central role in mediating the transfer of propulsive force from the legs into forward motion for youth medley swimmers.

Propulsive Distance and Center of Mass Velocity at Wall Release

Propulsive distance, though not significantly correlated linearly with turn time, ranked second in ANN importance (94.6%). This underscores the ANN's ability to capture indirect and interaction-based effects undetected by linear statistics. Propulsive distance reflects how effectively lower-limb extension generates displacement during the push-off, directly contributing to wall exit velocity and reducing the time required to resume swimming strokes (Pereira et al., 2015). Similarly, center of mass velocity at wall release demonstrated high ANN importance (90.2%), consistent with Cossor and Mason (2001), who identified wall exit velocity as a primary performance indicator. The high ranking of these variables in the ANN model, despite their lack of linear correlation, suggests their influence is contingent on other factors, such as trunk alignment, highlighting the interconnected nature of turn mechanics.

Methodological Implications of ANN-Based Modeling

The divergence between the correlation and ANN findings underscores the limitations of linear statistics in capturing the complexity of turn mechanics. This study employed a descriptive analytical design to gather kinematic data, but the analysis was intentionally twofold. The initial correlational analysis served to replicate traditional approaches, revealing their limitations. The subsequent predictive modeling with ANN was not merely for prediction but was used as an explanatory tool to overcome these limitations. Linear methods assume predictor independence and linearity, which are often violated in skilled motor tasks (Glazier, 2010). ANN models, however, are adept at modeling nonlinear relationships and uncovering hidden interactions, providing superior explanatory and predictive capacity (Bartlett et al., 2007; Maszczyk et al., 2016). By demonstrating that variables with no linear correlation can be highly important within a nonlinear model, this study validates the use of ANN as a more powerful tool for understanding the multifactorial nature of athletic performance (Carvalho et al., 2024).

Practical Implications for Coaching and Youth Development

The findings provide a clear, evidence-based hierarchy of factors for coaches working with youth medley swimmers. Improving somersault turn performance should focus on:

- Optimization of thigh extension angles: Coaching should emphasize a powerful but controlled push-off that avoids over-extension, facilitating a quicker transition to a streamlined position.
- Control of trunk alignment at wall exit: Drills should focus on maintaining a rigid, horizontal trunk posture during the push-off and glide to minimize drag.
- Enhancement of effective propulsive distance: Rather than focusing solely on maximal force production, training should aim to maximize the distance the CM travels during the push-off phase, which is a product of both force and technique.

This aligns with long-term athlete development principles emphasizing technical coordination and movement efficiency during adolescence (Lloyd et al., 2015). ANN-based feedback systems could eventually support individualized technique optimization in real-time (Matúš et al., 2025).

Conclusions

The present study provides novel insights into the kinematic determinants of somersault turn performance in competitive youth medley swimmers. By leveraging both linear and nonlinear analytical methods, we demonstrated that turn efficiency is governed by a complex interplay of lower-limb joint angles, trunk positioning, and propulsion mechanics. The ANN model successfully resolved the ambiguity of traditional analyses, revealing that thigh angle at maximum extension, propulsive distance, and center of mass velocity at wall release are the most influential contributors to turn time. These findings underscore the necessity of holistic, multi-factorial training interventions that prioritize the coordinated execution of the entire turn sequence—particularly the balance between force generation and drag reduction—rather than merely enhancing isolated components like maximal strength. The study also validates the utility of Artificial Neural Networks as a superior methodological tool for uncovering nonlinear interactions in biomechanical datasets, providing a more comprehensive and ecologically valid understanding of the factors influencing complex athletic skills.

Despite the valuable insights provided, several limitations should be acknowledged:

1. Sample Size and Generalizability: The study was conducted on a cohort of male youth medley swimmers. While this population is suitable for a detailed biomechanical analysis, the findings may not be fully generalizable to female athletes, different age groups, or athletes of varying performance levels. Future research should include larger and more diverse populations to validate and extend these results.

2. Scope of Kinematic Variables: While key lower-limb and trunk kinematics were analyzed, other factors such as upper-limb coordination, head position, and a direct measure of hydrodynamic drag were not included. Incorporating these variables in future 3D analyses could provide a more complete model of turn performance.

3. Environmental and Contextual Factors: Variability in swimmer fatigue and psychological state under non-race conditions can influence performance. Future research should investigate ecological validity by examining turns under competitive race conditions.

4. Integration with Physiological Metrics: Combining kinematic analyses with physiological data (e.g., muscle activation patterns via EMG) could enhance understanding of the neuromuscular strategies driving performance efficiency and allow for more targeted training interventions (Pereira et al., 2015).

5. ANN Model Refinement: Although the ANN effectively identified key contributors, further refinement using larger datasets, different architectures, and cross-validation techniques is recommended to improve predictive accuracy and robustness, enabling practical applications in real-time performance monitoring and coaching feedback (Carvalho et al., 2024).

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