Journal of Physical Education and Sport ® (JPES), Vol. 26 (issue 5), Art 98, pp. 967 - 978, May 2026
online ISSN: 2247 - 806X; p-ISSN: 2247 – 8051; ISSN - L = 2247 - 8051 © JPES

Original Article

Comparative analysis of the kinematic structure of rowing technique of female athletes at different qualification levels

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Published online: May 31, 2026
Accepted for publication: May 15, 2026
DOI:10.7752/jpes.2026.05098

Abstract
Background and Aim. Modern rowing development is characterized by higher density of competitive results and increasing demands for technical mastery of female athletes. Optimizing of the kinematic structure of the stroke cycle—by ensuring effective interaction among stroke rate, stroke length, and boat velocity— is a key determinant of competitive performance. However, comparative analyses of kinematic indicators in female single scullers of different qualification levels under competitive conditions remain insufficiently investigated. The purpose of the study was to conduct a comparative analysis of the kinematic structure of rowing technique of female single scullers of different levels of athletic qualification and to determine the most informative indicators influencing competitive performance efficiency. ***Material and Methods.*** The research involved 36 female single scullers divided into three groups: World's Elite Athletes (WEA, n = 12), Leading Ukrainian Athletes (LUA, n = 12), and Qualified Ukrainian Athletes (QUA, n = 12). Data were collected during a 2,000 m competitive race using pedagogical observation, video recording, and biomechanical analysis. The primary kinematic variables included stroke rate, stroke cycle duration, distance per stroke, boat velocity, joint angular parameters, blade–boat velocity ratio at the catch, intra-cycle velocity fluctuations, and micro-phase temporal structure of the stroke cycle. Statistical analysis involved calculation of mean values, standard deviations, and correlation coefficients ($p < 0.05$; $p < 0.01$). ***Results.*** Higher athletic qualification was associated with higher stroke rate, shorter stroke duration, and greater distance per stroke, resulting in superior average boat velocity. Elite athletes demonstrated more efficient temporal organization of micro-phases, minimized velocity loss at the catch, effective "active catch" mechanics, optimized proximal-to-distal force sequencing, and reduced intra-cycle velocity fluctuations. Strong correlations were found between average boat velocity and blade velocity at the catch ($r = 0.95$), distance per stroke ($r = 0.94$), stroke rate ($r = 0.90$), and selected joint angular and velocity parameters. Lower-qualified athletes exhibited prolonged transition phases, inefficient trunk and limb coordination, and greater kinematic variability**.** ***Conclusions.*** Athletic mastery in female single scullers is determined primarily by the efficiency of the biomechanical structure of the stroke cycle rather than by anthropometric characteristics. The integration of optimized stroke rhythm, effective blade–boat interaction, coordinated intersegmental movement, and minimized intra-cycle velocity losses constitutes the foundation of high-performance rowing. The findings may be applied to refine technical training and individualize preparation strategies to enhance competitive outcomes.
Key words: sculling biomechanics, movement indicators, oar-water interaction, stroke cycle, athletic mastery, competitive performance

Introduction

At the present stage of development of rowing, the problem of improving the technical mastery of female athletes is of particular relevance. The continuous increase of rivalry at the international sports arena, the growing demands on the level of sports results, and the need for effective realization of athletes' functional potential determine the search for new scientifically grounded approaches to the organization of the training process. Within the structure of rowers' sports preparedness, technical training is considered one of the key factors for achieving high sports results, since it is precisely the rational rowing technique that ensures efficient transfer of muscular effort to the oar, optimization of intra-cycle boat velocity, and reduction of the athlete's energy expenditure.

In recent years, the issue of improving rowing technique based on the analysis of its kinematic structure has occupied an important place in the research of national and international specialists. Particular attention was

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paid to the comparative study of technical characteristics of female rowers of different qualification levels, driven by the need to raise training and competitive performance efficiency.

Modern studies (Baudouin & Hawkins, 2020; Kleshnev, 2020) indicated that rowing technique represents a complex coordination structure in which temporal, spatial, and rhythmic characteristics of movement play a key role. The effectiveness of the stroke cycle execution is determined by the coordination between upper and lower limbs, the rational trajectory of the oar movement, the stability of postural structures, and the athlete's ability to minimize boat velocity losses during transitional phases of the cycle. Even minor disturbances in movement coordination can lead to deterioration of the hydrodynamic conditions of boat movement, reduced efficiency of force application, and increased energy cost of work.

The study of the kinematic structure of rowing technique of athletes of different qualification levels has got of particular importance in modern research. Analysis of scientific literature shows that highly qualified athletes are characterized by a more stable rhythm-temporal organization of the stroke cycle, optimal joint angular characteristics, rational distribution of effort across stroke phases, and an economical model of motor actions. It was established that highly qualified athletes are characterized by a more stable kinematic stroke structure, rational force distribution across movement phases, and an optimal ratio between drive and recovery phase durations. Several authors have reported that lower-qualified rowers exhibit excessive vertical and lateral trunk oscillations, reflecting reduced postural stability and suboptimal intersegmental coordination during the stroke cycle (Legge et al., 2024b; Minnock, 2017; Marinković et al., 2021; Kleshnev, 2020). Such excessive trunk displacement has been associated with diminished mechanical efficiency and increased intra-cycle variability in boat motion. Studies on coordination dynamics in rowing indicate that insufficient synchronization between upper and lower limbs, together with disturbances in stroke rhythm, negatively affects force transmission and movement efficiency. Research by Cuijpers et al. (2015) demonstrated that impaired interlimb coordination and deviations from stable in-phase patterns reduce mechanical effectiveness and compromise stroke consistency. Similarly, Doeksen (2018) emphasized that inadequate synchronization during transitional phases of the stroke limits effective torque transfer, particularly at the catch. From a performance-efficiency perspective, Thompson (2025) highlighted that rhythm disruptions and asynchronous segmental actions increase unnecessary energy expenditure and reduce propulsive effectiveness.

