Kaunas University of Technology
Faculty of Mechanical Engineering and Design

Biomechanical Analysis of Upper Limb Movements in Compulsory Element of Artistic Swimming

Master's Final Degree Project

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Project author

Assist. Prof. dr. Milda Dubosienė
Supervisor

Kaunas, 2026

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Mechanical Engineering (6211EX009)

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Declaration of Academic Integrity

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1. Task of the Master's Final Degree Project

Given to the student – Urtė Dambrauskaitė

1. **Topic of the project**

Biomechanical Analysis of Upper Limb Movements in Compulsory Element of Artistic Swimming

(In English)

Viršutinių galūnių judesių biomechaninė analizė dailiojo plaukimo privalomajame elemente

(In Lithuanian)

2. **Aim and tasks of the project**

Aim: To analyse the biomechanical characteristics of upper limb movements during the execution of a selected compulsory artistic swimming element.
Tasks:
1. To analyse scientific literature related to artistic swimming biomechanics and upper limb movement characteristics.
2. To substantiate and describe the research methodology for biomechanical analysis of upper limb movements during the selected compulsory element.
3. To perform kinematic and statistical analysis of the collected experimental data.
4. To present and justify the obtained results, comparing them with findings from other authors and formulating conclusions.

3. **Main requirements and conditions**

The Master's thesis shall be conducted as a scientifically grounded biomechanical study analysing upper limb movements during a selected compulsory artistic swimming element under controlled experimental conditions. The research is based on previously recorded underwater video data, which will be processed using computer-based motion analysis and appropriate statistical methods to obtain quantitatively justified and reliable results supported by relevant scientific literature.

4. **Additional requirements and conditions for the project, report and appendices**

Not applicable

1

Project author	Urtė Dambrauskaitė	[signature]	2026-02-09
	(Name, Surname)	*(Signature)*	*(Date)*
Supervisor	Assist. Prof. dr. Milda Dubosienė	[signature]	2026-02-09
	(Name, Surname)	*(Signature)*	*(Date)*
Head of study field programs	Kęstutis Pilkauskas		
	(Name, Surname)	*(Signature)*	*(Date)*

Dambrauskaitė Urtė. Biomechanical Analysis of Upper Limb Movements in Compulsory Element of Artistic Swimming. Master's Final Degree Project / supervisor Assist. Prof. dr. Milda Dubosienė; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Mechanical Engineering, Engineering Sciences

Keywords: artistic swimming, upper limb biomechanics, support sculling, kinematic analysis, movement asymmetry, Kinovea

Kaunas, 2026. 60 p.

Summary

This Master’s thesis analysed the biomechanical characteristics of upper limb movements during support sculling in selected artistic swimming positions. The study used underwater video recordings of one high-level artistic swimmer performing five standardized positions: Fishtail Right, Fishtail Left, Knight Right, Knight Left, and Vertical.

A two-dimensional video-based kinematic analysis was performed using Kinovea. Anatomical upper limb landmarks were digitized manually. Then Microsoft Excel was used to calculate hand speed, sculling, cycle duration, elbow angle, movement variability, and right-left asymmetry.

The results showed that upper limb movement patterns varied based on body position. The vertical position demonstrated the most symmetrical and balanced sculling pattern, with the smallest speed and cycle asymmetry between limbs.

Fishtail positions demonstrated moderate asymmetry, especially in elbow angle configuration. Knight positions showcased lower hand speed, greater speed and cycle asymmetry, and more constrained elbow movement, suggesting higher stabilization demands.

In conclusion, the study confirmed that body position influences hand-speed characteristics, rhythm, joint mechanics, and inter-limb coordination during support sculling. The findings support the use of video-based biomechanical analysis as a practical method for analysing upper limb biomechanics in artistic swimming.

Dambrauskaitė Urtė. Viršutinių galūnių judesių biomechaninė analizė dailiojo plaukimo privalomajame elemente. Magistro baigiamasis projektas / vadovė Asist.. Prof. dr. Milda Dubosienė; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Mechanikos inžinerija, Inžinerijos mokslai.

Reikšminiai žodžiai: dailusis plaukimas, viršutinių galūnių biomechanika, atraminis grybšnis, kinematinė analizė, judesių asimetrija, Kinovea.

Kaunas, 2026. 60 p.

Santrauka

Šiame magistro baigiamajame darbe analizuotos viršutinių galūnių judesių biomechaninės charakteristikos atliekant atraminį grybšnį pasirinktose dailiojo plaukimo padėtyse. Tyrime naudoti povandeniniai vaizdo įrašai, kuriuose viena aukšto meistriškumo dailiojo plaukimo sportininkė atliko penkias standartizuotas padėtis: dešiniąją „Fishtail“, kairiąją „Fishtail“, dešiniąją „Knight“, kairiąją „Knight“ ir vertikaliąją padėtį.

Dviejų dimensijų vaizdo pagrindu atlikta kinematinė analizė buvo vykdoma naudojant „Kinovea“ programinę įrangą. Anatominiai viršutinių galūnių orientyrai buvo skaitmenizuoti rankiniu būdu. Vėliau buvo naudojama „Microsoft Excel“ programa apskaičiuoti plaštakos greičiui, grybšnio ciklo trukmei, alkūnės kampui, judesio kintamumui ir dešinės bei kairės pusių asimetrijai.

Gauti rezultatai parodė, kad viršutinių galūnių judesių modeliai skyrėsi priklausomai nuo kūno padėties. Vertikalioji padėtis pasižymėjo simetriškiausiu ir labiausiai koordinuotu grybšnio modeliu, kuriame buvo nustatyta mažiausia greičio ir ciklo trukmės asimetrija tarp galūnių.

„Fishtail“ padėtyse nustatyta vidutinė asimetrija, ypač alkūnės kampo konfigūracijoje. „Knight“ padėtys pasižymėjo mažesniu plaštakos greičiu, didesne greičio ir ciklo trukmės asimetrija ir labiau apribotu alkūnės judesiu, o tai rodo didesnius stabilizavimo reikalavimus.

Apibendrinant galima teigti, kad tyrimas patvirtino jog kūno padėtis daro įtaką plaštakos greičio charakteristikoms, ritmui, sąnarių mechanikai ir viršutinių galūnių tarpusavio koordinacijai atliekant atraminį grybšnį. Gauti rezultatai pagrindžia vaizdo pagrindu atliekamos biomechaninės analizės taikymą, kaip tinkamą metodą viršutinių galūnių biomechanikai dailiajame plaukime analizuoti.

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Abbreviations:

2D – two-dimensional;

AS – artistic swimming;

fps – frames per second;

Hz – hertz;

SD – standard deviation;

T1, T2, T3 – trial 1, trial 2, trial 3.

Terms:

Biomechanics – the study of mechanical principles applied to human movement.

Kinematic analysis – analysis of movement characteristics such as position, displacement, velocity, cycle duration, and joint angle, without direct measurement of forces.

Support sculling – an artistic swimming technique in which cyclic hand and forearm movements are used to generate support and maintain body position in the water.

Hand speed – the calculated movement speed of the tracked hand point during support sculling, based on frame-to-frame coordinate displacement.

Cycle duration – the time required to complete one sculling movement cycle.

Cycle rate – the number of sculling cycles performed per second, expressed in hertz.

Elbow angle – the angle describing the relative position of the upper arm and forearm during support sculling.

Movement asymmetry – the difference between right and left upper limb movement characteristics, such as hand speed, cycle duration, or elbow angle.

Spatial calibration – the process of converting pixel-based measurements into real-world distance units using a known reference length.

Manual digitization – marking of anatomical landmarks frame-by-frame in video analysis software.

Introduction

Artistic swimming is a technically demanding sport that combines elements of swimming, dance, gymnastics, flexibility, strength, and motor coordination. A successful performance requires athletes to maintain controlled body positions, execute complex movements, while being inverted and partially submerged in water. The most important technical action in artistic swimming is sculling, which allows the athletes to support the body, maintain height, control balance, and stabilize in complex positions.

During support sculling the upper limbs play a central role, where the hands and forearms generate forces that help maintain the alignment of the body and prevent the loss of height. The success of this movement depends on several biomechanical factors such as hand speed, sculling rhythm, elbow joint angle, movement symmetry, and coordination between the upper limbs.

The biomechanical analysis of artistic swimming provides an objective way to evaluate the movement characteristics. Previous research has investigated sculling forces, hand trajectories, body position stability, and the relationship between physical abilities of the athletes and their performance outcomes. However, there remains a need for more position-specific analysis of upper limb mechanics during artistic swimming elements, especially under realistic conditions.

Therefore, the **main aim** of this work is to analyse the biomechanical characteristics of upper limb movements during the execution of a selected compulsory artistic swimming element. This was achieved by completing these tasks:

1. To analyse scientific literature related to artistic swimming biomechanics and upper limb movement characteristics.
2. To substantiate and describe the research methodology for biomechanical analysis of upper limb movements during the selected compulsory element.
3. To perform kinematic and statistical analysis of the collected experimental data.
4. To present and justify the obtained results, comparing them with findings from other authors and formulating conclusions.

1. Literature Review

The literature review in this project serves as the foundation for understanding the biomechanics of upper limb movements in artistic swimming. It involved collection, selection, and analysis of scientific articles related to this topic. The focus was to explore how upper limbs contribute to propulsion, stability, and execution quality during artistic swimming elements. The review included only articles from credible databases such as ScienceDirect and ResearchGate.

The scientific literature was categorised into four thematic sections: Biomechanics of Upper Limb Movements in Artistic Swimming, Key Movements in Compulsory Elements, Comparison of Research Methodologies, and Influence on Execution Quality. In each section the reviewed studies were analysed in terms of research aims, methodologies, analysed variables, and the selected participants of the studies.

1.1. Biomechanics of Upper Limb Movements in Artistic Swimming

Upper limbs play the main role in the execution of compulsory elements, and various sculling techniques. These movements require swimmers to produce continuous lift and drag forces to maintain elevated and stable body positions. The effectiveness of these sculling movements not only influence propulsion and stability, but also directly affect technical precision and performance scores according to judging criteria.

Force Production and Fluid Dynamics

The biomechanics of upper limbs are primarily influenced by fluid dynamics [1]. During sculling, lift forces are the main type of forces generated by the hands as the swimmers manipulate the angle of attack and hand speed to maximize lift during all sculling phases (Fig. 1).

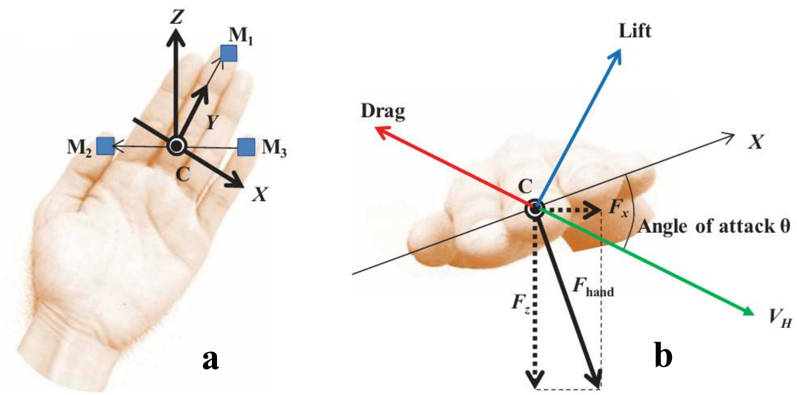


Fig. 1. Definitions of the local coordinate system on a hand (a) and a definition of the angle of attack, various components of the fore (b). [1]

Kinematic and Kinetic Characteristics

In standard sculling, a high cycle rate is necessary to maintain consistent force output [2]. On the other hand, contra-standard sculling relies on increased hand speed rather than frequency (Fig. 2). Despite the dynamic demands, joint stress in the shoulder, elbow, and wrist joints remains relatively low, however, poor technique could lead to increased shear forces, especially in the shoulder, highlighting the importance of technical precision.

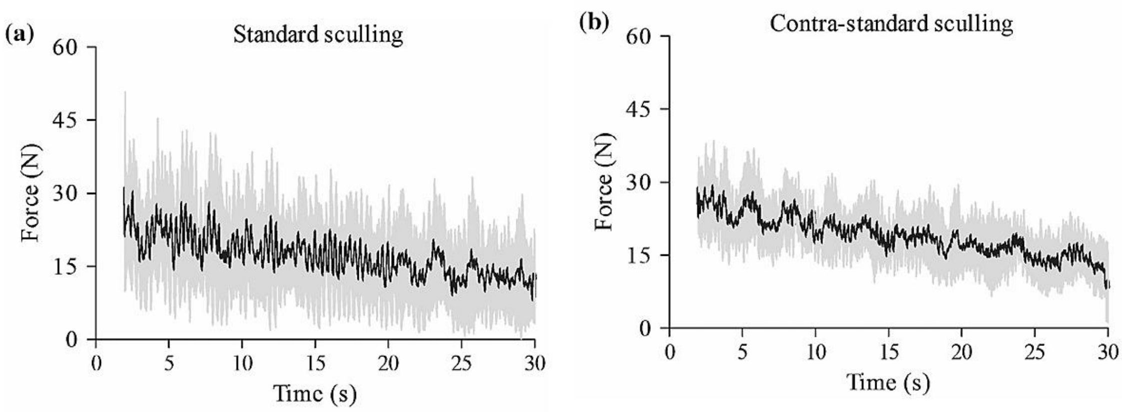


Fig. 2. Propulsive force mean and SD values during 30 s maximal standard and contra-standard sculling (a and b panels, respectively) [2]

Importance of Symmetry and Coordination

Symmetry and coordination of upper limb movements are essential for both biomechanical efficiency and performance quality [3]. Bilateral symmetry ensures balanced muscle activation, efficient propulsion, and reduced injury risk (Fig. 3). Asymmetrical arm movements can decrease propulsion efficiency and negatively impact spinal alignment.

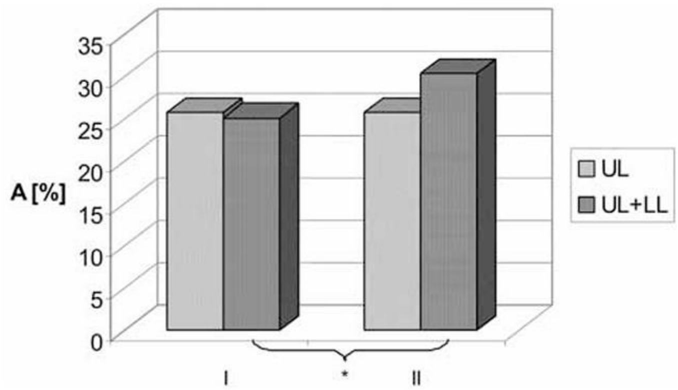


Fig. 3. Asymmetry of the upper extremities during the breaststroke: using only upper limbs (UL) and using both upper and lower limbs (UL+LL) [4] Group I – correct (symmetrical) lower limbs movement; Group II – incorrect (asymmetrical) lower limbs movement (* a significance level of $p<0.05$)

Assessment and Technological Innovations

In recent years, the technological tools for biomechanical analysis have advanced significantly [5]. Traditional software such as Kinovea and AutoCAD have been widely used for manual measurement of body angles and joint positions (Fig. 4). More recently, AI-based tools like MediaPipe have been used for real-time video analysis, allowing for faster and more objective evaluations of body positions [6]. These innovations have significant potential for improving coaching feedback and standardizing performance judging during competitions.

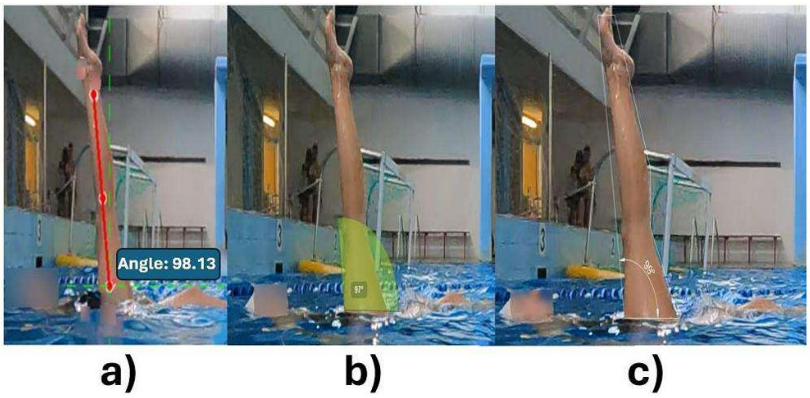


Fig. 4. In the ballet leg technique, panel a) shows the deviation angle via MediaPipe-based computer vision (=8.13°), panel b) shows the measured deviation angle via Kinovea (=7°), and the measured angle via gold standard AutoCAD (=9°) is shown in panel c). [6]

Summary

The biomechanics of upper limb movements in artistic swimming focus on generating lift forces, maintaining symmetry and coordination, and adapting movements characteristics based on technique demands. The combination of modern AI tools and biomechanical analysis is transforming both coaching and judging practices, enabling more precise and objective evaluation of athletes' performances.

1.2. Key Movements in Compulsory Elements

The compulsory elements of artistic swimming require precise and highly controlled upper limb movements to generate vertical propulsion, maintain body stability, and achieve technical accuracy. Sculling is the foundational technique that forms the basis of most upper limb movements in artistic swimming. There are two primary forms of sculling:

- **Flat Sculling** – primarily performed in a horizontal Back Layout position. The body is extended with face, chest, thighs and feet at the surface of the water (Fig. 5). The hands move laterally with a shallow angle of attack, generating lift forces needed to keep the body afloat [1].
- **Support Sculling** – used during inverted body positions (Fig. 5). This technique requires the swimmer to rotate the shoulder outward and turn the forearms and palms upwards to produce vertical lift [1].

Fig. 5. Flat sculling in the back-layout position (left) and support sculling in the vertical position (right) [1]

Hand Position and Angle Adjustments

Hand orientation plays an important role in generating efficient fluid forces during sculling. Across all phases of the sculling cycle, swimmers must demonstrate precise control of wrist positioning, forearm rotation, and to continuously adjust the angle of attack of the hands [1]. In previous studies, when athletes were sculling while remaining stationary in the upright position it, it was observed that during outward strokes, the palms were typically angled downward and outward, optimizing lift generation [7]. During inward strokes, the palms rotate upward and inward, allowing for smooth redirection of the flow without disrupting propulsion (Fig. 6).