Previous investigations by Harun, Nasruddin, Yusof, and Syahrom (2022, 2025) have emphasized that rowing performance results from the integrated interaction between anthropometric, physiological, biomechanical, and hydrodynamic factors. Their systematic analyses indicate that effective stroke mechanics are characterized by coordinated segmental sequencing, efficient force transmission to the oar blade, and optimized interaction between blade-generated hydrodynamic forces and boat acceleration. Within this framework, highly qualified rowers demonstrate smoother progression of boat velocity, reduced fluctuations of the body center of mass, and greater stability of stroke cycle parameters, reflecting refined coordination dynamics and mechanically efficient rowing locomotion. These findings are consistent with contemporary research indicating that stability of kinematic variables and synchronization of segmental actions are fundamental indicators of sports mastery (Cuijpers et al., 2015; Cuijpers, 2019; Marinkovic et al., 2021; Thompson, 2025). Stable movement patterns contribute to efficient force transmission to the oar, reduced intra-cycle velocity oscillations, and improved energetic economy, thereby enhancing overall rowing performance (Malikov et al., 2024).

Relevance is associated with the need to identify the most informative kinematic indicators influencing the effectiveness of female athletes' competitive performance. Despite the considerable number of studies devoted to the biomechanics of rowing, the problem of comparative analysis of the kinematic structure of rowing technique of athletes of different qualification levels remains insufficiently studied. Most existing works focus either on the analysis of individual phases of the stroke cycle or on the study of technique of highly qualified athletes without detailed comparison of biomechanical characteristics across different skill levels. The relationships between the rhythm-temporal structure of the cycle, movement speed characteristics, oar handle trajectory, and dynamics of intra-cycle boat velocity remain insufficiently explored.

Modern biomechanical technologies, including 3D video analysis, inertial sensors, and GPS systems (Buckeridge et al., 2024), have enabled more precise researches of differences in rowing technique among athletes of different qualification levels. The findings indicated that elite female rowers demonstrated more optimal oar angles of attack, synchronized movements, and a more economical kinematic stroke model.

In addition, an important issue remains the insufficient development of scientifically grounded criteria for assessing the technical preparedness of female athletes in rowing. In practice, coaches often rely primarily on visual methods of technique evaluation, which do not allow for objective assessment of spatial-temporal and speed parameters of movement. The lack of comprehensive biomechanical models of rowing technique limits the possibilities for individualization of the training process and timely correction of technical errors.

The analysis of contemporary literature confirms that comparative evaluation of the kinematic structure of rowing technique constitutes an effective methodological approach for objectively assessing technical preparedness and for substantiating the individualization of training programs. Detailed biomechanical examination of stroke kinematics enables the identification of performance-limiting factors and supports evidence-based technical refinement (Legge et al., 2024a; Penichet-Tomas et al., 2025). Moreover, applied biomechanical frameworks underline that systematic kinematic monitoring provides precise diagnostic feedback for optimizing stroke mechanics and adapting training interventions to the individual athlete (Kleshnev, 2020; Cruz et al., 2024). Collectively, these findings position comparative kinematic analysis as a fundamental tool in performance diagnostics and individualized technical development in rowing.

Thus, the review of scientific literature demonstrates that the level of athletic qualification is directly related to the characteristics of the kinematic structure of rowing technique. The available evidence highlights the need for further investigation of biomechanical characteristics of a stroke to optimize technical training in rowing. The purpose of this study was to conduct a comparative analysis of the kinematic structure of rowing technique of female athletes of different qualification levels in order to identify trends in the development of motor organization within the stroke cycle as athletic mastery increases and to determine key kinematic indicators influencing competitive performance.

Materials and Methods

Participants.

The study involved 36 female athletes specializing in rowing. The qualification levels included First-Class Athletes, Candidates for Master of Sport of Ukraine, Masters of Sport of Ukraine of International Class, and Honored Masters of Sport of Ukraine.

Intuition Ethical approach. The research program was approved by the Commission on Biomedical Ethics of the National University of Physical Education and Sport (Protocol No. 2, 19.02.2026).

Study Design.

Prior to the baseline experiment, contemporary aspects of technical preparation in rowing were analyzed. Sociological methods, including interviews with coaches and athletes as well as questionnaires, were conducted. Based on this analysis, the purpose and objectives of the study were formulated, and research methods were selected and tested. The pedagogical experiment method was applied throughout all stages of the study. Anthropometric methods (height chart, medical scales, measuring tape) were used to determine key morphological characteristics, including body height, body mass, lower limb length, arm span, and body proportions. To obtain kinematic characteristics of rowing movements of female athletes of different qualification levels and to analyze boat velocity dynamics throughout the stroke cycle, video recording method was applied. Two SONY Digital 8 cameras operating at 50 frames per second were used. One camera was positioned 1000 m from the start, and the other 100 m before the finish line. Both cameras were equipped with zoom lenses, enabling adjustment of focal length without loss of sharpness and allowing recording at distances of 10–40 m. Metrological requirements were strictly observed during data collection: tailwind velocity did not exceed 2 $m \cdot s^{-1}$; velocity of current did not exceed 0.05 $m \cdot s^{-1}$ and coincided with the direction of boat movement, which complies with acceptable conditions for recording official race results. The longitudinal axis of the camera lens was positioned perpendicular to the direction of movement. To determine real coordinates of the analyzed points, an external reference system (buoys placed every 10 m) and an internal reference system (boat outrigger length — 0.75 m) were used. Video analysis of the world's elite athletes (WEA) was conducted using footage from Stages I–II of the 2024 World Cup. Analysis of leading Ukrainian athletes (LUA) was based on recordings from the 2024 Ukrainian National Championship and Ukrainian Cup. Data for qualified Ukrainian athletes (QUA) were obtained from the 2024 Ukrainian Junior Championship in single sculls.