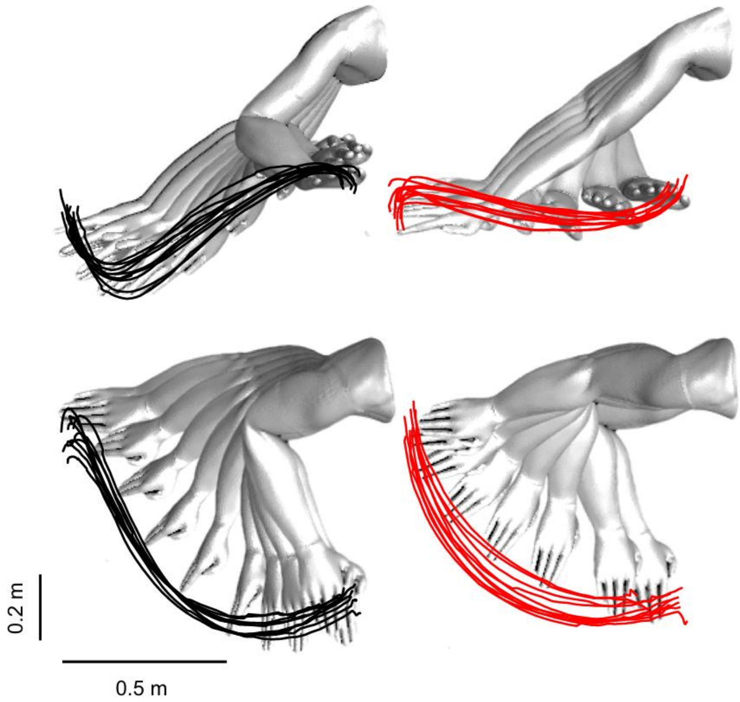


Fig. 6. Middle fingertip trajectories in the frontal (top) and transverse (bottom) planes, recorded using Qualisys cameras and overlaid on upper limb geometry at 0.05 s intervals. Black lines represent the downstroke phase, red lines the upstroke. The simulated limb motion closely matches the experimental kinematics [7]

Shoulder and Elbow Control

Stability and control of the arms during compulsory elements depend heavily on coordinated and balanced movements of the shoulders and elbows [1]:

- The shoulders must be externally rotated during support sculling to allow the hands to achieve optimal lateral force production.
- The elbows serve as controlled hinge points, typically flexed to approximately 90° during the sculling phase and then slightly extended during the recovery [8].
- This coordinated motion enables swimmers to accurately direct hand forces, supporting vertical elevation and alignment in figure such as the Vertical Position [9].

Propulsion Timing and Cycle Rate

The timing of hand movements and sculling cycle rate can reflect how the swimmer produces and maintains force, but its effect depends on the type of sculling being performed. As it is stated in previous research [2]:

- In standard sculling, using a high cycle rate can be a useful tactic to increase force.
- In contra-standard sculling – increasing the cycle rate is not the recommended strategy, as it may make the swimmer fatigue faster and consequently lose force (Fig. 7).
- Transitions between out-sculling and in-sculling must be fluid and gap-free to prevent loss of vertical momentum or drop in position.

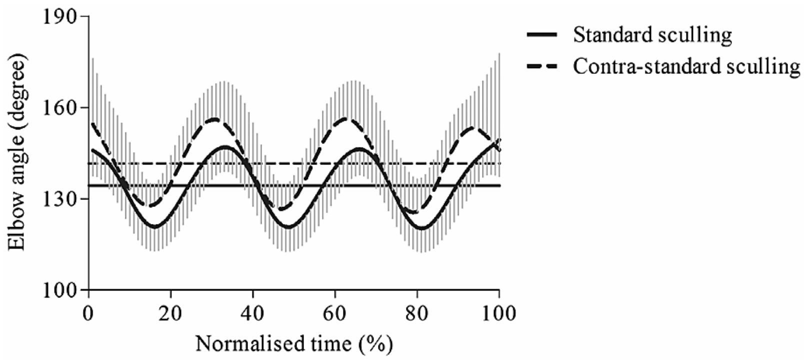


Fig. 7. Elbow angles mean values and SD along three cycles of standard and contra-standard sculling techniques. [2]

Symmetry and Coordination

Bilateral symmetry of hand and arm movements is necessary to avoid any alignment or stability errors during performance:

- Even minor asymmetries in hand pressure or path can lead to body wobble, reduced vertical stability, and technical score deductions [3].
- Coordination between both arms ensures that force vectors are evenly distributed, supporting an upright and correct execution of figures.

Summary

Successful performance of compulsory elements in artistic swimming relies on a combination of advanced sculling techniques, precise hand orientation, joint control, and symmetrical timing of the movement. It is essential for the athlete to be able to adapt stroke mechanics based on the positional demands. These biomechanical principles both enhance the performance quality and scoring outcomes.

1.3. Comparison of Research Methodologies

The study of upper limb biomechanics in artistic swimming involves a wide range of research methodologies, each with its own focus, advantages and disadvantages. These methods can be grouped into four categories: Biomechanical Measurements, Kinematic Video Analysis, Physiological and Morphological Testing, and Computational Modeling. This section analyses and compares these methodologies in terms of accuracy, practicality and application.

Biomechanical Measurements

Biomechanical setups, such as motion capture, pressure sensors and force plates are commonly used to directly measure forces and joint movements [10]. One previous study combined 3D motion capture with hand pressure sensors (Fig. 8) to precisely measure lift and drag forces during sculling [1]. Another study used tethered swimming tests with underwater cameras [2]. However, the tethering setup may have influenced natural swimming mechanics. In previous research computational fluid dynamics with inverse dynamics was integrated to estimate joint loads [7]. Such biomechanical measurement techniques provide accurate and detailed insights for technique optimization. On the other hand, they are very complex, can have limited sample sizes and artificial conditions can prevent the results applicability to real-world training and competition scenarios.

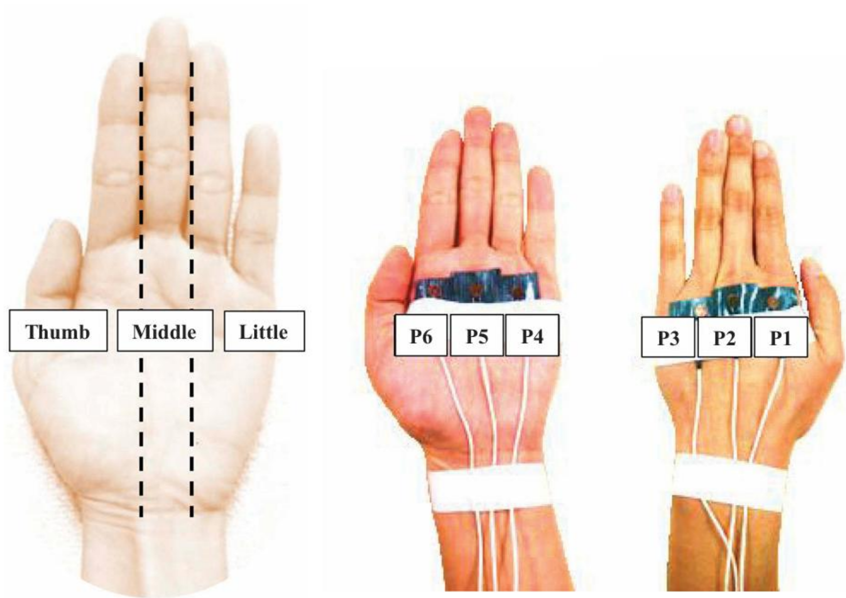


Fig. 8. The hand area is divided into three and the attachment position of the six pressure sensors on the palm side and the dorsal side. [1].

Kinematic Video Analysis

Kinematic video analysis techniques, both manual and AI-driven, are widely used to analyse body kinematics in realistic, training and competition environments (Fig. 9). Previous research applied Kinovea software for video analysis across more than 100 international teams, providing valuable insights under practical field conditions [11]. Furthermore, in another study, a four-camera SwimPro system was used to find kinematic parameters of swimming start movement together with Dartfish ProSuite 4.0 and IQ LAB software [12]. A third study compared a kinematic video analysis method with biomechanical measurements method for measuring vertical countermovement jump. They used a smartphone and Kinovea video method for kinematic video analysis method and professional motion capture system for biomechanical measurement method [13]. They concluded that the smartphone and Kinovea setup was valid, reliable, useful and cost-effective for this measurement.

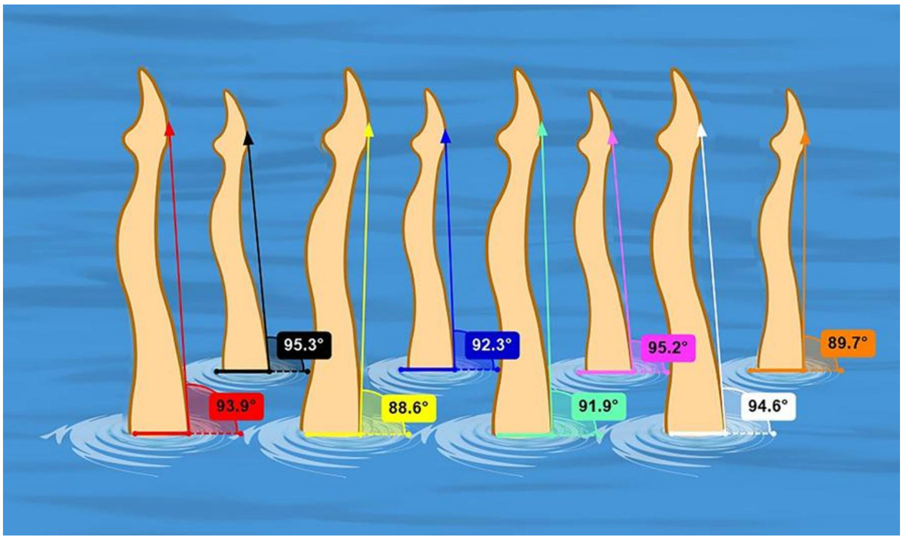


Fig. 9. Angle of Vertical Position with one leg (Fishtail or Bent Knee) and measurement of deviation from right angle. Using the Kinovea software, a line was drawn from the most prominent of the instep to the most front point of the thigh above the water. Then the average value of leg angle deviations deviated from right angle of 8 team members was calculated [11].

Physiological and Morphological Testing

The physiological and morphological testing methods are often used for the early athlete screening process, with the aim to predict the performance potential. One study used anthropometric data, flexibility assessments and lung capacity tests to identify successful athletes. Such approach is fast and low cost, although it does not capture real technique execution [14]. Second analysed study examined the link between rhythmic ability and performance scores, finding that while coordination is important, it is not a strong predictor on its own [15]. This study also suggested that the artistic swimming performance is influenced by accumulated training and competition experience (Table 1). The last study used various physiological, morphological and performance-based tests to examine the relationships between body composition, strength, swimming performance, and artistic swimming element scores [16]. The researchers have concluded that strength and swimming ability were related to better execution of some artistic swimming elements.

Table 1. Follow-up ANOVA results for rhythmic ability and artistic swimming performance by competitive category, adjusted for experience. [15]

Variables	Category (n)	M (95% CI)	SE	F	P	Partial η^2
Rhythmic Ability	Senior (9)	22.66 (21.04-24.28)	0.80	1.888	0.164	0.081
	Junior (7)	21.03 (17.79-22.31)	0.63			
	Comen (31)	22.27 (21.60-22.94)	0.14			
Artistic Swimming Performance	Senior	6.40 (5.73-7.08)	0.33	2.021	0.145	0.086
	Junior	5.84 (5.31-6.37)	0.26			
	Comen	6.41 (6.13-6.69)	0.14			

Computational Modeling and Simulation

In some research, advanced simulation tools such as computational fluid dynamics (CFD) and the SWUM model are used to enhance the theoretical understanding of the movement and the force production in swimming (Fig. 10). One reviewed study analysed the application of these tools in swimming biomechanics and demonstrated how they contribute to modelling propulsion and hydrodynamic forces [17]. It can be concluded that computational modelling provides valuable theoretical insights into force patterns, however it highly depends on assumptions and model simplifications.

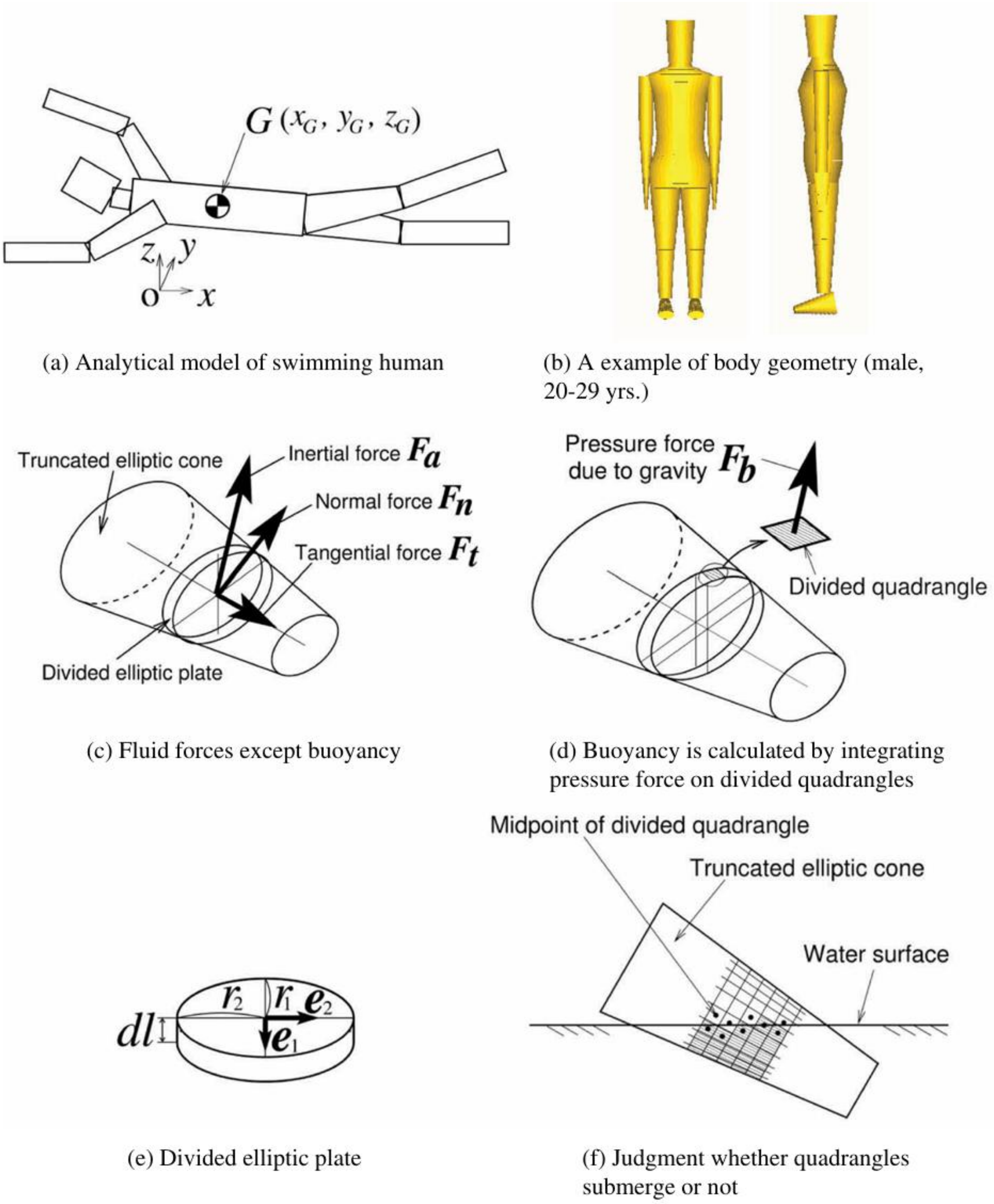


Fig. 10. Illustration of SWUM principles: (a) analytical human model; (b) sample body geometry; (c) fluid forces excluding buoyancy; (d) buoyancy via pressure integration; (e) divided elliptic plate; (f) submersion check of quadrangles [17].

In Conclusion, no single research method is fully sufficient on its own to capture the complexity of upper limb biomechanics in artistic swimming. The most effective research method integrates biomechanical measurements, kinematic video analysis and physiological and morphological testing (Table 2). Each of these methods contribute to a higher level of understanding the full picture.

Table 2. Summary of Comparison of Research Methodologies

Method Type	Best For	Limitations
Biomechanical Force/Motion Analysis	Technical optimization in elite athletes	Costly, small sample sizes, artificial lab conditions
Video Analysis (Traditional & AI)	Large group comparisons, competition analysis	Lower accuracy in complex/underwater settings
Morphological/Physiological Testing	Talent identification, group-level screening	Does not reflect dynamic technical execution
Computational Modeling	Theoretical modelling of movement and hydrodynamics	Requires real-world data for accuracy and validation

1.4. Influence on Execution Quality

The biomechanics of upper limb movements strongly influence the quality of execution of compulsory elements in artistic swimming. Successful performance depends not only on the strength of the athlete, but also on the precision, control, coordination and balance of the limb movements.

Force Generation and Body Position Maintenance

One of the main requirements in artistic swimming is for the athlete to be able to maintain body elevation above water. This is achieved through continuous generation of lift and drag forces by the hands during sculling. These forces are specifically important during inverted compulsory elements [1]. Any disruptions in the sculling movement can cause stability issues and visible drops in height, consequently leading to reduced execution scores. Therefore, smooth and uninterrupted sculling is crucial for maintaining height and overall position quality.