Biomechanical analysis of the kinematic structure of motor actions was performed using the "Lumax" software package. As a result of computer-assisted video analysis, quantitative indicators of rowing technique of female single scullers of different qualification levels were obtained, including: joint angles at the elbow, knee, and shoulder (°); linear velocities of these joints and boat velocity ($m \cdot s^{-1}$); horizontal oar blade velocity ($m \cdot s^{-1}$); duration of the stroke cycle and its phases (s); distance covered per stroke; and the trajectory of the oar handle. All quantitative indicators were calculated automatically using the Lumax software.

Statistical analysis data.

Experimental data were processed using methods of mathematical statistics in accordance with established methodological recommendations. The arithmetic mean, standard deviation, and Pearson's correlation coefficient (r) were calculated. Differences between independent samples were assessed using the Mann–Whitney U test, while differences between dependent samples were evaluated using the Wilcoxon test at a significance level of $p = 0.05$. Statistical analysis was performed using standard software packages (Excel, Statistica 12).

Results

Biomechanical analysis of motor technique of athletes of different qualification levels made it possible to determine the characteristics of rowing locomotion technique in single sculls. The average time for completing the 2000 m distance was 7 min 40 s for world's elite athletes (WEA), 7 min 58 s for leading Ukrainian athletes (LUA), and 8 min 40 s for qualified Ukrainian athletes (QUA) at the stage of specialized basic training. The presented data indicate that elite athletes spend less time per stroke cycle while covering a greater distance per stroke compared to QUA athletes (Table 1).

Table 1. Spatial and temporal characteristics of rowing locomotion in female athletes of different qualification levels in single sculls

Indicators	Statistical parameter	Female Athletes		
		WEA (n=12)	LUA (n=12)	QUA (n=12)
Stroke rate 1000 m before the finish	$\bar{x}$	35	33	31*
	S	1.36	1.06	1.53
Stroke duration (s)	$\bar{x}$	1.71	1.8	1.94*
	S	0.1	0.15	0.17
Distance per stroke (m)	$\bar{x}$	9.5	9.17	7.21*
	S	0.91	0.85	1.01

Note. World's Elite Athletes (WEA); Leading Ukrainian Athletes (LUA); Qualified Ukrainian Athletes (QUA); * Differences are statistically significant at $p < 0.05$.

The biomechanical parameters of the stroke were examined during the catch phase, the drive phase (beginning, middle, and finish), the oar extraction, and the recovery. The angles of trunk inclination, oar blade angle of attack, as well as knee and elbow joint angles were analyzed (Table 2). Comparative analysis did not reveal a statistically significant influence of anthropometric characteristics on angular parameters. It was established that, at the moment of the catch, world-ranking leaders demonstrate an elbow joint angle 6–7° greater than that observed in the QUA group, which ensures a more effective water catch. Excessive trunk inclination (by 5–6°) of QUA athletes delays the adoption of the optimal working position.

Beginning of the drive phase. The analysis showed that in the QUA group, the elbow joint angle in this phase is 18° smaller than in the WEA and LUA groups. This deviation was classified as the technical error known as "early arm pull," which resulted in inefficient involvement of the back and leg muscles in generating propulsive force. QUA athletes also demonstrated an increased trunk inclination of 6–8°. Considering that the key objective of this phase is to overcome body mass inertia and rapidly change the direction of movement, this finding indicated slower postural transition dynamics of less qualified female rowers.

Middle and finish of the drive phase. In mid-drive, differences in trunk inclination angle (4–7°) were associated with uneven movement execution by QUA athletes during the drive phase. At the end of the drive, statistically significant differences in trunk inclination were also identified in this group, indicating the technical error referred to as "body layback collapse," which complicated the timely transition to the recovery phase. In the middle of the recovery phase, lower-qualified athletes demonstrated an elbow joint angle differing by 15° compared to highly qualified athletes, indicating insufficient speed of arm return to the starting position.

Table 2. Joint Angular Characteristics of Female Athletes of Different Qualification Levels and Oar Blade Angles During the Stroke Cycle

Time Point	Angle measured (°)												
	Female athletes												
	WEA (n=12)					LUA (n=12)				QUA (n=12)			
	Statistical Parameter	Shoulder-forearm	Torso-Vertical	Thigh-Shin	Oar in Water	Statistical Parameter	Shoulder-forearm	Torso-Vertical	Thigh-Shin	Statistical Parameter	Shoulder-forearm	Torso-Vertical	Thigh-Shin
Catch	$\bar{x}$	171	23	55	90	170	24	53	89	164	28	57	80
	S	1.15	1.98	1.5	1.10	1.25	2	1.60	1.10	6	2.05	1.4	1.10
Beginning of the drive phase	$\bar{x}$	177	19	64	-90	178	17	62	-90	159*	25*	62	-90
	S	0.98	1.39	1.9	0	1	1.39	1.8	0	5.15	2.33	1.9	0
Middle of the drive phase	$\bar{x}$	142	4	102	-90	140	6	103	-90	140	11	103	-90
	S	1.91	1.47	1.36	0	2.1	1.47	1.36	0	2.1	3.74	1.36	0
Finish of the drive phase	$\bar{x}$	50	-25	149	60	47	-26	147	60	45	-39*	147	50
	S	1.74	1.94	1.94	3.48	1.74	2.94	1.94	5.48	1.74	8	1.94	5.48
Middle of the recovery phase	$\bar{x}$	126	20	123	3	126	20	120	4	113	19	119	5
	S	0.9	1.67	2.24	1.16	0.7	1.67	1.9	1.26	2.52	4.89	2.1	1.26

Note. World's Elite Athletes (WEA); Leading Ukrainian Athletes (LUA); Qualified Ukrainian Athletes (QUA); *Negative torso-vertical angle values at the end of the drive phase indicate backward trunk lean;
Differences are statistically significant at $p < 0.05$

Amplitude Characteristics. Based on the analysis of the spatial organization of body segments, movement amplitudes were determined. The trunk amplitude in the QUA group was 67°, which substantially exceeded the values observed in WEA (48°) and LUA (50°) groups. At the same time, knee joint amplitude of QUA (90°) was lower than that of elite athletes (94°). The elbow joint amplitude throughout the stroke cycle was 121° (WEA), 123° (LUA), and 119° (QUA). The reduced amplitude in QUA athletes resulted from incomplete elbow extension at the beginning of the drive phase.