Symmetry and Coordination

Symmetry of upper limb movements is the main indicator of technical skill and sculling quality. This bilateral symmetry helps the swimmer maintain controlled and centred body position. On the other hand, asymmetrical actions can result in tilting, misalignment and lower overall execution of artistic swimming positions [3]. Additionally, coordination of upper and lower limbs is important as asymmetrical movements in swimming can worsen the performance [4]. Therefore, high-level performance depends on the synchronization of the limbs.

Speed and Timing of Movements

The hand speed and cycle rate of the sculling must be adjusted according to the specific requirements of each element. For example, in standard sculling, a high cycle rate enhances the force output and propulsion [2]. Similarly, in static inverted positions like Vertical, both hand speed and amplitude must remain consistent throughout the whole sculling process [3]. Optimal performance depends on precise timing between the strokes of both hands, and any delay or inconsistency or timing can disrupt movement fluidity and lead to score deductions.

Joint Mechanics and Force Application

Ideal force application depends on the correct alignment and motion of the shoulder, elbow, and wrist joints. Efficient execution of the support scull technique depends on coordinated movement of several arm joints and not just moving the hands back and forth [1]. It requires shoulder external rotation, controlled elbow flexion and forearm supination and pronation. In conclusion, incorrect upper limb joint positioning reduces the required force generation and therefore can weaken sculling efficiency, lower body elevation and cause visible inconsistencies in artistic swimming figure shapes.

Relationship Between Biomechanical Execution and Artistic Impression

Even though artistic swimming creativity adds to artistic impression and choreography difficulty, movement execution quality still must be balanced (Fig. 11). In previous research it was observed that even though the swimmers did multiple difficult and complex choreography details, this did not automatically lead to highest score [11]. This shows that difficulty and choreography are not enough, and the routine also needs clean execution, precise body lines, symmetry, height and control, which solely depends on the quality of the sculling motions.

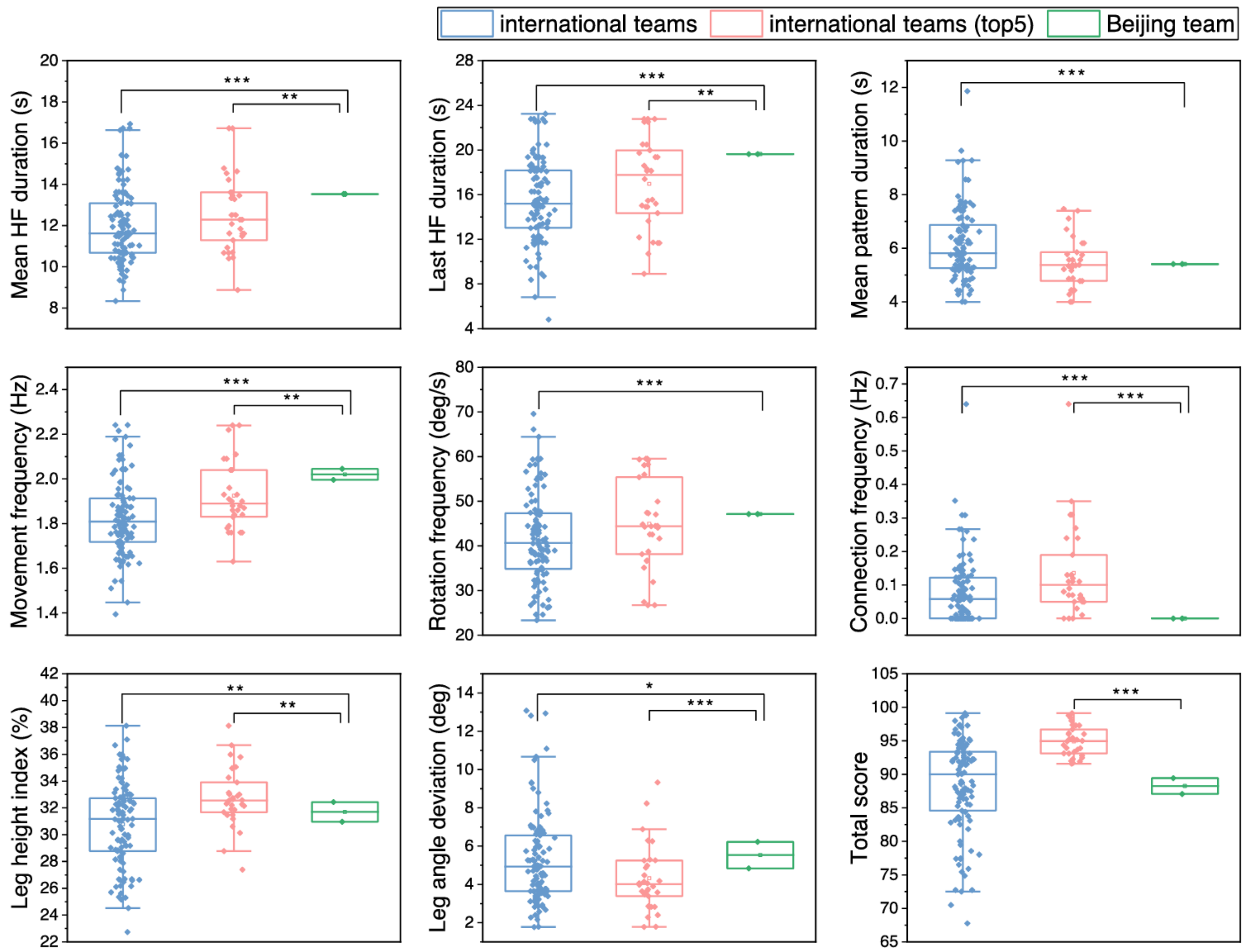


Fig. 11. Comparison of total score and hybrid figure execution indicators between international teams, top 5 international teams, and Beijing team [11].

Key Takeaways

Previous research shows that biomechanical efficiency is closely linked to the quality of technical execution in artistic swimming. Deficiencies in upper limb biomechanics often result in visible performance issues, such as loss of height, body instability and lack of control, which leads to lower judging scores. To address these issues, training should focus on developing physical strength and refining the technical precision of upper limb movements.

1.5. Literature Review Results

Gaps and Future Research Directions

Regardless of recent advancements in researching the biomechanics of artistic swimming, several research gaps remain, that limit the practical application of findings to training, judging, and performance enhancement. Addressing these gaps is essential to improve both scientific understanding and real-world outcomes.

One of the major gaps is the lack of element-specific analysis of support scull. While general sculling mechanics have been studied, there is no research of the biomechanical demands of individual compulsory elements [1, 2]. This limits the ability to adjust training methods to specific requirements of each movement. Another issue is the narrow demographic focus, as most studies involve small samples of elite swimmers, and do not offer any insights for younger, non-elite, or male swimmers [2, 3, 16].

Additionally, multiple studies rely on 2D video analysis or isolated measurements, instead of full 3D underwater motion analysis. As a result, the roles of the shoulder, elbow, and wrist during support sculling remain underexplored [1, 7]. Furthermore, there is limited research on how the coordination of upper and lower limbs affects the execution of artistic swimming performances [3]. Finally, fatigue is another factor that has not yet been research in depth. Given the length and complexity of artistic swimming routines, understanding how fatigue alters the biomechanics is critical to improve consistency and prevent execution errors.

In conclusion, future research should focus on developing element-specific biomechanical analysis, using underwater 3D motion capture, and expanding the variety of participants. The fatigue and full-body coordination should also be taken into consideration. This will support evidence-based training, safer performance, and more objective judging.

This project contributes to addressing several identified research gaps, by conducting a position-specific analysis of support sculling biomechanics. The study expands the current understanding of upper limb movement patterns across different body positions and demonstrates the practical application of underwater video based biomechanical analysis in artistic swimming.

2. Experimental Methodology for Upper Limb Biomechanical Analysis

The analysis of upper limb biomechanics in artistic swimming requires such approach that can capture rapid and cyclic movements. The investigation of support sculling during compulsory elements demands balance between measuring accuracy and practical feasibility. Therefore, the chosen methodology must be grounded in established biomechanical research while remaining suitable for pool-based data collection (Fig. 12).

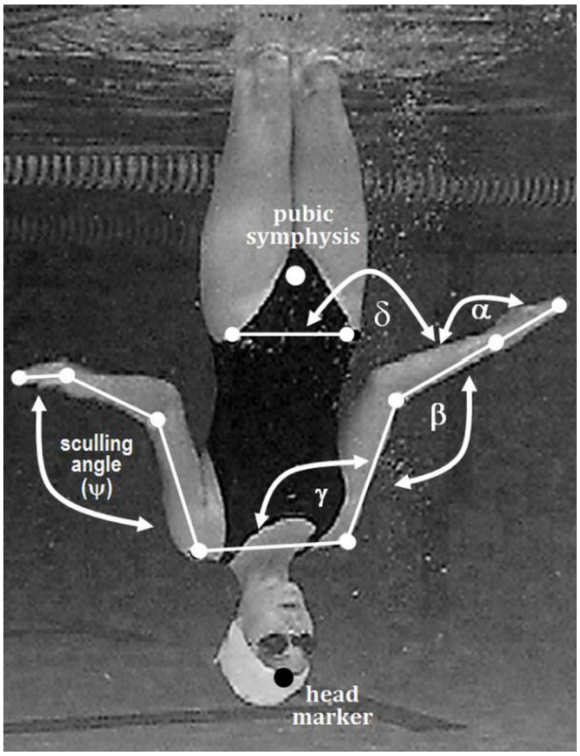


Fig. 12. Body marker placement for upper limb joint and sculling angle analysis [3].

2.1. Selected Experimental Methodology

The selected methodology was based on a 2D kinematic analysis of upper limb movements during support sculling in artistic swimming. This specific approach was chosen because support sculling is a cyclic movement that is performed primarily in the frontal plane when the swimmer remains in the stable inverted body position. Consequently, a 2D video-based method was considered suitable for identifying changes in upper limb movement patterns across the different body positions.

In this study, a single-participant repeated-measures design was used to compare upper limb kinematics across five standardized artistic swimming positions performed at designated heights. In this experiment the same participant performed each position under comparable conditions, allowing for within participant comparison across several artistic swimming elements. The analysed positions were repeated in trials and included Fishtail Right, Fishtail Left, Knight Right, Knight Left, and Vertical Position.

The upper limb motion was captured using a single underwater camera that was positioned underwater, perpendicular to the swimmer's frontal plane. The camera setup enabled visual recording of the arm movements during support sculling while maintaining realistic performance conditions. Then, anatomical landmarks of the upper limb were tracked frame by frame to calculate key biomechanical variables, such as hand speed, cycle rate, elbow angle, and movement variability measures (Fig. 13).

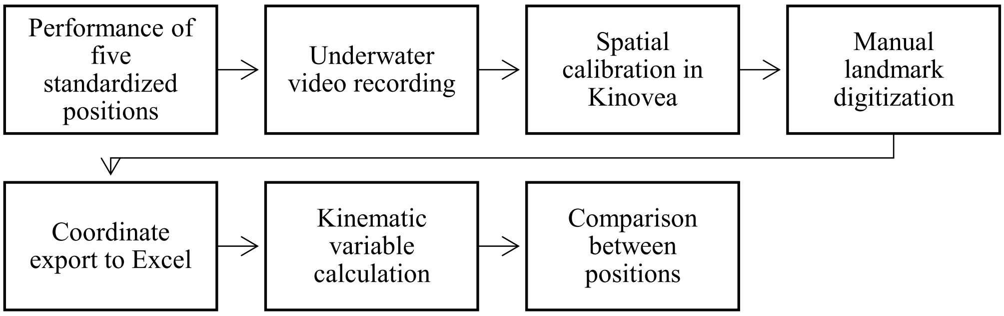


Fig. 13. Workflow of the experimental methodology used for upper limb kinematic analysis.

In summary, this selected methodology provided a practical method for analysing upper limb biomechanics of the support scull under realistic conditions. By combining controlled body position performance, underwater video recording and repeated trials, this approach allowed consistent within-participant comparison of kinematic variables across the selected artistic swimming elements.

2.2. Methodology Suitability in Relation to Experimental Aims

The 2D kinematic video analysis methodology was selected based on the already established methodological model [12] and its scientific relevance to artistic swimming biomechanics research (Fig. 14). Even though previous studies analysed the support sculling in 3D methods [1], 2D kinematic analysis was considered applicable in this specific study as the support sculling ir performed mostly in the frontal plane.

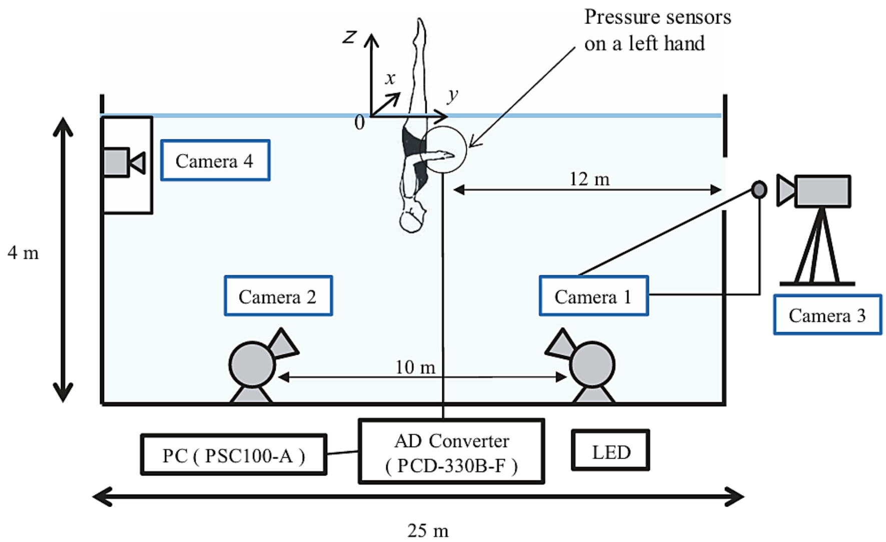


Fig. 14. Experimental apparatus and a layout of cameras. [1]

The previous research has demonstrated that key biomechanical variables can be extracted from underwater video recordings. This is especially useful when combined with force measurements, as these methods together can better explain the obtained data [2]. These findings confirm that the 2D video analysis is a suitable method for analysing the upper limb biomechanics in artistic swimming.

Table 3. Mean ± SD of the kinematic and kinetic variables obtained for standard and contra-standard sculling techniques over different time moments (20, 40, 60 and 80%) of the 30 s maximal exertion. [2]

	20%	**40%**	**60%**	**80%**
Hand speed (m/s)	1.81 ± 0.18	1.78 ± 0.14^{a}	1.72 ± 0.13^{b}	1.65 ± 0.13^{ab}
Cycle rate (cycles/s)	2.3 ± 0.2	2.2 ± 0.1	2.2 ± 0.2	2.1 ± 0.2
Elbow mean angle (°)	137.7 ± 4.5	138.7 ± 5.7	138.4 ± 4.5	136.6 ± 5.0
Elbow angular velocity during flexion (°/s)	156.4 ± 31.2	158.1 ± 34.4	145.8 ± 21.4	133.8 ± 18.9
Elbow angular velocity during extension (°/s)	148.3 ± 19.8	144.4 ± 20.3	143.8 ± 19.3	130.1 ± 15.0
Wrist angular velocity during flexion (°/s)	142.6 ± 32.5	163.0 ± 43.7	148.0 ± 50.4	129.3 ± 44.4
Wrist angular velocity during extension (°/s)	139.1 ± 44.4	156.8 ± 52.1^{c}	132.0 ± 33.8	127.9 ± 42.4^{c}
Maximum Force (N)	35.54 ± 12.14^{d}	29.10 ± 7.91^{e}	25.30 ± 7.07	22.84 ± 6.45^{de}
Relative maximum force (N/kg)	0.63 ± 0.20^{f}	0.54 ± 0.14^{g}	0.46 ± 0.11	0.42 ± 0.09^{fg}
Mean force (N)	23.32 ± 7.04^{hi}	19.41 ± 4.97^{j}	17.48 ± 5.24^{h}	17.17 ± 4.63^{ij}
Relative mean force (N/kg)	0.43 ± 0.12^{kl}	0.36 ± 0.09^{m}	0.32 ± 0.08^{k}	0.28 ± 0.08^{lm}

The use of high-speed underwater video recordings is justified by the rapid and cyclical nature of the support scull. Previous biomechanical studies have used high frame rate (50-200 Hz) underwater video with manual digitization to analyse the timing, hand speed, and joint angle changes more accurately [2]. The use of underwater cameras, combined with manual digitization confirmed that video-based methods can capture upper limb dynamics during sculling. In this project, the trials were recorded with GoPro HERO 11 camera (Fig. 15) at 1080p resolution and 240 frames per second. However, since the further analysis in Kinovea was performed at 30 frames per second, the effective temporal resolution of the coordinate data was 30 Hz. This frequency was considered sufficient for comparative evaluation of cyclic support sculling patterns.

Fig. 15. GoPro HERO11 camera used to record underwater support sculling trials.

One more key reason for selecting this specific methodology was its compatibility with standardized performance evaluation in artistic swimming (Fig. 16). Earlier studies have shown that various kinematic indicators can be reliably measured using calibrated 2D video analysis and are associated with performance outcomes in competition [11]. Hence, applying a similar approach in this experiment allowed the examination of how different body positions influence sculling technique.