Velocity Characteristics. The analysis of instantaneous velocity of the hand center of mass, shoulder joint, and knee joint made it possible to further differentiate technical characteristics. Knee joint velocity at the beginning of the drive phase was: WEA — 0.7 m·s⁻¹, LUA — 0.85 m·s⁻¹, QUA — 0.69 m·s⁻¹. In mid-drive, an intensive increase in velocity was observed due to active leg extension: WEA — up to 1.2 m·s⁻¹, LUA — up to 1.1 m·s⁻¹, QUA — only up to 0.7 m·s⁻¹.

The insufficient leg extension velocity of QUA athletes during this phase limits effective acceleration of body mass. At the end of the drive, knee velocity decreased in all groups due to complete lower-limb extension (Figure 1).

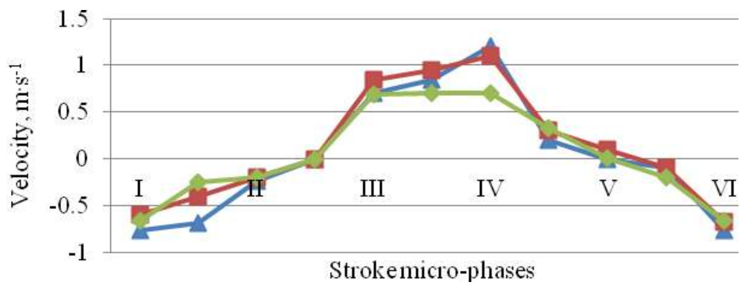

Figure 1. Changes in Knee Joint Angular Velocity of Female Athletes of Different Qualification Levels During the Stroke Cycle in Single Sculling

Note. I – stroke preparation phase (recovery); II – catch; III – beginning of the drive phase; IV – drive; V – finish of the drive; VI – recovery;

– WEA; – LUA; – QUA

Shoulder Joint Velocity Dynamics

Shoulder joint velocity (Figure 2) increased from the onset of the drive phase in all groups. In this phase the indicators were: in group of WEA — 0.55 m·s⁻¹, in group of LUA — 0.63 m·s⁻¹, in group of QUA — 0.54 m·s⁻¹.

By mid-drive, velocity increased markedly, reaching a maximum in WEA group (0.92 m·s⁻¹), compared with 0.76 m·s⁻¹ in LUA group and 0.70 m·s⁻¹ in QUA group.

At the end of the drive phase, highly qualified athletes (WEA and LUA) demonstrated negative shoulder joint velocity (−0.1 m·s⁻¹), indicating timely reversal of the movement vector and efficient transition to recovery phase.

In contrast, QUA athletes maintained positive velocity (0.5 m·s⁻¹), reflecting inertial continuation of backward trunk motion. This technical error delays recovery initiation and limits further within-cycle boat acceleration.

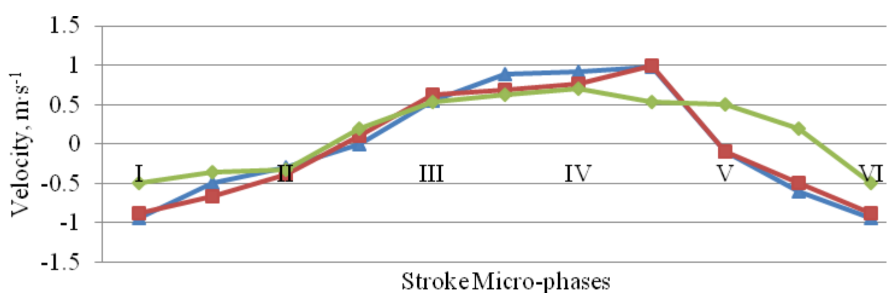

Figure 2. Changes in Knee Joint Angular Velocity of Female Athletes of Different Qualification Levels During the Stroke Cycle in Single Sculling

Note. I – stroke preparation phase (recovery); II – catch; III – beginning of the drive phase; IV – drive; V – finish of the drive; VI – recovery

– World's Elite Athletes;
– Leading Ukrainian Athletes;
– Qualified Ukrainian Athletes

Dynamics of Hand Center of Mass Velocity and Its Influence on Boat Speed

An increase of hand center of mass velocity (Figure 3) was recorded from the onset of the drive phase. In this phase the indicators were: in group of WEA — 1.7 m·s⁻¹, in group of LUA — 1.5 m·s⁻¹, in group of QUA — 0.5 m·s⁻¹. Maximum values occurred at mid-drive: (WEA) — 2.2 m·s⁻¹, (LUA) — 2.0 m·s⁻¹, (QUA) — 1.35 m·s⁻¹. At the end of the drive phase, velocity decreased. In WEA and LUA groups, values became negative (−0.2 m·s⁻¹ and −0.4 m·s⁻¹ respectively), whereas QUA maintained positive velocity (0.47 m·s⁻¹).

Positive shoulder and hand center of mass velocities at the end of the drive of QUA athletes indicated a delayed transition to recovery. This impaired timely trunk vector reversal and reduces drive phase efficiency. Consequently, within-cycle boat velocity gain in QUA group was only 0.99 m·s⁻¹, compared with 1.2 m·s⁻¹ (WEA) and 1.12 m·s⁻¹ (LUA) group.