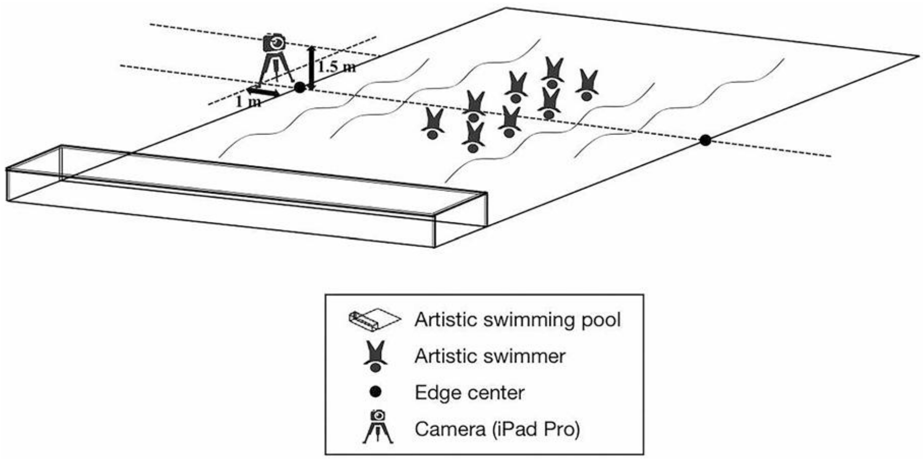


Fig. 16. The Camera position for team free routine trials of Beijing Artistic Swimming Team. [11]

The use of manual and semi-automatic video analysis tools further supports the choice of methodology. Prior research has demonstrated that marker-less 2D computer vision tools, like MediaPipe, show similar results with already established video analysis software, such as Kinovea and AutoCAD (Fig. 4) [6]. As a result, these findings support the use of Kinovea manual digitization as a practical method for obtaining kinematic data, especially in the case when multi-camera motion-capture systems are not viable.

Finally, the selected methodology offers a balance between measurement accuracy and realistic execution. Unlike the tethered force measurements or complex multi-camera 3D systems, a single-camera underwater setup allows the swimmer to perform the elements without any external constrains. The selected approach aligns with the methodological recommendations in recent artistic swimming research, which emphasize the importance of accessible, repeatable, and non-invasive tools for biomechanical analysis [6].

In conclusion, the chosen 2D underwater video-based kinematic methodology is supported by prior artistic swimming biomechanics research and is well aligned with the aim of this study. This method allowed the analysis of the upper limb movement patterns across standardized artistic swimming positions and enabled the swimmer to perform the sculling under realistic conditions.

2.3. Experimental Design and Data Collection Procedures

The experimental design was created to analyse upper limb movement characteristics of support sculling under controlled but realistic artistic swimming conditions. Since support sculling is used to maintain body height and stability in several compulsory positions, the data collection procedure had to ensure that the swimmer performed each position in consistent and comparable manner. As a result, the experiment was structured around standardized body positions, controlled height, repeated trials and underwater video recordings.

A single-participant repeated-measures design was applied for this experiment. One high-level artistic swimmer performed five artistic swimming positions, which allowed the analysis of upper limb kinematics to be compared across different body configurations. This approach was appropriate as the main goal was to examine how the same swimmer adapted the support sculling mechanics when body position changed.

Overall, this methodology provided a structured framework for analysing position-dependant differences in upper limb kinematics during support sculling. By combining controlled position execution, repeated trials, and video-based measurement, the procedure allowed meaningful comparison of the selected biomechanical variables.

2.4. Description of the Experimental Methodology

2.4.1. Participant

The participant of this study was a high-level artistic swimmer (ranking number 2 in Lithuania) had over five years of competitive artistic swimming experience and was actively training at the time of data collection (Fig. 17). The inclusion criteria required the participant to be free from any upper limb injuries for at least six months prior to testing.

Informed consent was obtained before participation. For confidentiality, the participant was assigned the anonymized identifier $A1$ for data storage and analysis.

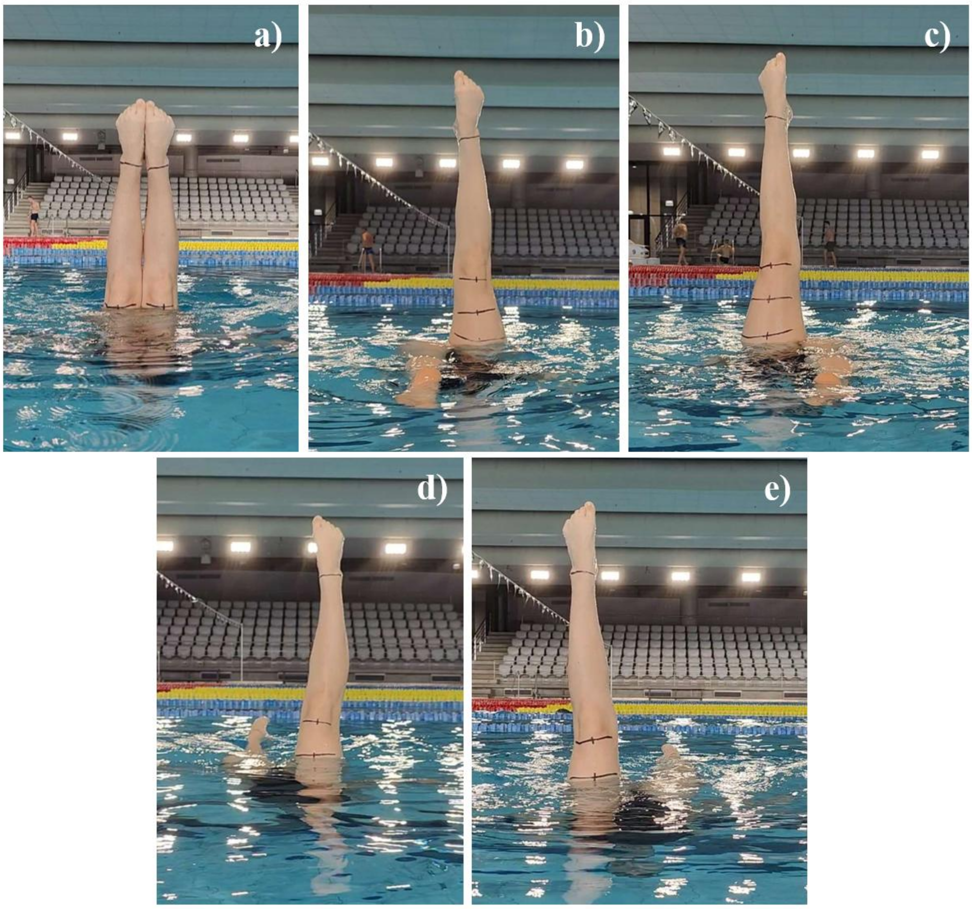


Fig. 17. Standardized artistic swimming positions analysed during biomechanical data collection: a) Vertical; b) Fishtail Right; c) Fishtail Left; d) Knight Right; e) Knight Left

2.4.2. Experimental Environment

Data collection was conducted in an indoor 50 m swimming pool with uniform water depth of 2.2 m and controlled lighting conditions (Fig. 18). Environmental conditions such as water clarity and surface reflections were monitored to ensure consistent video quality across trials.

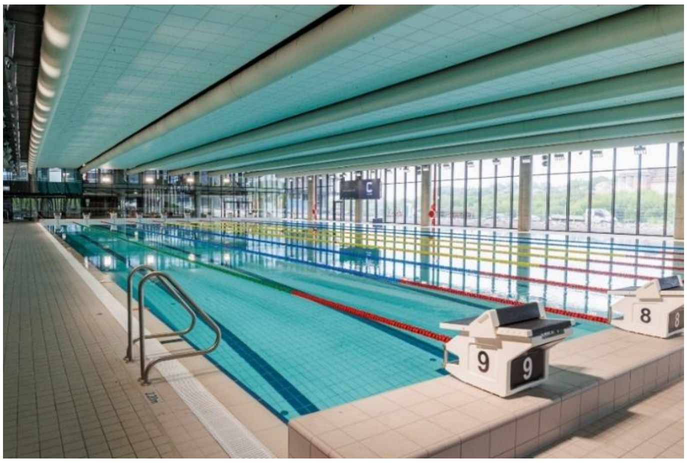
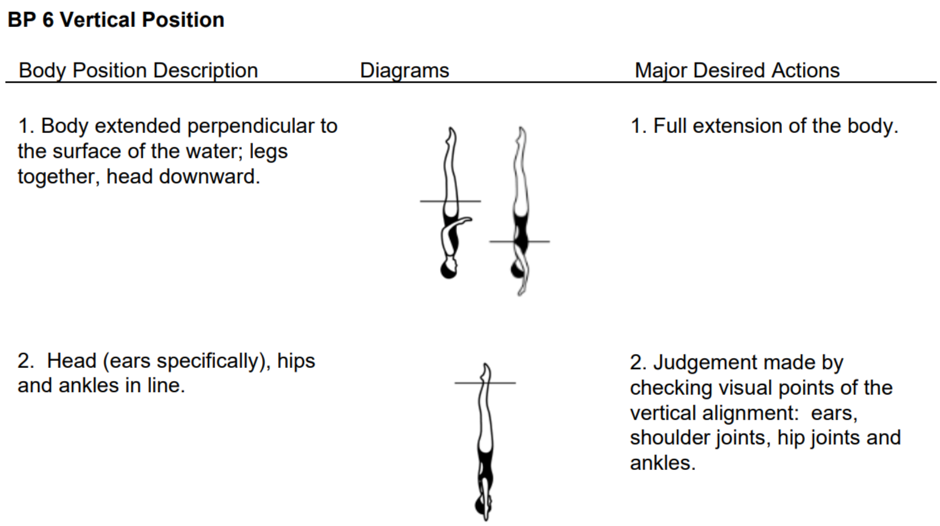


Fig. 18. Indoor swimming pool used for biomechanical data collection

2.4.3. Analysed Artistic Swimming Positions

For the analysis of support scull, five artistic swimming positions were selected: Vertical (Fig. 19), Fishtail Right, Fishtail Left, Knight Right and Knight Left (Fig. 20). These positions were selected because they require continuous support sculling to maintain body height and stability, while also requiring different body configurations and stabilization demands on the upper limbs.

The official body-position descriptions were used to define the required alignment of the body during each position [18]. Fishtail and Knight positions involved asymmetric body configurations, while the Vertical position represented the symmetrical reference condition. Therefore, this allowed the study to additionally compare upper limb sculling mechanics between symmetrical and asymmetrical positions (Fig. 17).

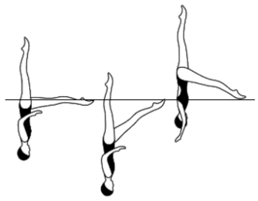


BP 6 Vertical Position

Body Position Description	Diagrams	Major Desired Actions
1. Body extended perpendicular to the surface of the water; legs together, head downward.		1. Full extension of the body.
2. Head (ears specifically), hips and ankles in line.		2. Judgement made by checking visual points of the vertical alignment: ears, shoulder joints, hip joints and ankles.

Fig. 19. Official description of the Vertical position [18]. (BP 6 Vertical Position)

BP 8 Fishtail Position

Body Position Description	Diagrams	Major Desired Actions
1. Body extended in **Vertical Position** with one leg extended forward**.** The foot of the forward leg is at the surface of the water regardless of the height of the hips.		1. See BP 6 **Vertical Position** for body alignment. The foot of the forward leg must be at the surface of the water. Hip joints must be on a horizontal line.

BP 17 Knight Position

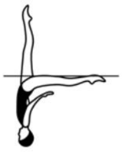
Body Position Description	Diagrams	Major Desired Actions
1. Lower back arched, with hips, shoulders and head on a vertical line.		1. Arch is in the lower part of the spine only.
2. One leg vertical.		2. Vertical alignment through ears, shoulder joints, hip joints and ankle of the vertical leg.
3. Other leg extended backward with the leg at the surface of the water and as close to horizontal as possible.		3. Hip joints and shoulder joints on a horizontal line with both of these alignments 'square' and parallel to each other. The top of the horizontal extended leg faces upward.

Fig. 20. Official descriptions of the Fishtail and Knight positions [18]. (BP 8 Fishtail Position and BP 17 Knight Position)

2.4.4. Position Height Standardization

For this experiment, each artistic swimming position was performed at a standardized height according to the Official Artistic Swimming Position Height Chart [19]. The selected height levels were chosen based the technical characteristics and support demands of each analysed position (Fig. 21).

- **Fishtail Position** – 8.5 height level was selected, because this position is performed with one leg extended vertically and the foot of the other leg is at the surface of the water, in front of the body.
- **Knight Position –** 7.5 height level was chosen, because the position involves a more complex and asymmetric body configuration, with one leg vertical, and the other extended backward with the foot at the water surface, making a slightly lower standardized height more realistic and repeatable.
- **Vertical Position** – 6.5 height level was selected, as this position requires both legs to be held together above the water surface, increasing the support demand compared with the single-leg positions.

The selected height values also reflected the highest technically stable height that the participant could maintain repeatedly across trials without loss of alignment or control.

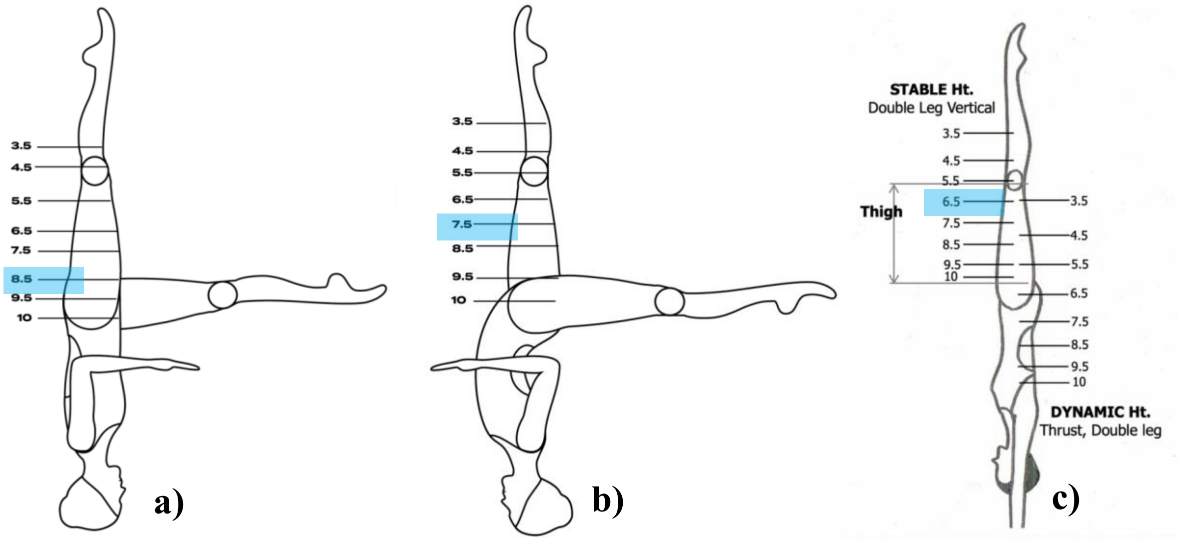


Fig. 21. Official height reference levels selected for the analysed artistic swimming positions: a) Fishtail; b) Knight; c) Vertical [19]

The target height for each position was marked directly on both of the participant's legs using a waterproof skin marker (Fig. 22). The participant was instructed to keep the respective marker line at the water surface during each trial, ensuring that each trial was performed at a consistent elevation.

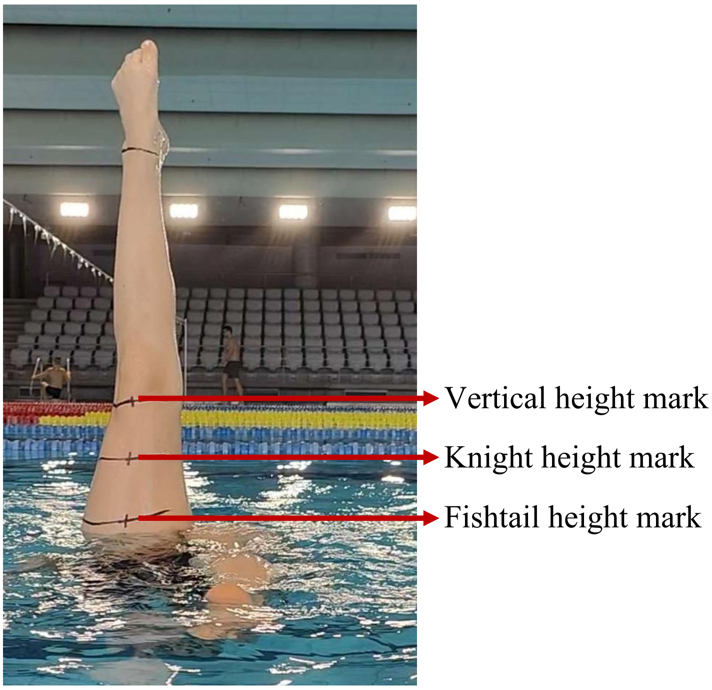


Fig. 22. Position-specific height markings used to standardize body elevation during data collection.

The height standardization was important, because changes in body elevation alter the support demand placed on the upper limbs. In case the participant performed one of the trials higher or lower than the other, it could influence all the analysed biomechanical variables and prevent the detection of variable changes from one position to another. For this reason, the height marking procedure was used to improve comparability between the repeated trials and positions.

2.4.5. Instrumentation and Camera Setup

During this experiment the motion of the upper limb was recorded using a GoPro HERO 11 camera. The camera settings were set at 1080p resolution and 240 frames per second. The camera was mounted on a stable support so that the position of it does not vary among the trials. The underwater camera was positioned approximately 1.0-1.2 m below water surface aligned to the typical depth of the hands during support sculling. The participant was then positioned approximately 2-3 m away and facing the camera (Fig. 23).

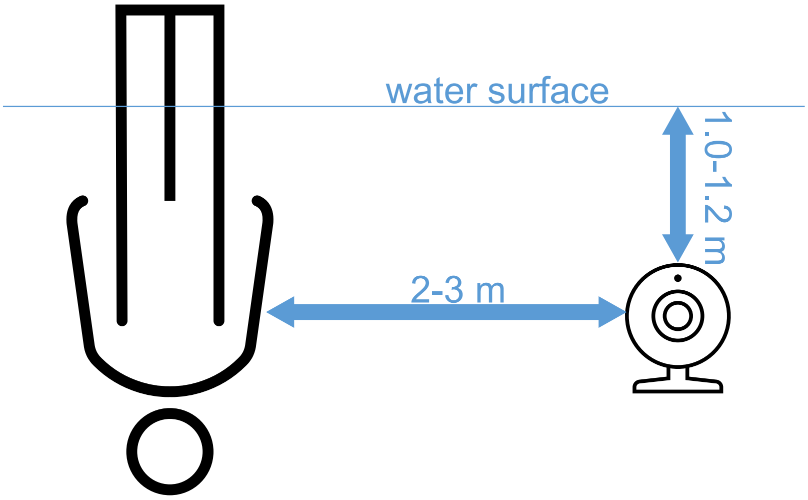


Fig. 23. Underwater camera position relative to the swimmer during support sculling analysis.