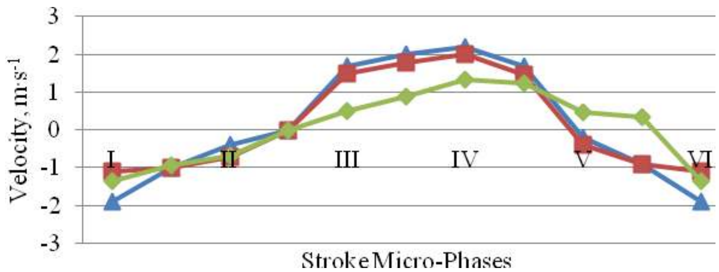

Figure 3. Changes in Hand Center of Mass Velocity of Female Athletes of Different Qualification Levels During the Stroke Cycle in Single Sculling.

Note. I – stroke preparation phase (recovery); II – catch; III – beginning of the drive phase; IV – drive; V – finish of the drive; VI – recovery

– World's Elite Athletes;
– Leading Ukrainian Athletes;
– Qualified Ukrainian Athletes

Analysis of Oar Blade–Boat Velocity Ratio During the Catch Phase

Catch efficiency is determined by the ratio of horizontal oar blade velocity (V_blade) to boat velocity (V_boat). To prevent hydrodynamic braking at blade entry, the blade must have horizontal velocity relative to the boat that exceeds the boat's velocity relative to the water and be directed opposite to boat movement.

The analysis showed that in group of highly qualified athletes (WEA and LUA) in the moment of catch the positive **difference in velocities** was observed: WEA: V_blade = 4.8 m·s⁻¹ at V_boat = 4.5 m·s⁻¹; LUA: V_blade = 4.6 m·s⁻¹ at V_boat = 4.34 m·s⁻¹

This excess ensures the immediate generation of propulsive force from the moment of the the contact of oar blade with the water. In contrast, excessive acceleration of the blade prior to the catch leads to increased energy expenditure and "slippage" of the oar without an adequate increase in system velocity due to mass inertness. In the group of QUA athletes, equality of the blade and boat velocities at the beginning of the drive phase was recorded (V_blade = V_boat = 3.58 m·s⁻¹). The absence of preliminary horizontal blade acceleration results in braking upon water entry. This created a biomechanical dissonance: despite the rower's considerable efforts during working with the handle, the intra-cycle velocity of the boat decreased, as confirmed by kinematic analysis data (Fig. 4). Thus, the absence of an "active catch" is a critical technical error that deprives rowers of the ability to effectively use the boat's inertia. Thus, absence of an "active catch" represents a critical technical error limiting effective use of boat inertia.

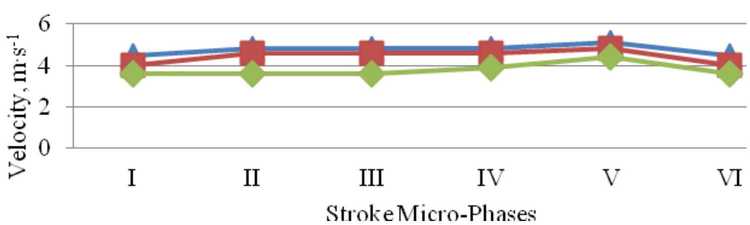

Figure 4. Changes in of oar Blade Velocity of Female Athletes of Different Qualification Levels During the Stroke Cycle in Single Sculling.

Note. I – stroke preparation phase (recovery); II – catch; III – beginning of the drive phase; IV – drive; V – finish of the drive; VI – recovery

– World's Elite Athletes;
– Leading Ukrainian Athletes;
– Qualified Ukrainian Athletes

Oar Handle Trajectory Analysis

Kinematic analysis revealed significant differences in the spatial organization of the oar handle motion during the recovery (preparation) phase. In groups of highly qualified athletes (WEA and LUA), the handle trajectory during this period is close to a horizontal line (Figure 5), which minimizes unnecessary movements of the center of mass and helps maintain the boat's dynamic balance.

In contrast, female athletes of the QUA group demonstrated a pronounced arcuate trajectory during the recovery phase. The decrease of the handle level at the beginning of the approach to the catch was caused by excessive relaxation of the shoulder and forearm flexor muscles. This technical error forced the athletes to perform an additional vertical movement to lift the handle before the catch, which increased the duration of the phase and created excessive load on the chest muscles.

A wider amplitude of vertical oscillations of the handle in qualified rowers compared to elite athletes lead to irrational energy expenditure and destabilization of the boat along the heeling and trim axes. The obtained data confirm that the straightness of the trajectory during the recovery period is a key indicator of technical mastery and efficiency of rowing locomotion.

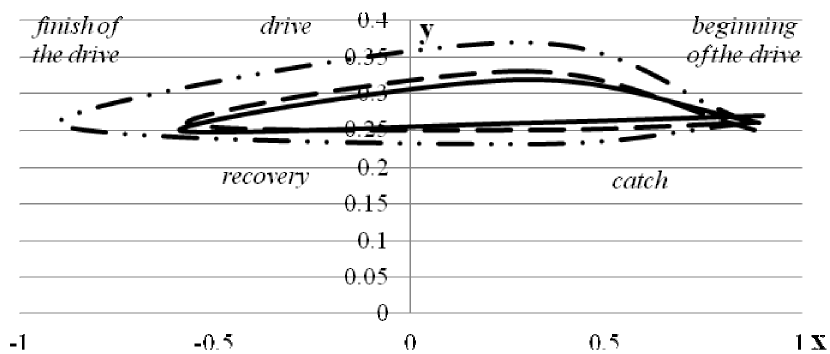

Figure 5. The Oar Handle Trajectory of Female Athletes of Different Qualification Levels During the Stroke Cycle in Single Sculling

– World's Elite Athletes;

– Leading Ukrainian Athletes;

– Qualified Ukrainian Athletes

Rhythm–Temporal Structure of the Stroke Cycle

The rowing rhythm, defined as the ratio of the duration of the support (drive) and preparation (recovery) phases, at the finish segment of the distance was: in the group WEA — 1:1.1; in the group LUA — 1:1.2; in the group QUA — 1:1.2.