Additionally, another recording was done above the water using a smartphone camera (Fig. 24). These additional recordings were used as a supplementary reference to monitor the position height marker relative to the waterline and were not included in the kinematic analysis for upper limb motion.

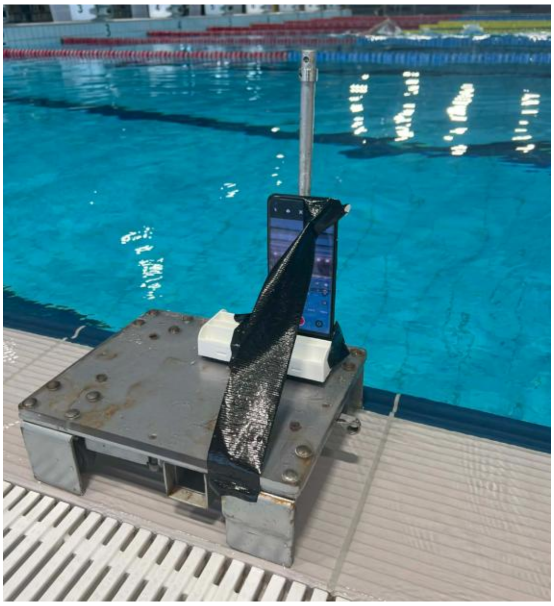


Fig. 24. Instrumentation and Camera Setup

2.4.6. Calibration and Plane Alignment

Spatial calibration was performed using a 1 m calibration stick marked with black duct tape at both ends (Fig. 25). The calibration stick was recorded underwater using the same camera position as the experimental trials. This recording was used to establish the pixel-to-length conversion factor required for subsequent kinematic analysis.

Fig. 25. Calibration stick used for spatial scaling and plane alignment

The calibration stick was aligned approximately parallel to the swimmer's frontal plane. This was necessary because the two-dimensional analysis depended on the assumption that the main movement occurred in the calibrated plane. The known distance between the two marked endpoints of the calibration stick was later defined in Kinovea as 100 cm.

This calibration approach did not allow full correction of optical distortion or out-of-plane movement. However, it provided a practical and repeatable scaling procedure suitable for pool-based two-dimensional underwater analysis when calibration grids or multi-camera systems were not available.

2.4.7. Anatomical Landmark Marking

Before data collection, selected upper limb anatomical landmarks were marked using a skin-safe waterproof marker. The marked locations included the acromion (shoulder), lateral epicondyle (elbow), mid-forearm point, ulnar styloid (wrist), and the fingertip of the middle finger (Fig. 26).

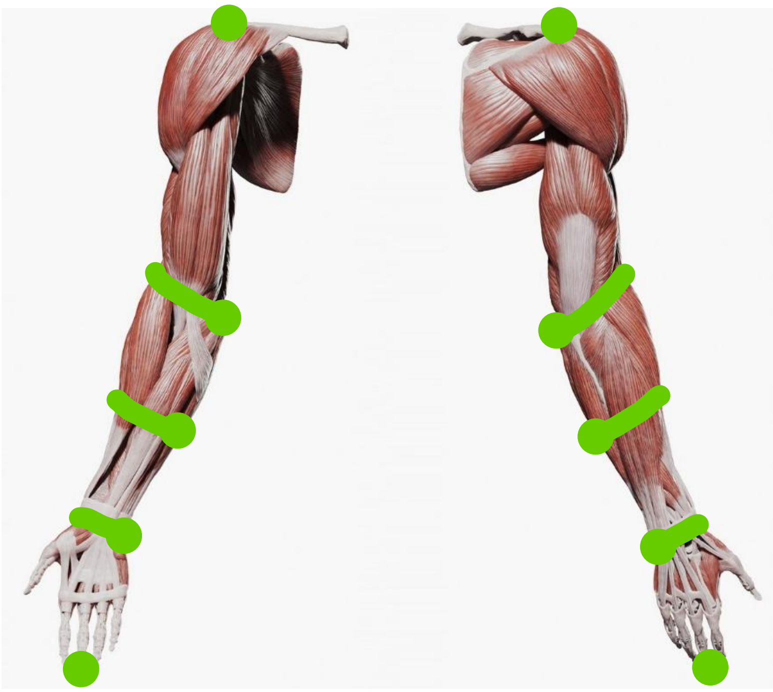


Fig. 26. Anatomical landmark marking used for upper limb kinematic analysis.

For the final kinematic analysis, four landmarks per upper limb were digitized: shoulder, elbow, mid-forearm point and wrist. These landmarks were selected because they allowed reconstruction of the main upper limb segments involved in support sculling and calculation of elbow angle, forearm orientation, and hand-speed-related variables.

2.4.8. Experimental Procedure

Before starting the experiment, the participant completed a standardized warm-up consisting of approximately 10 minutes of light swimming followed by preparatory support-scull drills. After the warm-up, the participant performed the five selected artistic swimming positions in repeated trials.

For each trial, the participant first assumed the required position and began support sculling to stabilize the target height. Each trial lasted 15 seconds. The first 3 seconds and the last 2 seconds were excluded from analysis, leaving a 10-second steady-state interval for kinematic processing. This ensured that the analysis focused on stable support sculling and not the transition into or out of the position.

Each artistic swimming position was performed three times, resulting in 15 trials in total. Minimum rest period between the trials was set to about 60 seconds and between different positions it was at least 3 minutes. The main purpose of this was to limit the fatigue effect on the results and maintain a consistent execution quality for data collection.

In conclusion, the developed methodology enabled analysis of upper limb kinematics during support sculling under realistic conditions. Even though the single-camera two-dimensional approach did not allow direct measurement of hydrodynamic forces, or out of plane movement, it provided a practical method for comparing the participant's upper limb movement patterns across standardized artistic swimming positions.

2.5. Relevance of the Methodology for Artistic Swimming Biomechanics

The selected methodology is both relevant and appropriate for investigating upper limb biomechanics in artistic swimming. The support scull is the primary technique used by the artistic swimmers to create upward support and maintain the height and control of the position [1]. Upper limb motion plays a dominant role in performance execution, therefore making it a relevant variable for analysis of support sculling.

During stationary support sculling, the arms and hands move in a repetitive, cyclic pattern that occurs predominantly within the frontal plane when the swimmer maintains a fixed position [2]. This movement characteristic allows key biomechanical parameters, such as hand velocity, sculling cycle rate, elbow joint angle, and hand orientation, to be captured using a 2D video-based approach (Fig. 7).

Previous biomechanical studies in artistic swimming have demonstrated that these variables provide useful insight into technique differences and propulsive strategies without requiring complex three-dimensional motion capture systems [2].

The use of underwater video was appropriate given the rapid and continuous nature of sculling movements. Previous studies have used video-based approaches to analyse support sculling and upper limb symmetry in artistic swimming, including recordings at 50 Hz during repeated support scull cycles [3]. In addition, video-based artistic swimming analyses using Kinovea have been performed at 30 Hz for comparative performance assessment [11]. In the present study, the trials were recorded at 240 fps, providing high-frame-rate source footage for visual inspection and movement review. However, because the Kinovea digitization was performed at 30 fps, the effective temporal resolution of the exported coordinate data was 30 Hz. Since support sculling is a repeated cyclic movement and the analysis focused on comparative movement patterns rather than direct force measurement, this analysed frequency was considered sufficient for comparing support sculling characteristics across standardized positions.

For this experiment, the use of one underwater camera allowed the swimmer to perform the position under conditions that are close to real training and performance conditions. The participant was able to move freely, therefore avoiding movement constrains associated with tethered or laboratory-based measurement systems [2]. Supplementary above water recording using a smartphone camera provided additional information regarding body height relative to the water surface. While this footage was not used for kinematical analysis, it supported the interpretation of underwater upper limb mechanics, by confirming that trials were performed under comparable vertical load conditions (Fig. 25) [11].

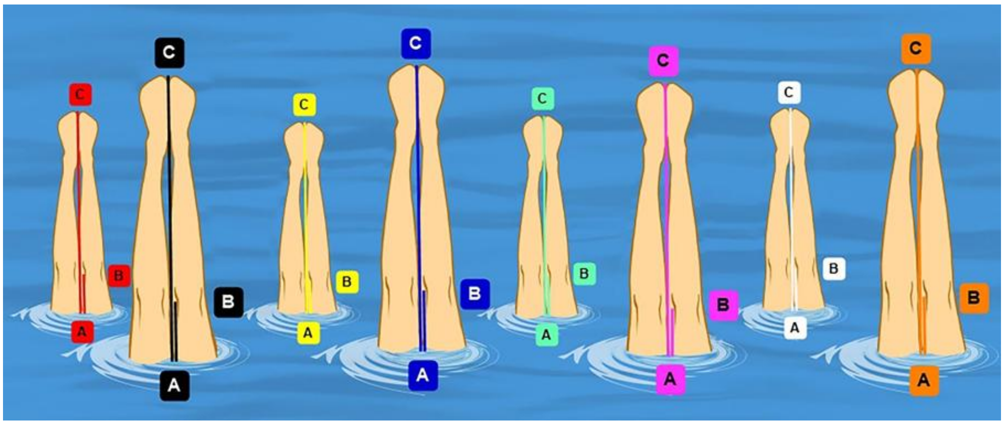


Fig. 27. Leg height index measurement for assessing vertical body elevation. [11]

For this study, a calibrated 2D video-based method was a better choice than multi camera 3D motion capture or direct force measurement, since these advanced systems are difficult to apply in a pool environment, and could restrain the natural movement of the swimmer. Therefore, the selected method allowed the participant to perform the positions freely, while still providing the coordinate data needed to calculate the desired kinematic variables (Fig. 28) [6].

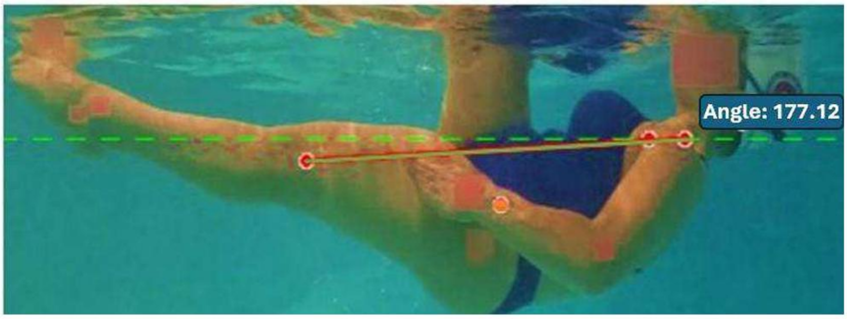


Fig. 28. Video-based shoulder-knee angle measurement during ballet leg execution. [6]

In conclusion, the chosen methodology is well aligned with the aim of this study and the biomechanical characteristics of support sculling in artistic swimming. It enables the analysis of upper limb movement patterns under realistic pool-based conditions and supports comparison of the same participant's kinematic variables.

2.6. Video-Based Kinematic Analysis Using Kinovea

Video-based kinematic analysis was performed using Kinovea software. Kinovea was chosen since it allows visual inspection of video recordings, spatial scaling, manual frame-by-frame digitization, and export of coordinate data of upper limb movements for further processing (Fig. 29).

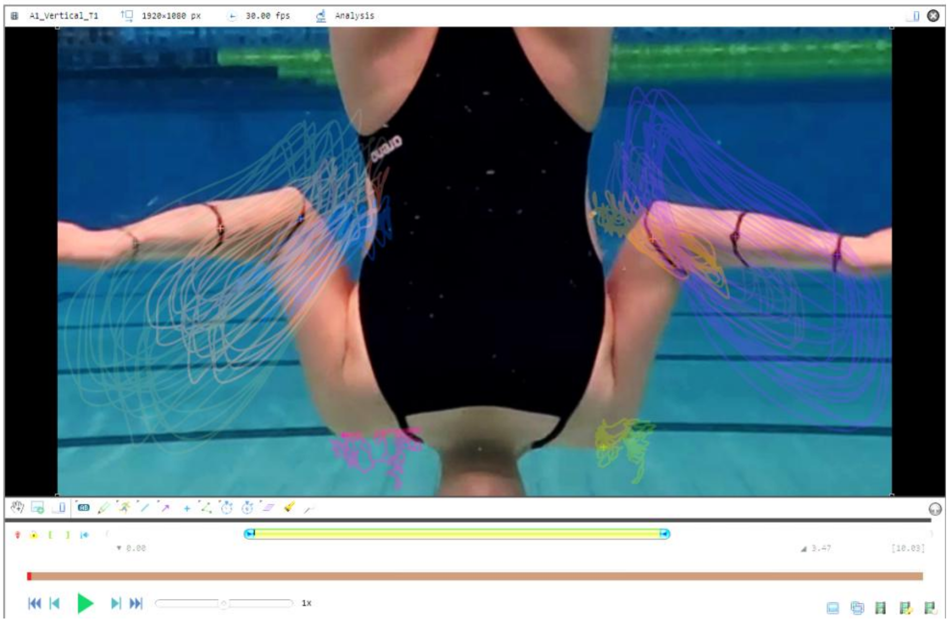


Fig. 29. Kinovea workspace showing manual tracking of upper limb movements

The original underwater recordings were captured at 1080p resolution and 240 frames per second, however, due to the analysis settings in Kinovea, the videos were processed at 30 frames per second. This makes the effective temporal resolution of the exported coordinate data 30 Hz, providing 300 analysed frames for each 10 s analysis window. Before digitization, each recording was visually inspected to confirm that the swimmer remained within the camera field of view and that the upper limbs were visible throughout the selected analysis interval.

2.6.1. Spatial Calibration and Scaling

Spatial calibration was performed in Kinovea to prepare for manual digitization by converting the pixel-based coordinates into real distance measurements. For this, a 1 m calibration stick was recorded underwater using the same camera position and recording setup as the experimental trials (Fig. 30).

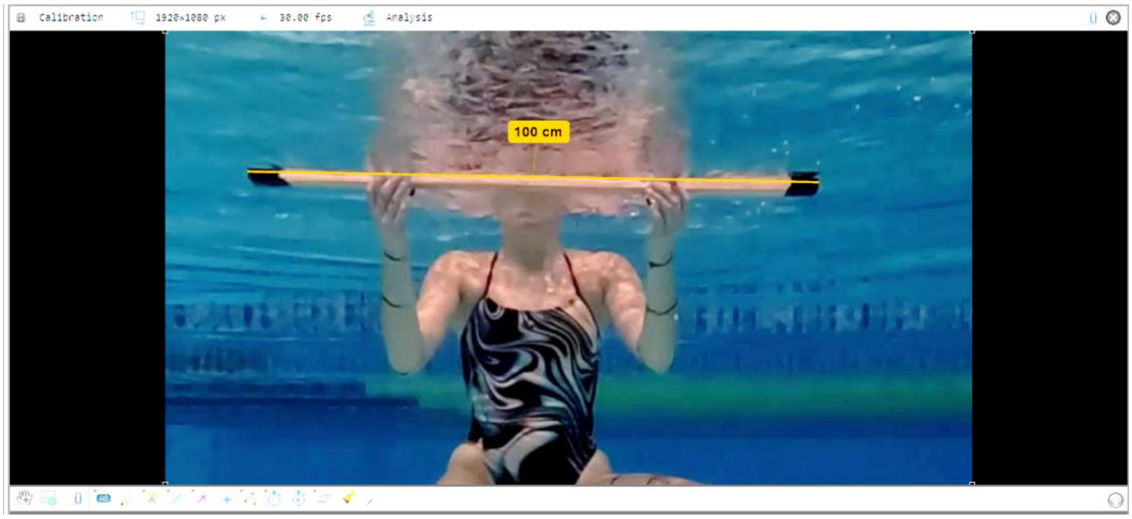


Fig. 30. Spatial calibration in Kinovea using a 100 cm underwater reference distance.

In Kinovea, the known distance between the two marked endpoints of the calibration stick was defined as 100 cm, which allowed the exported coordinate data to be expressed in centimetres rather than pixels.

2.6.2. Manual Digitization of Anatomical Landmarks

Upper limb movements were analysed through manual digitization of anatomical landmarks in Kinovea. The same landmark set was used consistently across all analysed trials to ensure comparability between positions and repetitions.

The following anatomical landmarks were digitized on both upper limbs:

- Acromion – shoulder landmark;
- Lateral epicondyle – elbow landmark;
- Mid-forearm point;
- Ulnar styloid – wrist landmark.

A total of eight landmarks were tracked, with four landmarks on the right upper limb and four landmarks on the left upper limb. These specific landmarks were selected to represent the main upper limb segments involved in support sculling and to allow analysis of shoulder, elbow, forearm, and wrist movement patterns (Fig. 31). During digitization, the wrist marker was the most consistently visible distal landmark, so it was used for hand-speed calculation.

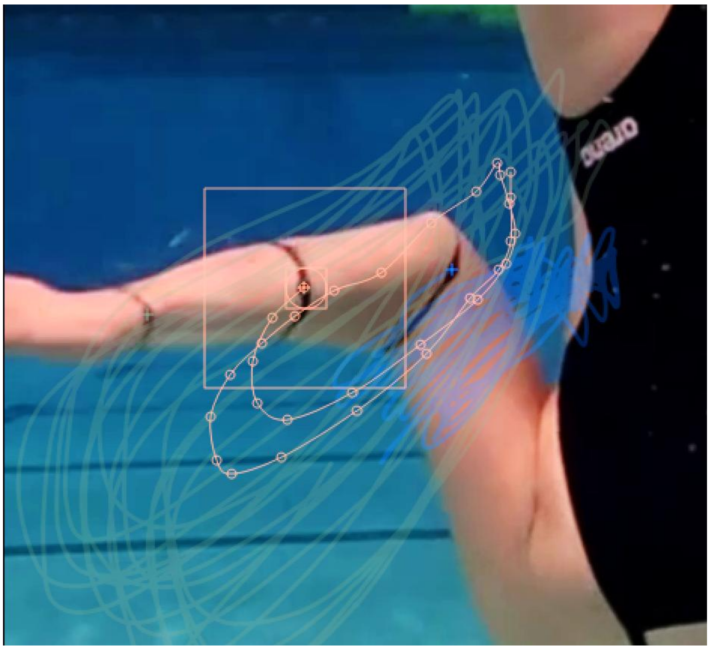


Fig. 31. Manual digitization of upper limb landmarks during underwater support sculling

After digitization, the landmark trajectories were visually reviewed in Kinovea to identify possible point-placement errors. When necessary, individual frames were corrected manually before the coordinate data were exported for further processing.

2.7. Data Export and Kinematic Variable Calculation

After manual digitization in Kinovea, two-dimensional coordinate data were exported to Microsoft Excel for further processing. The exported dataset contained time values and calibrated coordinate data for the right and left upper limb landmarks. The calculations were first performed separately for each trial and then averaged by position. All calculations were performed separately for the right and left sides to evaluate both general support sculling characteristics and side-to-side differences.

In this study, hand speed was calculated using the displacement of the distal tracked landmark located at the wrist region. Therefore, the term hand speed refers to the speed of this tracked distal upper limb point during support sculling. Hand speed was calculated from the frame-to-frame displacement of the tracked point using the horizontal and vertical coordinate changes between consecutive frames:

$$v = \frac{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}}{t_i - t_{i-1}}, \quad (1)$$

where x_i and y_i are the coordinates of the tracked hand point at the current frame, x_{i-1} and y_{i-1} are the coordinates at the previous frame, and $t_i - t_{i-1}$ is the time interval between frames. Speed was first calculated in cm/s and then converted to m/s by dividing the value by 100. Mean hand speed and standard deviation were calculated for each trial.

Forearm orientation was calculated using the elbow and mid-forearm landmarks. The angle of the forearm segment was determined using the arctangent function:

$$\theta = \tan^{-1}\left(\frac{y_{MF} - y_E}{x_{MF} - x_E}\right) \quad (2)$$

where E represents the elbow landmark and MF represents the mid-forearm landmark. The resulting angle was expressed in degrees. Deviation from vertical was then calculated as the absolute difference between the forearm angle and the vertical reference direction. This variable was used to describe how closely the forearm segment was oriented relative to the vertical axis during support sculling.

Elbow angle was calculated from the shoulder, elbow, and mid-forearm landmarks. Two vectors were defined: one from the elbow to the shoulder and one from the elbow to the mid-forearm. The angle between these vectors was calculated using the dot-product formula:

$$\alpha = \cos^{-1}\left(\frac{\overrightarrow{ES} \cdot \overrightarrow{EMF}}{|\overrightarrow{ES}||\overrightarrow{EMF}|}\right), \quad (3)$$

where $\overrightarrow{ES}$ is the vector from the elbow to the shoulder and $\overrightarrow{EMF}$ is the vector from the elbow to the mid-forearm. The calculated angle was expressed in degrees. Mean elbow angle and elbow angle standard deviation were calculated for each trial to describe the average elbow position and the amount of elbow movement variation during support sculling.

Sculling cycle characteristics were determined from the repeated vertical movement pattern of the tracked hand point. Local peaks in the hand vertical coordinate were identified when the value at the current frame was greater than the values in the preceding and following frames and exceeded the mean vertical coordinate threshold for that trial. The time values corresponding to the identified peaks were used to calculate cycle duration:

$$T = t_{peak(i)} - t_{peak(i-1)}, \tag{4}$$

where T is the duration of one sculling cycle. Cycle rate was calculated as the inverse of the mean cycle duration:

$$f = \frac{1}{\bar{T}}, \tag{5}$$

where f is cycle rate in hertz and $\bar{T}$ is the mean cycle duration. Mean cycle duration, cycle duration standard deviation, peak count, and cycle rate were calculated separately for the right and left sides.

Additional side-to-side comparison variables were calculated to describe asymmetry between the right and left upper limbs. These included the absolute difference between right and left mean hand speed, the absolute difference between right and left mean elbow angle, and the absolute difference between right and left mean cycle duration. Shoulder vertical range was also calculated as the difference between the maximum and minimum shoulder y-coordinate during the analysed trial.

For each trial, the calculated variables were summarized as trial-level outcome measures. These values were then grouped by artistic swimming position to calculate position-level descriptive statistics, including mean and standard deviation values. This workflow converted the exported Kinovea coordinate data into the final kinematic variables that were then used for comparison of the analysed body positions.

3. Results

This section presents the results of the biomechanical analysis of upper limb movements during support sculling across five artistic swimming positions. For each position, three trials were analysed to evaluate movement consistency and position-specific differences in upper limb kinematics.

The analysis focused on key kinematic variables, including hand speed, cycle duration, and elbow joint angle. These variables were selected to describe distal upper limb movement, temporal control, and joint mechanics during support sculling.

3.1. Overview of Analysed Variables

The biomechanical analysis focused on three groups of kinematic variables describing upper limb motion during support sculling: hand kinematics, cycle characteristics, and joint kinematics (Table 4).

Table 4. Summary of analysed kinematic variables, units, and functional interpretation

Variable Group	Metric	Unit	Functional interpretation
Hand kinematics	Mean hand speed	m/s	Distal upper limb movement speed
	Hand speed SD	m/s	Speed variability
Cycle characteristics	Cycle duration	s	Sculling rhythm
	Cycle duration SD	s	Temporal consistency
Joint kinematics	Elbow angle	deg	Upper limb joint configuration
	Elbow angle SD	deg	Elbow movement variability

Hand kinematics were represented by mean hand speed and hand speed variability, calculated separately for the right and left upper limbs. These variables were used to describe the movement speed of the tracked distal upper limb point and to assess differences between limbs.

Cycle characteristics included cycle duration and cycle duration variability, derived from peak detection in the vertical displacement of the tracked hand point. These measures describe the temporal structure and consistency of the sculling movement.

Joint kinematics were characterized by elbow angle and elbow angle variability. These variables provided insight into the mechanical configuration of the upper limb and the consistency of elbow movement during support sculling. In addition, asymmetry metrics were calculated for hand speed, cycle duration, and elbow angle to evaluate right-left differences between limbs.

Together, these variables provided a structured description of movement speed, temporal rhythm, joint configuration, and right-left coordination across the analysed body positions.

3.2. Results by Position

The results are organised according to body position to compare upper limb movement characteristics under different biomechanical constraints. For each position, the analysed variables are examined across three trials to assess movement consistency. Differences between positions are then evaluated to identify changes in movement speed, coordination, and joint mechanics.

This structure enables within-position analysis of movement consistency and between-position comparison of kinematic patterns.

3.2.1. Fishtail Right

In the Fishtail Right position, clear differences were observed in upper limb kinematics, particularly in hand speed and elbow joint behaviour. The right limb demonstrated higher mean hand speed than the left limb. Despite this difference, the temporal characteristics of the movement remained highly consistent between limbs, with cycle duration showing minimal side-to-side variation.

The summarized kinematic results (Table 5) show that both limbs maintained a stable rhythmic structure. Low cycle variability values indicate consistent execution across trials, suggesting that the participant was able to preserve timing control despite the asymmetrical body position.

Table 5. Summary of kinematic variables for right and left limbs in the Fishtail Right position

R hand speed (m/s)	L hand speed (m/s)	Speed asymmetry (m/s)	R cycle duration (s)	L cycle duration (s)	Cycle asymmetry (s)	R elbow angle (deg)	L elbow angle (deg)	Angle asymmetry (deg)
1.706 ± 0.618	1.551 ± 0.587	0.156	0.646 ± 0.033	0.645 ± 0.042	0.002	110.660 ± 31.414	123.684 ± 38.424	13.024

Elbow joint kinematics further highlighted differences in movement strategy between limbs. The left elbow operated at consistently higher angles throughout the cycle, showing a more extended joint configuration, while the right elbow exhibited comparatively lower angles. This suggests a functional asymmetry in which the two limbs used different joint configurations during support sculling.

As illustrated in Fig. 32, both limbs exhibited smooth and periodic elbow angle patterns, characteristic of continuous support sculling. There were no abrupt disruptions in the signal. However, the left limb consistently reached higher peak angles, reinforcing the presence of asymmetrical joint mechanics. The right limb, in contrast, showed deeper flexion phases, indicating a different mechanical role during the sculling cycle.

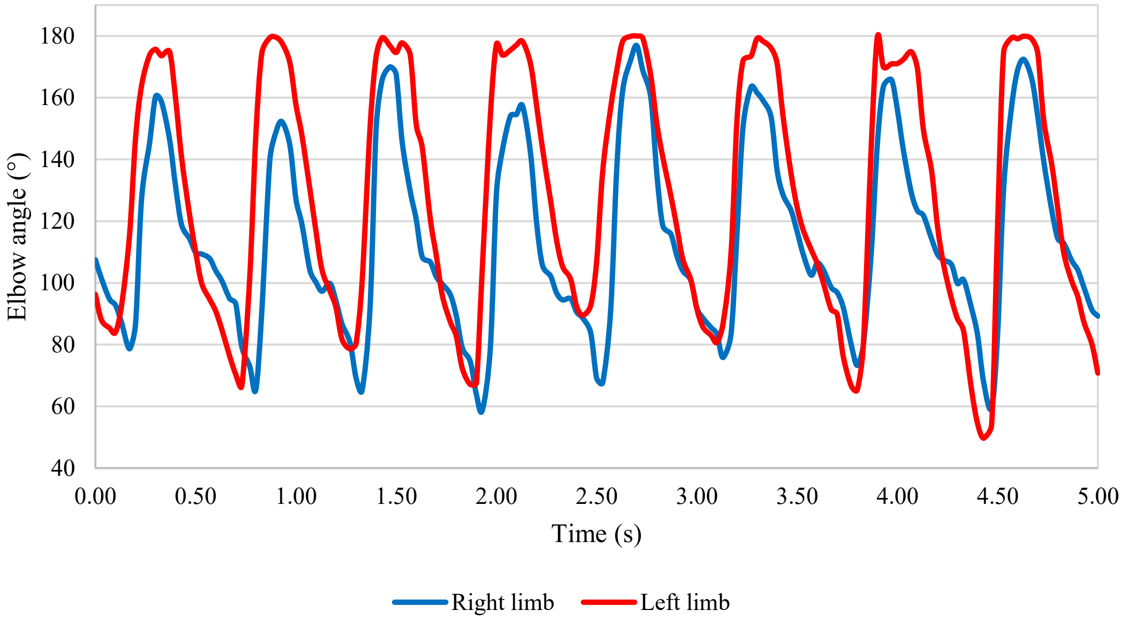


Fig. 32. Elbow angle during support sculling in the Fishtail Right position (right vs left limb)

Elbow angle variability was comparable between limbs, suggesting that both movement strategies were executed with a similar level of repeatability. This indicates that the observed asymmetry was not a result of instability, but rather a consistent adaptation to the positional demands of the Fishtail Right configuration.

In summary, the Fishtail Right position showed a coordinated but asymmetric movement pattern. Higher hand speed was observed in the right limb, while the left limb showed a more extended elbow configuration. Despite these differences, the participant maintained stable cycle timing and consistent execution across trials.

3.2.2. Fishtail Left

In the Fishtail Left position, the movement pattern remained coordinated but showed a different distribution of inter-limb characteristics compared with the Fishtail Right position. Hand speed values were more balanced between limbs, with the left limb showing slightly higher mean hand speed. This suggests a shift in the side with greater movement speed corresponding to the change in body configuration.

The summarized results (Table 6) indicate that, despite minor side-to-side differences in hand speed, the timing of the movement remained stable. Cycle duration was consistent across both sides, and low variability values confirm that the participant maintained a steady, rhythmic pattern throughout the trials.

Table 6. Summary of kinematic variables for right and left limbs in the Fishtail Left position

R hand speed (m/s)	L hand speed (m/s)	Speed asymmetry (m/s)	R cycle duration (s)	L cycle duration (s)	Cycle asymmetry (s)	R elbow angle (deg)	L elbow angle (deg)	Angle asymmetry (deg)
1.581 ± 0.639	1.663 ± 0.588	0.082	0.656 ± 0.070	0.672 ± 0.036	0.016	119.204 ± 39.432	116.066 ± 38.049	3.138

Elbow joint kinematics revealed a different asymmetry pattern compared with the Fishtail Right position. In this case, the right elbow exhibited slightly higher mean angles than the left, indicating a more extended configuration of the limb. This inversion of joint behaviour suggests that the participant adapted upper limb mechanics according to the active side of the position, redistributing movement roles between limbs to maintain balance and vertical stability.

As shown in Fig. 33, both limbs displayed smooth and periodic elbow angle trajectories, consistent with continuous support sculling. The cyclical pattern was preserved without abrupt fluctuations, indicating stable execution. However, subtle differences in peak amplitudes between limbs confirm the presence of asymmetrical joint strategies. Compared with the Fishtail Right position, the magnitude of elbow angle asymmetry was lower, suggesting more balanced coordination between limbs.

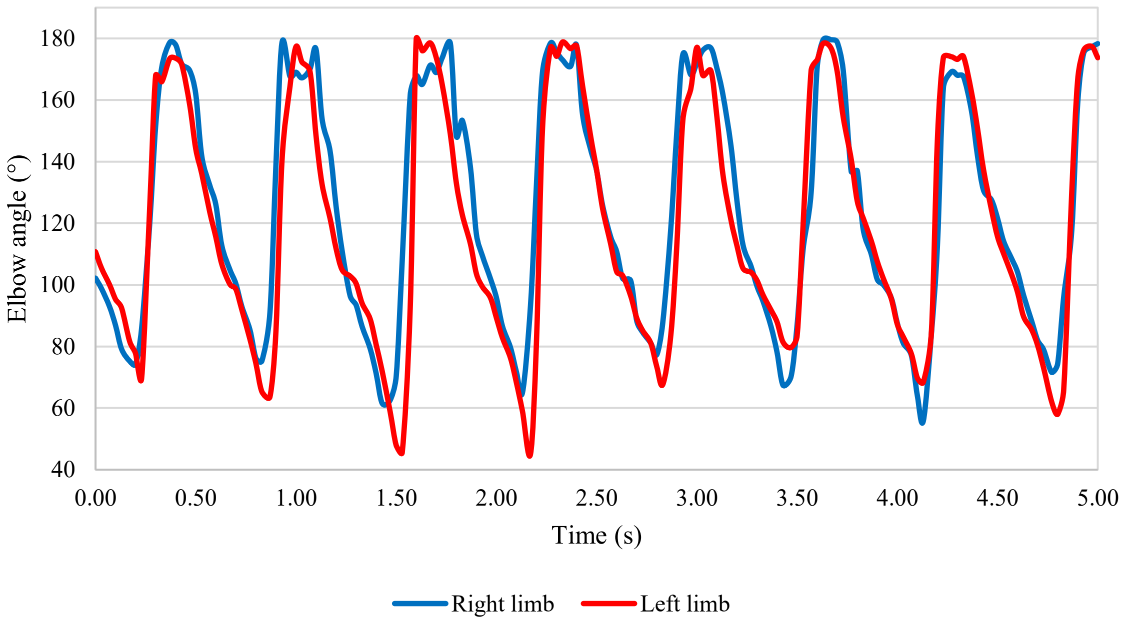


Fig. 33. Elbow angle during support sculling in the Fishtail Left position (right vs left limb)

Elbow angle variability remained comparable between the right and left sides, indicating that both movement patterns were executed with similar consistency. This suggests that the observed asymmetry does not appear to result from instability but rather reflects a consistent adaptation to the positional demands of the Fishtail Left configuration.

Overall, the Fishtail Left position demonstrated a coordinated and stable movement pattern with reduced inter-limb asymmetry compared with the Fishtail Right position. The redistribution of hand speed and elbow joint configuration between limbs highlights the participant's ability to adapt movement strategy according to body orientation while maintaining consistent timing and control.

3.2.3. Knight Right

The Knight Right position showed a clear reduction in hand speed compared with both Fishtail positions. Mean hand speed was lower for both limbs, with the right limb showing higher mean hand speed than the left. In the Knight Right position, the participant used a slower and more constrained support sculling pattern, with greater emphasis on maintaining body stability rather than increasing distal upper limb movement speed.

The summarized results (Table 7) show that, although hand speed was reduced, temporal control remained relatively stable. Cycle duration was slightly longer compared with the Fishtail positions, and cycle variability increased, particularly for the right limb. This suggests that maintaining rhythmic consistency became more challenging under the altered biomechanical constraints of the Knight Right position.

Table 7. Summary of kinematic variables for right and left limbs in the Knight Right position

R hand speed (m/s)	L hand speed (m/s)	Speed asymmetry (m/s)	R cycle duration (s)	L cycle duration (s)	Cycle asymmetry (s)	R elbow angle (deg)	L elbow angle (deg)	Angle asymmetry (deg)
1.243 ± 0.503	1.066 ± 0.430	0.177	0.679 ± 0.116	0.709 ± 0.035	0.031	105.396 ± 18.109	108.391 ± 22.516	3.922

Elbow joint kinematics revealed a more compact movement strategy compared with the Fishtail positions. Both limbs operated at lower mean elbow angles, indicating a more flexed configuration throughout the sculling cycle. This reduction in elbow angle suggests that the participant used a more constrained joint position while maintaining vertical stability and balance.

Fig. 34 shows the cyclical pattern of elbow movement remained clearly visible; however, the waveform exhibited reduced amplitude and slightly increased irregularity compared to previous positions. Peaks were less pronounced, and transitions between flexion and extension phases appeared less smooth, particularly in the right limb. This supports the observation of increased cycle variability and reduced movement efficiency.