Optimal phase ratio is critical for maintaining within-cycle velocity.

The optimal ratio of phases is a critical factor in maintaining intra-cycle velocity: excessive preparation (recovery) duration leads to a loss of boat inertia, while an irrationally short one leads to insufficient restoration of muscle resources for the next cycle.

Phase analysis of the temporal structure **(Fig. 6):**

1. Catch phase (from blade rotation to blade entry). In the QUA group, the duration of this phase was 0.20 s, which exceeds the values of the LUA and WEA groups by 0.06–0.08 s. In this phase, all groups demonstrated a decrease in boat velocity due to hydrodynamic resistance during blade entry: in WEA group by 0.47 $m \cdot s^{-1}$, in LUA group by 0.37 $m \cdot s^{-1}$, and in QUA group by 0.65 $m \cdot s^{-1}$. The more pronounced velocity drop and the prolonged nature of the phase in the QUA group indicated a technical error described as "blade distancing from the water" prior to the catch.

2. First half of the drive (up to the perpendicular position of the oar). The duration of this phase in the QUA group (0.47 s) was significantly longer than in LUA (0.39 s) and WEA (0.36 s) groups. The key objective of this stage is power generation through active leg extension. To optimize propulsive force, it is necessary to synchronize trunk and seat (sliding seat) movement, avoiding premature pelvic advance or early backward trunk lean. The increase in boat velocity during this phase was 0.58 $m \cdot s^{-1}$ in QUA group compared to 0.36 $m \cdot s^{-1}$ in the higher-qualified athletes groups, which can be explained by the compensatory nature of the effort following the substantial velocity loss at the catch.

3. Second half of the drive (until blade exit from the water). The phase duration is identical across all groups (0.4 s). However, the efficiency of boat acceleration differs: in the WEA and LUA groups, the velocity increase was 0.44 $m \cdot s^{-1}$ and 0.43 $m \cdot s^{-1}$, respectively, whereas in KSU it was only 0.34 $m \cdot s^{-1}$. The reduced efficiency in the KSU group is due to incomplete extension of the lower limbs and premature loss of contact with the foot stretcher before completion of the support phase, leading to a deficit in final stroke power.

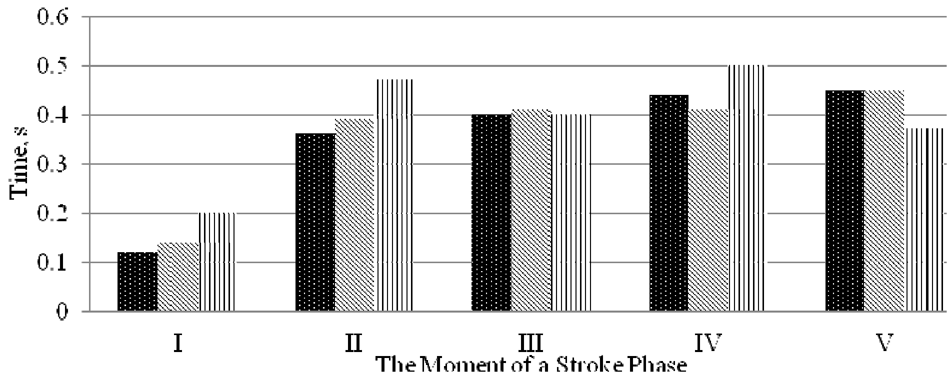

Figure 6. The Duration of a Stroke Micro-Phases of Female Athletes of Different Qualification Levels During the Stroke Cycle in Single Sculling

Note. I – catch–beginning of the drive phase; II – beginning of the drive phase–middle of the drive phase III – middle of the drive–finish of the drive; IV – finish of the drive–middle of recovery; V – middle of recovery–catch

– World's Elite Athletes;
– Leading Ukrainian Athletes; – Qualified Ukrainian Athletes

Analysis of the Dynamics of the Recovery (Non-Support) Phases of the Cycle

Fourth phase (beginning of recovery). The duration of the period from blade extraction to the perpendicular position of the oar in the QUA group was 0.5 s, which exceeds the values of the WEA and LUA groups by 0.06–0.09 s. The main objective of this phase is effective compensation for the rower's body mass inertia and rapid reversal of the movement vector into the recovery direction. An increase in boat velocity was recorded in this phase: by 0.22 $m \cdot s^{-1}$ in WEA group, by 0.24 $m \cdot s^{-1}$ – in LUA, whereas in QUA it was only 0.15 $m \cdot s^{-1}$ (Table 3). The extended duration of this phase in the QUA group indicates slower dynamics in restructuring the working posture and inefficient use of the boat's inertial glide.

Fifth phase (final part of recovery). In the QUA group, the duration of this phase was 0.37 s, which is on average 0.08 s shorter than in the elite groups. The rhythmic structure of the slide toward the catch should ensure smooth system movement. The reduction in the duration of the fifth phase observed in the group of qualified athletes indicates an accelerated slide toward the foot stretcher. A sharp acceleration at the beginning of recovery causes an impulsive increase in boat hull velocity followed by abrupt deceleration, leading to degradation of the system's kinetic energy and a decrease in the average center-of-mass velocity over the cycle.