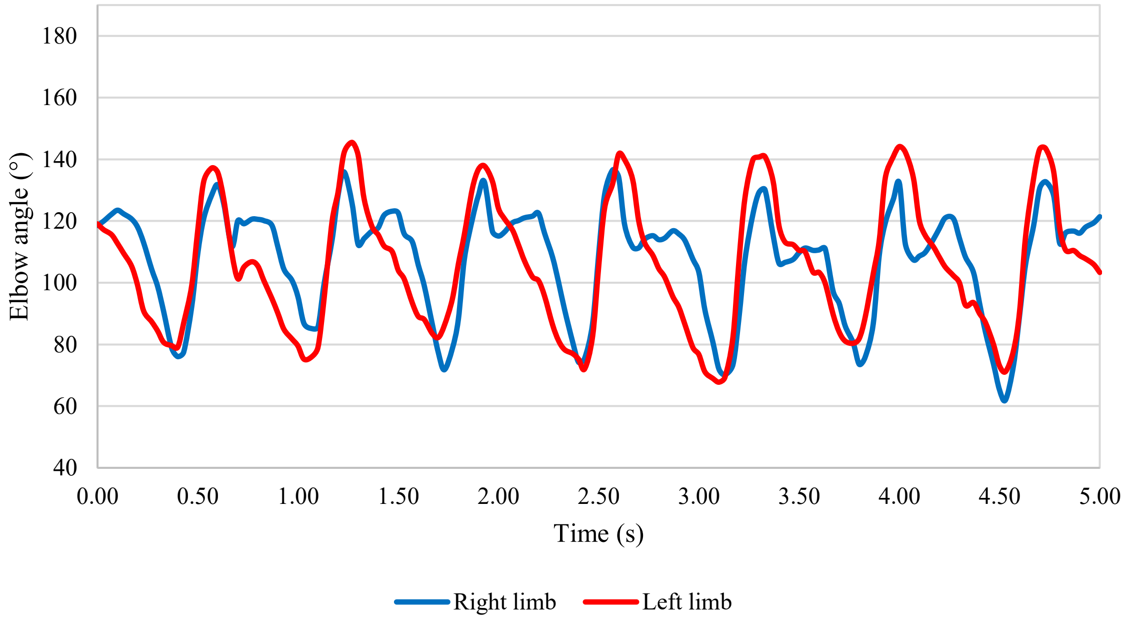


Fig. 34. Elbow angle during support sculling in the Knight Right position, right vs left limb.

Inter-limb asymmetry was more pronounced in this position, with differences observed in both hand speed and temporal parameters. The right limb demonstrated higher hand speed and a slightly shorter cycle duration, while the left limb showed lower hand speed and a longer cycle duration. This indicates a less balanced coordination pattern compared with the Fishtail positions.

Elbow angle variability was lower than in the Fishtail positions, suggesting a more restricted elbow movement range. This reduction in variability should not be interpreted as improved stability alone, but rather as a possible indication of constrained joint motion imposed by the positional demands of the Knight Right configuration.

Overall, the Knight Right position was characterized by lower hand speed, increased cycle variability, and a more flexed elbow configuration compared with the Fishtail positions. These findings suggest that the participant used a more constrained support sculling strategy in this position, with greater right-left differences in movement speed and timing.

3.2.4. Knight Left

In the Knight Left position, movement characteristics showed the greatest inter-limb asymmetry among the analysed positions. Mean hand speed was substantially higher for the left limb than for the right limb, indicating a clear side-to-side difference in distal upper limb movement speed. Compared with the Knight Right position, mean hand speed remained lower than in the Fishtail positions, suggesting that both Knight positions required a more constrained support sculling strategy.

The summarized results (Table 8) demonstrate that cycle duration differed more noticeably between limbs than in the previously analysed positions. The left limb exhibited a shorter mean cycle duration, while the right limb demonstrated a longer and less consistent cycle. Additionally, cycle duration variability increased considerably, particularly for the left limb. Rhythm was less consistent in the Knight Left position than in the Fishtail positions.

Table 8. Summary of kinematic variables for right and left limbs in the Knight Left position

R hand speed (m/s)	L hand speed (m/s)	Speed asymmetry (m/s)	R cycle duration (s)	L cycle duration (s)	Cycle asymmetry (s)	R elbow angle (deg)	L elbow angle (deg)	Angle asymmetry (deg)
1.051 ± 0.531	1.286 ± 0.556	0.235	0.671 ± 0.062	0.611 ± 0.170	0.060	99.341 ± 17.958	99.283 ± 20.150	2.217

Elbow joint kinematics revealed a more symmetrical mean joint configuration compared with the Knight Right position, with both limbs operating at relatively similar elbow angles throughout the movement cycle. However, despite similar mean elbow angle values, the temporal behaviour of the limbs differed considerably. This indicates that the observed asymmetry was primarily associated with movement speed and cycle timing rather than static elbow joint configuration.

As illustrated in Fig. 35, both limbs maintained a cyclical elbow movement pattern characteristic of continuous support sculling. Nevertheless, the waveform demonstrated increased irregularity and reduced smoothness compared with the Fishtail positions. The left limb displayed more abrupt transitions between flexion and extension phases, while the right limb showed longer plateau phases and delayed recovery patterns. These characteristics indicate a less synchronized inter-limb movement strategy in this position.

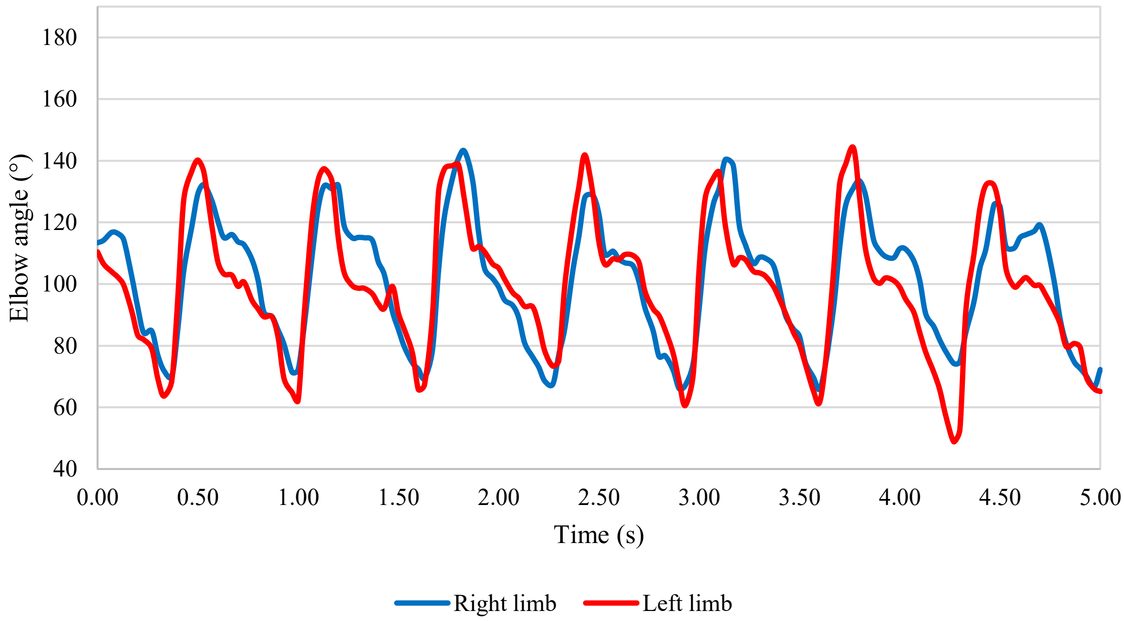


Fig. 35. Elbow angle during support sculling in the Knight Left position, right vs left limb.

Compared with all previously analysed positions, the Knight Left position exhibited the highest values of speed asymmetry and cycle asymmetry. This indicates a substantial imbalance in movement speed and temporal coordination between limbs. Despite this asymmetry, elbow angle variability remained relatively low, suggesting that the participant maintained a constrained elbow movement pattern throughout the task.

The reduced elbow angle variability observed in this position was likely associated with limited movement freedom caused by the biomechanical demands of the Knight configuration. Rather than reflecting improved movement consistency, the lower variability may indicate a more restricted movement strategy used to maintain body position.

Overall, the Knight Left position demonstrated the most asymmetric and least temporally consistent movement pattern among the analysed positions. The combination of increased speed asymmetry, increased cycle asymmetry, and constrained joint mechanics suggests that this position imposed greater coordination demands on the participant compared with the Fishtail and Vertical positions.

3.2.5. Vertical

The Vertical position demonstrated the most balanced and symmetrical movement pattern among all analysed positions. Mean hand speed values were nearly identical between the right and left limbs, indicating an even distribution of distal upper limb movement during support sculling. Compared with the Fishtail and Knight positions, the Vertical position exhibited the smallest inter-limb differences in both hand speed and temporal parameters.

The summarized results (Table 9) indicate highly stable temporal organization of the movement. Cycle duration remained nearly identical between limbs, while cycle variability values were among the lowest of all analysed positions. These findings suggest a highly consistent rhythmic structure during execution of the Vertical position.

Table 9. Summary of kinematic variables for right and left limbs in the Vertical position

R hand speed (m/s)	L hand speed (m/s)	Speed asymmetry (m/s)	R cycle duration (s)	L cycle duration (s)	Cycle asymmetry (s)	R elbow angle (deg)	L elbow angle (deg)	Angle asymmetry (deg)
1.776 $\pm$ 0.724	1.756 $\pm$ 0.681	0.020	0.659 $\pm$ 0.030	0.658 $\pm$ 0.036	0.002	111.743 $\pm$ 33.101	109.855 $\pm$ 35.364	2.253

Elbow joint kinematics were also highly symmetrical. Mean elbow angle values differed only minimally between limbs, and the calculated angle asymmetry was substantially lower than in the Fishtail positions. This indicates a balanced joint configuration between the right and left upper limbs during maintenance of vertical body alignment.

In Fig. 36, both limbs exhibited smooth, repetitive, and clearly cyclical elbow movement patterns throughout the analysis period. The right and left elbow angle curves followed a similar rhythm across most cycles, with peak flexion and extension occurring at comparable time points. Compared with the Knight positions, the movement pattern appeared more continuous and less segmented, suggesting more balanced inter-limb coordination.

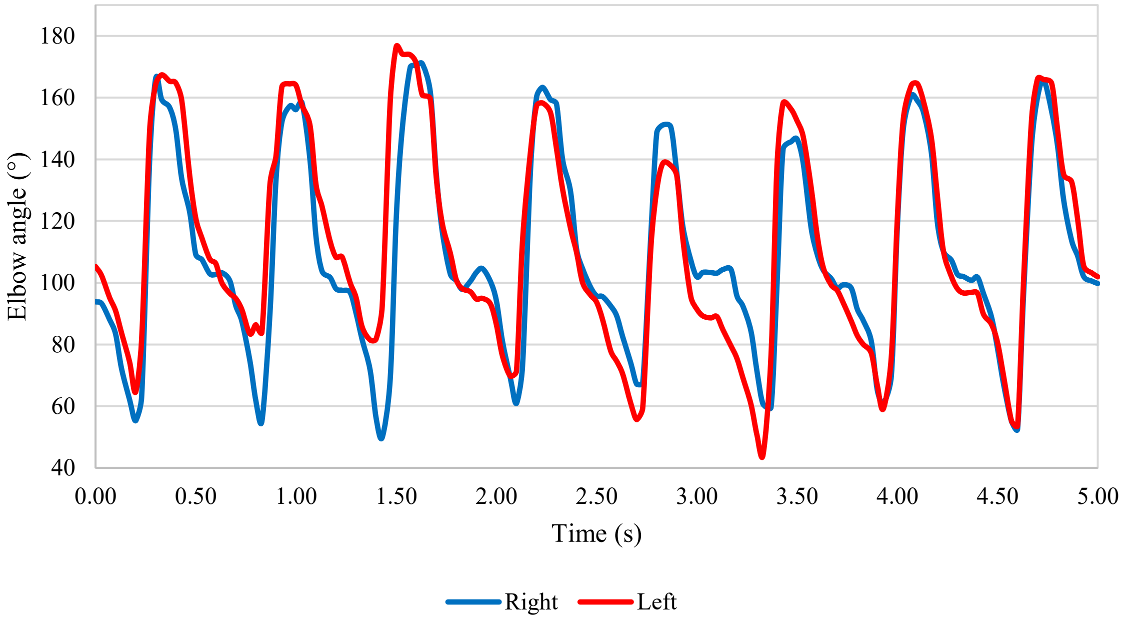


Fig. 36. Elbow angle during support sculling in the Vertical position, right vs left limb.

The Vertical position also demonstrated relatively low cycle variability, indicating stable temporal control across repeated sculling cycles. Although elbow angle variability remained moderate due to the naturally cyclic nature of support sculling, the movement pattern itself remained repeatable and coordinated between limbs.

Compared with asymmetric positions such as Fishtail and Knight configurations, the Vertical position required less compensatory adjustment between limbs. The reduced asymmetry values suggest that the participant was able to maintain a more symmetrical support sculling strategy, with movement speed and cycle timing distributed more evenly between the right and left upper limbs.

Overall, the Vertical position demonstrated the highest level of inter-limb symmetry and temporal consistency among all analysed positions. These findings suggest that the symmetrical body configuration of the Vertical position allowed a more balanced support sculling pattern compared with positions involving greater asymmetrical body alignment.

3.3. Comparison Between Positions

Comparison of the analysed positions revealed substantial differences in hand-speed characteristics, inter-limb coordination, temporal organization, and elbow joint mechanics during support sculling (Table 10). These findings indicate that upper limb movement strategy changed according to the biomechanical demands imposed by different body configurations.

Table 10. Summary of kinematic variables for right and left limbs across all analysed positions

Position	R hand speed (m/s)	L hand speed (m/s)	Speed asym. (m/s)	R cycle duration (s)	L cycle duration (s)	Cycle asym. (s)	R elbow angle (deg)	L elbow angle (deg)	Angle asym. (deg)
Fishtail Right	1.706 ± 0.618	1.551 ± 0.587	0.156	0.646 ± 0.033	0.645 ± 0.042	0.002	110.660 ± 31.414	123.684 ± 38.424	13.024
Fishtail Left	1.581 ± 0.639	1.663 ± 0.588	0.082	0.656 ± 0.070	0.672 ± 0.036	0.016	119.204 ± 39.432	116.066 ± 38.049	3.138
Knight Right	1.243 ± 0.503	1.066 ± 0.430	0.177	0.679 ± 0.116	0.709 ± 0.035	0.031	105.396 ± 18.109	108.391 ± 22.516	3.922
Knight Left	1.051 ± 0.531	1.286 ± 0.556	0.235	0.671 ± 0.062	0.611 ± 0.170	0.060	99.341 ± 17.958	99.283 ± 20.150	2.217
Vertical	1.776 ± 0.724	1.756 ± 0.681	0.020	0.659 ± 0.030	0.658 ± 0.036	0.002	111.743 ± 33.101	109.855 ± 35.364	2.253

The Vertical position demonstrated the most symmetrical and balanced movement pattern among all analysed positions (Fig. 37). Mean hand speed values were nearly identical between the right and left limbs ($1.776\ m/s$ and $1.756\ m/s$, respectively), while speed asymmetry and cycle asymmetry remained minimal ($0.020\ m/s$ and $0.002\ s$) (Table 10). Additionally, cycle variability values were among the lowest across all analysed positions. These results indicate stable temporal organization and balanced inter-limb coordination during support sculling in the Vertical position.

In contrast, both Fishtail positions demonstrated greater inter-limb differences in hand speed and elbow joint configuration (Fig. 37). The Fishtail Right position showed a clear right-left difference in hand speed and the greatest elbow angle asymmetry among all analysed positions ($13.024°$) (Table 10). The Fishtail Left position demonstrated a more balanced distribution of hand speed between limbs, although cycle asymmetry remained higher than in the Vertical position. These findings suggest that Fishtail positions required position-specific inter-limb adaptations to maintain body alignment and stability.

The Knight positions demonstrated the greatest changes in movement organization compared with the Vertical and Fishtail positions (Fig. 37). Both Knight configurations showed lower mean hand speed values and greater inter-limb asymmetry. The Knight Left position exhibited the highest speed asymmetry (0.235 m/s) and cycle asymmetry (0.060 s), indicating the greatest imbalance in movement speed and temporal coordination between limbs (Table 10). Similarly, the Knight Right position demonstrated increased inter-limb differences in both hand speed and cycle timing compared with the Vertical position.

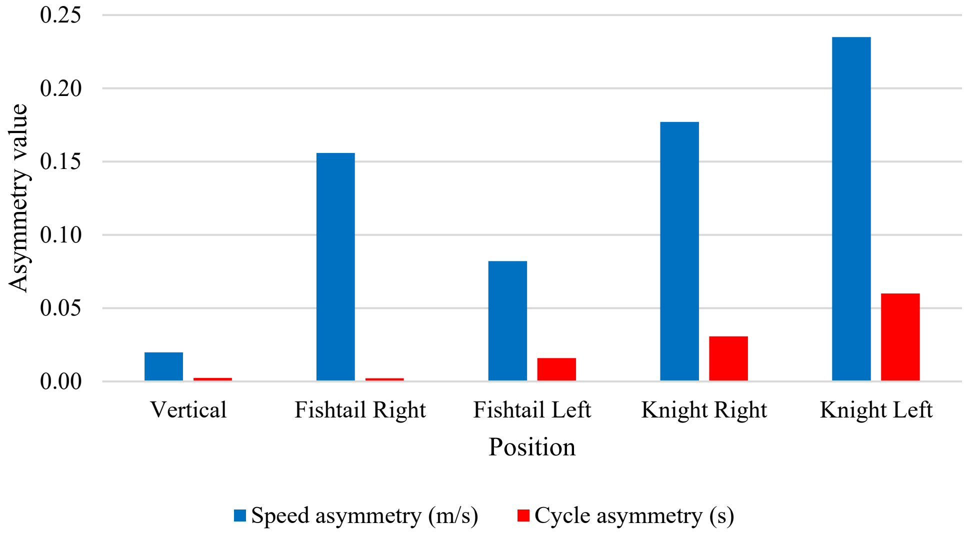


Fig. 37. Comparison of hand speed and cycle asymmetry across analysed positions.