Table 3. Boat velocity in the micro-phases of the stroke cycle in female rowers of different qualification levels in single sculls

The Moment of a Stroke Phase	Boat Velocity, $m \cdot s^{-1}$					
	Female Athletes					
	WEA (n=12)		LUA (n=12)		QUA (n=12)	
	$\bar{x}$	S	$\bar{x}$	S	$\bar{x}$	S
Catch–beginning of the drive phase (1)	4.18	0.59	4.13	0.61	3.27	0.48
Beginning of the drive phase–middle of the drive phase (2)	4.54	0.27	4.49	0.35	3.85	0.32
Middle of the drive–finish of the drive (3)	4.98	0.47	4.76	0.53	4.19	0.59
Finish of the drive–middle of recovery (4)	5.1	0.86	5	0.9	4.34	0.97
Middle of recovery–catch (5)	4.65	0.91	4.5	0.88	3.89	0.93
The average boat velocity in the stroke cycle	4.71	0.51	4.57	0.65	3.9	0.7

Rhythmic structure and intra-cycle velocity of the boat

Analysis of phase rhythm. Significant differences between groups of athletes were found in micro-phase rhythm (from the 1st phase to the 5th phase): WEA group: 1 : 3.0 : 3.3 : 3.4 : 3.5; LUA group: 1 : 3.5 : 2.9 : 2.9 : 3.2; QUA group: 1 : 2.3 : 2.0 : 2.5 : 1.8.

It was established that in the QUA group the support (drive) phase (micro-phases 2 and 3) is significantly shorter than in the elite athletes' groups. The ratio of 2.3: 2.0 indicated insufficient time for the realization of power potential and effective boat acceleration.

During the recovery, the duration of the 5th micro-phase in the WEA and LUA groups exceeded that of the 4th, whereas in the QUA group an inverse relationship was observed. This inversion indicates a delayed return of the trunk and arms immediately after blade extraction, leading to premature deceleration of the system. Statistically significant differences ($p < 0.05$) were recorded in the 1st and 4th micro-phases.

Boat velocity dynamics. Analysis of intra-cycle velocity fluctuations (Fig. 7) showed that the maximum values are reached at the end of the drive phase: WEA group — 5.1 $m \cdot s^{-1}$; LUA group — 4.83 $m \cdot s^{-1}$; QUA group — 4.42 $m \cdot s^{-1}$. Minimum velocity occurred at the catch: in WEA group — 4.2 $m \cdot s^{-1}$, in the LUA group — 4.0 $m \cdot s^{-1}$, in the QUA group — 3.23 $m \cdot s^{-1}$. Such a pronounced decrease of velocity in the QUA group is explained by a combination of factors: the absence of propulsive force, environmental resistance, hydrodynamic braking during blade entry, and the inertial resistance of the rower's body mass during the reversal of the movement vector.

The pattern of boat acceleration during the drive phase also differed. In group highly qualified athletes (WEA, LUA), velocity increased rapidly throughout the entire drive. In the QUA group, within the "beginning–middle of the drive" interval, only a slight positive trend is observed, and only toward the end of the phase the velocity increased substantially, indicating low efficiency in the initial stage of force application.

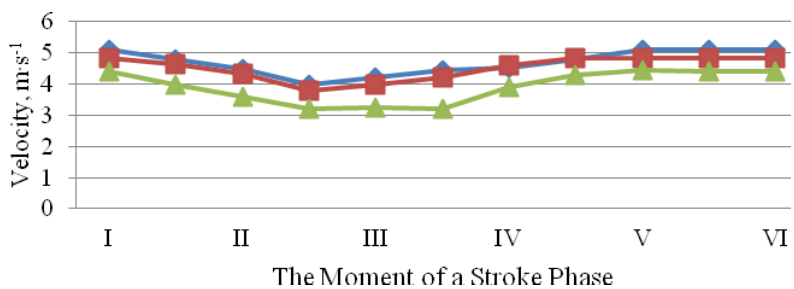

Figure 7. Changes in of Boat Velocity of Female Athletes of Different Qualification Levels During the Stroke Cycle in Single Sculling:
Note. I – stroke preparation phase (recovery); II – catch; III – beginning of the drive phase; IV – drive; V – finish of the drive; VI – recovery

– World's Elite Athletes;
– Leading Ukrainian Athletes;
– Qualified Ukrainian Athletes

Correlation analysis of factors determining boat velocity

To identify the key biomechanical determinants exerting the greatest influence on competitive performance, a pairwise correlation analysis was conducted. Statistically significant relationships ($p < 0.05$ and $p < 0.01$) were identified between average boat velocity and parameters of the kinematic structure of the rowing stroke cycle.

The strongest correlations were established for the following integral and kinematic indicators ($p < 0.01$):

Integral parameters: distance per stroke cycle ($r = 0.94$), stroke rate ($r = 0.90$), and total cycle duration ($r = 0.80$).• Velocity characteristics: horizontal blade velocity at the catch ($r = 0.95$), angular velocity of the shoulder ($r = 0.79$) and knee ($r = 0.74$) joints, as well as the velocity of the hands' center of mass at the end of the drive phase ($r = 0.78$).

Spatiotemporal parameters: elbow joint angle at the beginning of the drive ($r = 0.76$), trunk inclination angle at the end of the drive ($r = 0.74$), as well as the duration of the transition phases from catch to drive ($r = 0.71$) and from the end of the drive to recovery ($r = 0.78$).

The identified relationships confirm that rowing efficiency was limited not only by the power of the working phases but also by the velocity of restructuring intersegmental interactions at the boundary moments of the cycle. The particular importance had an "active catch" (blade velocity exceeding boat velocity) and the minimization of inertial losses during the reversal of trunk movement direction.

Alongside the key determinants, a number of parameters were identified that demonstrated weak or statistically insignificant relationships with boat velocity.

Weak correlation ($p < 0.05$): Positive: angle between the upper arm and forearm during the support phase ($r = 0.32$), total drive duration ($r = 0.36$), as well as the average velocity of the hands' and trunk center of mass during the support period (r = 0.31). Negative: oar displacement magnitude (r = –0.41) and duration of the recovery phase (r = –0.37).

No correlation: No significant influence on boat velocity was found for parameters such as the oar angle relative to the water surface (r = –0.01) and the knee joint angle (thigh–shank) (r = –0.01).