Elbow joint mechanics also differed substantially between positions (Fig. 38). The Fishtail positions generally demonstrated higher mean elbow angles and greater angular asymmetry, especially in the Fishtail Right position. In contrast, the Knight positions were characterized by lower mean elbow angles, indicating a more flexed and constrained upper limb configuration during support sculling. The Vertical position showed relatively low elbow angle asymmetry, supporting the interpretation of a more symmetrical joint movement pattern.

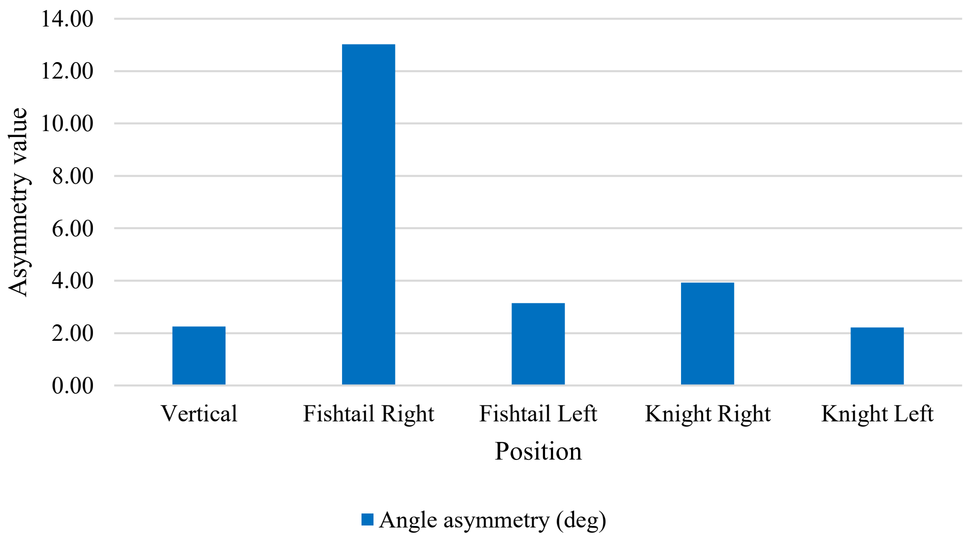


Fig. 38. Comparison of elbow angle asymmetry across analysed positions

Overall, the comparison between positions demonstrated a clear shift from the symmetrical and temporally stable movement pattern observed in the Vertical position toward more asymmetric and constrained movement patterns in the Fishtail and Knight positions. As body-position complexity increased, inter-limb asymmetry became more pronounced and temporal coordination became less balanced. These findings suggest that asymmetric artistic swimming positions require greater position-specific adaptation of upper limb support sculling mechanics.

3.4. Variability and Consistency Analysis

Variability and consistency analysis was performed to evaluate how stable the participant's upper limb movement patterns were across the analysed artistic swimming positions. While mean values describe the general movement characteristics of each position, variability measures provide additional information about the repeatability of hand speed, cycle timing, and elbow joint motion during support sculling.

Hand speed variability differed between positions (Fig. 39). The Vertical position showed the highest hand speed standard deviation for both limbs ($0.68\ m/s$), while the Knight Right position showed the lowest hand speed variability ($0.43\ m/s$). This indicates that the magnitude of hand speed fluctuation changed according to body position. In general, the Knight positions showed lower hand speed variability than the Vertical and Fishtail positions, suggesting a more restricted hand movement pattern during these positions.

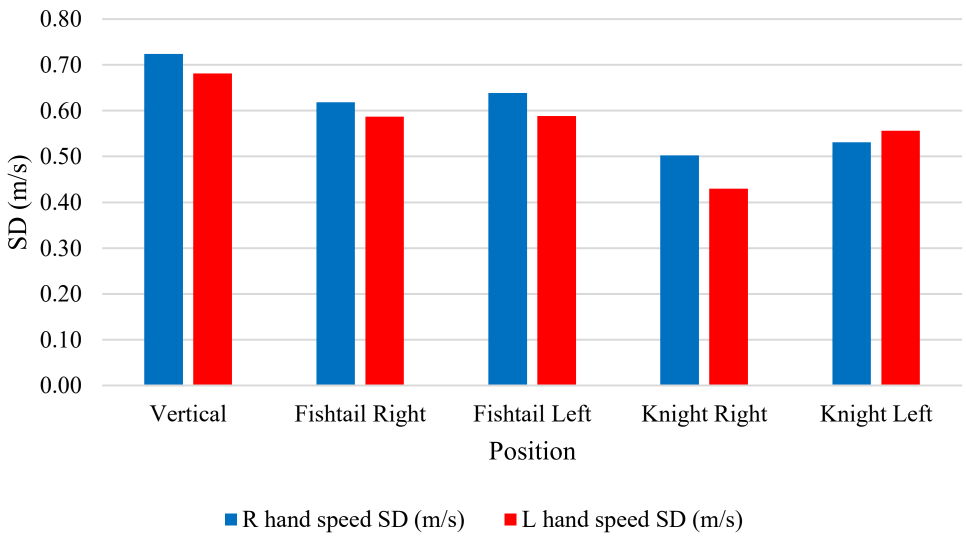


Fig. 39. Comparison of hand speed variability across analysed positions.

Cycle duration variability was used to assess the consistency of sculling rhythm (Fig. 40). The Vertical and Fishtail Right positions showed the lowest cycle asymmetry ($0.05\ s$) and relatively stable cycle timing between limbs. In contrast, the Knight positions demonstrated greater differences in cycle duration between the right and left sides, especially in the Knight Left position ($0.170\ s$). This suggests that maintaining symmetrical timing became more challenging in the Knight configurations.

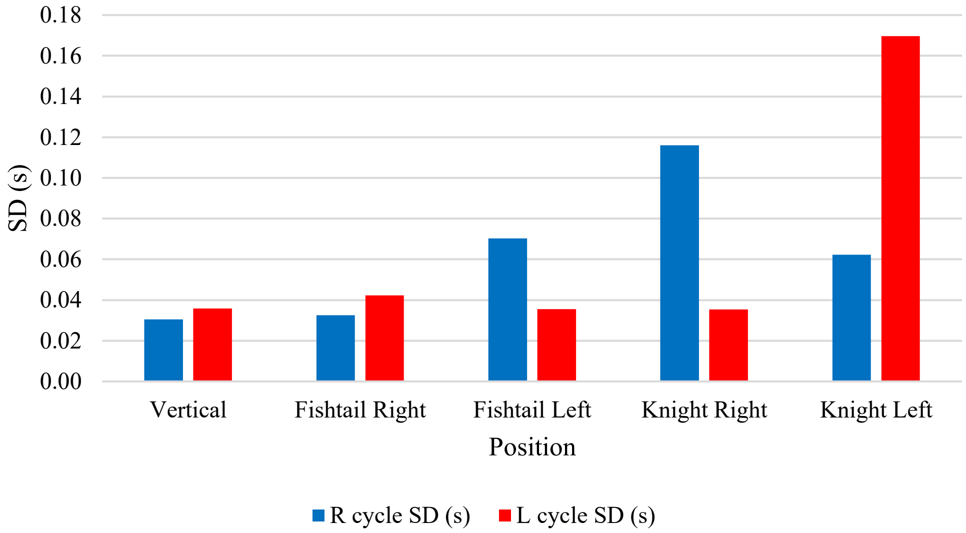


Fig. 40. Comparison of cycle duration variability across analysed positions.

Elbow angle variability also differed between positions (Fig. 41). The greatest variability was observed in the Fishtail Left position, where elbow angle standard deviation exceeded 38° for both limbs. In contrast, the Knight positions demonstrated the lowest elbow angle variability, with values of approximately $18 - 23°$. These results suggest that elbow movement was more restricted in the Knight positions, while the Fishtail positions showed larger fluctuations in joint configuration during support sculling.

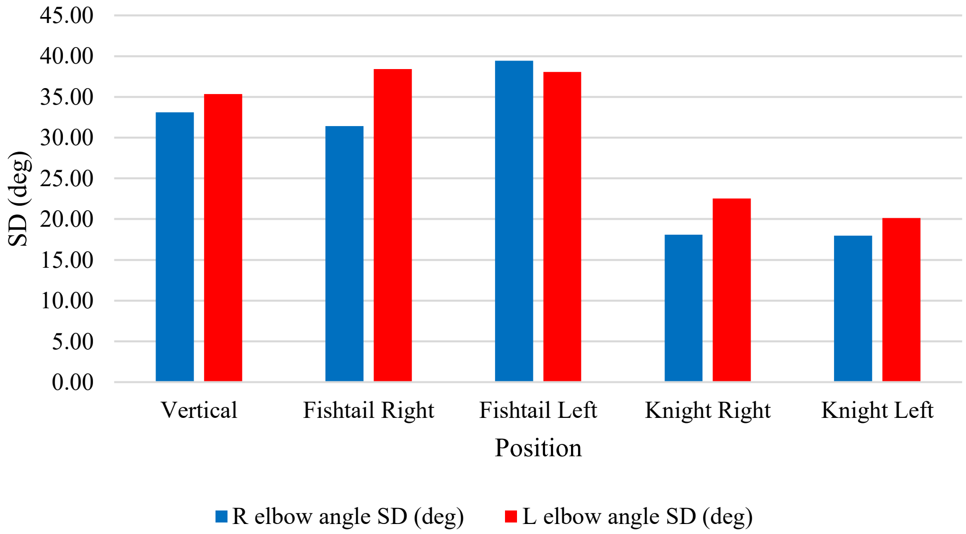


Fig. 41. Comparison of elbow angle variability across analysed positions.

The combination of speed, cycle, and elbow angle variability shows that movement consistency did not change in the same way for all variables. For example, the Knight positions showed lower elbow angle variability, but greater cycle timing asymmetry. Therefore, lower variability in one variable should not automatically be interpreted as better movement control. In the Knight positions, reduced elbow angle variability most likely reflected a more constrained joint movement strategy, while increased cycle variability indicated less consistent temporal coordination between limbs.

Overall, the variability analysis showed that body position influenced the consistency of upper limb mechanics during support sculling. The Vertical position demonstrated the most balanced right-left coordination and stable temporal structure, while the Fishtail positions showed greater elbow movement variability. The Knight positions showed more restricted elbow motion but greater timing asymmetry, indicating that different body configurations required different upper limb coordination strategies.

3.5. Summary of Key Findings

The analysis showed clear position-dependent differences in upper limb sculling mechanics across the five analysed artistic swimming positions. The Vertical position demonstrated the highest average hand speed and the most balanced right-left movement pattern. Mean hand speed in the Vertical position was approximately $1.77\ m/s$, with very small speed asymmetry between limbs ($0.020\ m/s$). This indicates that the Vertical position showed the most symmetrical support sculling pattern among the analysed positions.

The Fishtail positions showed moderately lower hand speed compared with the Vertical position. Average hand speed was approximately $1.63\ m/s$ in Fishtail Right and $1.62\ m/s$ in Fishtail Left, representing an approximate 8% decrease compared with the Vertical position. However, the Fishtail Right position showed noticeably greater elbow angle asymmetry (13.02°) compared with the Vertical and Fishtail Left positions. This shows that, although hand speed remained relatively high in the Fishtail positions, asymmetric body configuration influenced upper limb joint positioning.

The Knight positions demonstrated the lowest hand speed values. Average hand speed was approximately $1.16\ m/s$ in Knight Right and $1.17\ m/s$ in Knight Left, representing an approximate 34% decrease compared with the Vertical position. This suggests that the Knight positions required a more constrained support sculling strategy, with lower distal upper limb movement speed compared with the Vertical and Fishtail positions.

Cycle duration remained relatively similar across most positions, generally ranging from approximately $0.64\ s$ to $0.69\ s$, corresponding to a cycle rate of approximately $1.44 - 1.56\ Hz$. This indicates that the main differences between positions were not primarily related to sculling rhythm, but rather to hand speed, elbow joint configuration, and right-left asymmetry.

The greatest speed asymmetry was observed in the Knight Left position ($0.235\ m/s$), followed by Knight Right ($0.177\ m/s$) and Fishtail Right ($0.156\ m/s$). The smallest speed asymmetry occurred in the Vertical position ($0.020\ m/s$). Therefore, the Vertical position can be interpreted as the most symmetrical condition in this dataset, while the Knight positions created greater right-left differences in support sculling mechanics.

Elbow angle also varied between positions. The lowest average elbow angles were observed in the Knight positions, especially Knight Left at approximately 99.3°, while the Fishtail positions showed larger elbow angles, averaging approximately $117°$. This suggests that the participant used a more flexed elbow configuration during Knight positions and a more extended elbow configuration during Fishtail positions.

Overall, the results indicate that body position influenced upper limb sculling mechanics in the analysed participant. The Vertical position showed the most symmetrical and temporally stable pattern, the Fishtail positions showed moderate asymmetry with relatively high hand speed, and the Knight positions showed lower hand speed, greater right-left asymmetry, and more constrained elbow mechanics.

3.6. Comparison of Results with Previous Studies

Prior research has reported that support sculling is used to maintain inverted positions and that hand and forearm movements generate upward fluid forces needed to balance the swimmer's vertical load [1]. In this study, the Vertical Position demonstrated the smallest right-left differences in hand speed and cycle duration, which supports the interpretation that symmetrical body alignment is associated with a more balanced support sculling pattern.

Previous research on body stability and support scull kinematics has shown that upper limb sculling plays an important role in maintaining body alignment during artistic swimming positions [17]. In this project, the Vertical position showed the most stable and symmetrical movement pattern, while the Knight positions showed greater right-left differences in hand speed and cycle timing. These findings are consistent with the idea that changes in body position influence support sculling mechanics and require different upper limb movement strategies.

The importance of the observed right-left symmetry study is also supported by previous research on support scull symmetry and vertical position stability. Maintaining an inverted vertical position has been linked to coordinated upper limb support sculling, while movement asymmetry may affect body stability and movement fluidity [3]. In the present study, the Vertical position showed the lowest speed asymmetry and cycle asymmetry, whereas the Knight positions showed the greatest right-left differences.

The findings of the experiment also agree with previous work showing that support sculling is a cyclic movement characterized by repeated hand and forearm actions [17, 3]. In the analysed trials, cycle duration remained relatively stable across most positions, ranging approximately from $0.64\ s$ to $0.69\ s$. This indicates that the participant maintained a generally consistent sculling rhythm across positions and supports the idea that sculling rhythm is an important component of body-position control in artistic swimming.

Previous biomechanical research has shown that elbow motion contributes to support sculling mechanics and that the elbow does not remain fixed throughout the sculling cycle [17]. In the present study, elbow angle differed between body positions, with lower average elbow angles observed in the Knight positions and higher elbow angles observed in the Fishtail positions. This suggests that the participant adapted upper limb joint configuration according to the mechanical demands of each body position.

Comparison with previous studies shows that the present results are consistent with previous biomechanical findings. The findings agree with existing literature that support sculling is a cyclic upper limb action used to maintain vertical support, that right-left symmetry is important for body stability, and that elbow flexion-extension contributes to sculling mechanics. However, direct numerical comparison with previous studies is limited because previous research used different participants, body positions, sculling types, task intensities, and measurement methods.

Conclusions

1. The scientific literature analysis showed that upper limb movements are essential for maintaining body position, generating propulsion, and ensuring execution quality in artistic swimming. Previous research emphasizes the importance of sculling mechanics, hand speed, cycle rate, elbow joint control, symmetry, and coordination in artistic swimming positions. The literature also showed that video-based kinematic analysis is a practical and widely used method for studying sculling motions, especially when full 3D motion capture or direct force measurement is not applicable. However, the review identified a need for more position-specific analysis of support sculling mechanics, particularly in realistic underwater conditions.

2. The developed methodology was appropriate for this study because it allowed upper limb movement during support sculling to be analysed in realistic conditions. A 2D underwater video-based approach was used, with spatial calibration, manual landmark digitization in Kinovea, and further kinematic variable calculation in Microsoft Excel. Using this method allowed the calculation of hand speed, cycle duration, elbow angle, variability, and right-left asymmetry. Even though the single camera 2D approach does not allow direct force measurement or full 3D motion analysis, it provided a practical, repeatable, and realistic framework for comparative biomechanical analysis.

3. The kinematic analysis revealed clear differences in upper limb movement characteristics between the analysed artistic swimming positions. The vertical position demonstrated the most symmetrical and coordinated support sculling pattern, with nearly identical right- and left-hand speed values ($1.776\ m/s$ and $1.756\ m/s$ respectively), minimal speed asymmetry ($0.020\ m/s$), and stable cycle timing (cycle asymmetry being $0.002\ m/s$). Fishtail positions showed slightly lower hand speed (right hand average – $1.644\ m/s$, left hand average – $1.607\ m/s$) and position-dependent asymmetry, especially in elbow angle configuration (average angle asymmetry $8.081\ deg$). Knight positions demonstrated even lower hand speed (right hand average – $1.147\ m/s$, left hand average – $1.176\ m/s$), greater cycle asymmetry ($0.045\ s$ average), and more constrained elbow movement, indicating higher stabilization demands. Overall, the results showed that body position influences hand-speed characteristics, rhythm, joint mechanics, and inter-limb coordination during support sculling.

4. The obtained results are consistent with previous studies showing that support sculling is a cyclic upper limb action used to maintain body position and stability in artistic swimming. The higher symmetry observed in the Vertical position agrees with literature emphasizing the importance of coordinated right-left upper limb movement for maintaining stable vertical alignment. In contrast, the increased right-left asymmetry and lower hand speed observed in the Fishtail and Knight positions suggest that asymmetric body configurations require position-specific changes in upper limb movement strategy. These findings support the importance of comparing kinematic results with previous biomechanical research and confirm that hand speed, cycle timing, and elbow joint behaviour provide meaningful information for evaluating technical execution during support sculling.

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Appendices

Appendix 1. Use of generative artificial intelligence tools

ChatGPT [31] was used for language editing and grammar checking of selected thesis paragraphs. Example prompt: “Check this paragraph for grammar, spelling and continuity errors.” All suggestions were reviewed and edited before including the final text in the thesis.