Practical significance and implementation prospects

The obtained results provide a foundation for the development of biomechanical models of the kinematic structure of rowing locomotion. The identified determinants allow for a scientifically grounded design of technical training programs for female athletes at the stage of specialized basic training, ensuring targeted influence on the most significant elements of the movement cycle.

Discussion

The present findings confirm the hypothesis that sporting mastery in rowing is determined predominantly by the efficiency of the biomechanical structure of movement rather than by anthropometric characteristics. The absence of statistically significant anthropometric differences between groups indicates their structural homogeneity, allowing performance disparities to be attributed primarily to technical preparedness. This aligns with Smith et al. (2021), who emphasized that technique-related variables outweigh purely physical parameters when distinguishing elite from sub-elite female rowers.

Spatial–temporal indicators further support this conclusion. Elite athletes (WEA) demonstrated higher stroke rate, shorter stroke duration, and greater distance per stroke, resulting in superior 2000 m performance. These characteristics reflect optimal integration of stroke frequency and length within the locomotor structure of rowing (Gamali et al., 2020), confirming that performance depends on coordinated temporal organization rather than isolated force production. Similar conclusions regarding the interaction between stroke rate, technique, and boat speed have been reported by Ettema et al. (2025).

Critical differences were identified in the rhythm of micro-phases, particularly during the transitions "catch–beginning of drive" and "end of drive–recovery." Highly qualified athletes executed these transitions more rapidly and precisely, minimizing velocity losses at directional changes of the oar. Kleshnev (2010, 2020, 2024) consistently identified catch efficiency and temporal precision during stroke transitions as key determinants of boat acceleration patterns and overall speed. The prolonged catch duration and greater velocity drop observed in QUA athletes confirm that ineffective blade entry increases hydrodynamic braking and disrupts propulsion continuity. This interpretation is supported by Holt et al. (2021), who demonstrated that excessive deceleration during catch and early drive negatively affects mean boat velocity.

Kinematic analysis revealed that elite rowers exhibited superior proximal-to-distal force sequencing, particularly reflected in elbow joint angle at the beginning of the drive, trunk inclination at the end of the drive, and optimized knee and shoulder angular velocities. These parameters indicate efficient intersegmental coordination and effective transmission of force along the kinetic chain. Such findings are consistent with contemporary biomechanical evidence emphasizing the importance of trunk stabilization and coordinated neuromuscular activation in elite rowing (Legge et al., 2024; Pitto et al., 2024; Duchene et al., 2025). Reduced leg extension velocity and delayed shoulder reversal in QUA athletes indicate disrupted coordination, limiting early-phase propulsion efficiency (Ettema et al., 2025; Duchene et al., 2025).

Particular importance was attributed to the "active catch." The positive differential between blade and boat velocity in elite groups ensured immediate propulsive impulse and minimized hydrodynamic braking. Legge et al. (2024) and Harun and Syahrom (2025) emphasize that blade–boat velocity interaction is a decisive determinant of propulsion efficiency, while classical biomechanical models also highlight the mechanical consequences of suboptimal blade entry timing (Zatsiorsky & Yakunin, 1991). The equality of blade and boat velocities observed in QUA athletes confirms insufficient preparatory blade acceleration and ineffective use of system inertia.

Intra-cycle boat velocity analysis demonstrated that elite athletes maintained smoother acceleration profiles with smaller deceleration amplitudes, particularly during non-support phases. Minimization of velocity oscillations is recognized as fundamental for optimizing mean boat speed (Soper & Hume, 2004; Veličkaitė, 2021). The pronounced fluctuations observed in QUA athletes, especially at the catch, reflect inefficient force onset and delayed trunk vector reversal. Warmenhoven et al. (2022) similarly identified intra-cycle velocity stability as a determinant of female rowing success.

The spatial organization of oar handle trajectory during recovery provided additional evidence of technical mastery. Elite athletes maintained near-horizontal handle paths, minimizing vertical oscillations and preserving dynamic balance of the boat. Previous studies have identified handle path linearity and controlled hull kinematics as indicators of mechanical efficiency (Harfield, 2016; Gravenhorst, 2015; Bentivoglio, 2023). In contrast, excessive vertical oscillations observed in QUA athletes increased mechanical work and destabilized the system.

Finally, correlation analysis confirmed that boat velocity is most strongly associated with integral and kinematic indicators such as horizontal blade velocity at the catch, stroke rate, distance per stroke, shoulder and knee angular velocities, and transition phase durations. These findings reinforce the conclusion that rowing performance depends on the precise temporal and kinematic orchestration of the entire stroke cycle rather than on isolated force variables.

Overall, the results demonstrate that elite rowing performance in single sculls is characterized by: (1) optimized stroke rhythm and temporal structure; (2) efficient proximal-to-distal force sequencing; (3) effective blade–boat velocity interaction at the catch; and (4) minimized intra-cycle velocity fluctuations. The integration of these biomechanical determinants constitutes the primary mechanism underlying superior competitive performance.

Conclusion

The results of the study indicate that differences in sporting mastery among female single scull rowers are primarily determined by biomechanical efficiency rather than anthropometric characteristics. Higher qualification levels were associated with the ability to minimize inertial losses during transitional phases of the stroke cycle, maintain elevated intra-cycle boat velocity, and ensure coordinated proximal-to-distal force transmission.

Elite athletes demonstrated optimized stroke rhythm, effective active catch mechanics, smoother acceleration patterns, reduced intra-cycle velocity fluctuations, and greater stability of angular and temporal parameters. In contrast, lower-qualified rowers exhibited prolonged transition phases, increased kinematic variability, and decreased efficiency of force application.

For the first time, specific quantitative angular, rhythmic, and velocity indicators of the motor structure of the stroke have been established for elite and qualified female single scullers under competitive conditions. These markers provide objective criteria for biomechanical monitoring of technical mastery and may serve as reference parameters for modeling optimal stroke structure and individualizing training programs at the stage of specialized basic training.

Conflict of interest. The authors state that there are no conflicts of interest.

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