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Advances in the Application of Wearable Inertial Sensors in Swimming Performance Analysis: A Systematic Review

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ADMINISTRATIVE INFORMATION

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Review Stage at time of this submission - Piloting of the study selection process.

Conflicts of interest - None declared.

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Amendments - This protocol was registered with the International Platform of Registered Systematic Review and Meta-Analysis Protocols (INPLASY) on 16 February 2026 and was last updated on 16 February 2026.

INTRODUCTION

Review question / Objective To systematically review English-language studies published between 2020 and 2026 to comprehensively understand the current applications of wearable inertial sensors in swimming training and performance analysis. The review aims to (i) characterize IMU configurations (sensor type, placement, sampling, processing), (ii) map performance outcomes across swimming phases (start, free-swim, turn, finish), (iii) summarize validity/verification approaches against reference methods, and (iv) identify methodological gaps and future directions.
Review Question: How are wearable inertial sensors (IMUs) utilized to assess kinematic and kinetic variables in high-level competitive swimming, and what is the validity of these methods compared to reference standards?

Condition being studied Swimming performance analysis in high-level, elite, or professional swimmers.

METHODS

Participant or population Inclusion: Competitive swimmers described as elite, high-level, or professional (e.g., national or international competitors, members of high-performance squads, or explicitly author-defined elite cohorts).
Exclusion: Studies conducted exclusively in non-competitive or recreational samples; studies involving non-human participants; studies focusing on aquatic exercises other than competitive swimming strokes.

Intervention The use of wearable inertial sensors or Inertial Measurement Units (IMUs) worn on the body during swimming.

Description: Devices must explicitly employ inertial sensing technology, typically consisting of a tri-axial accelerometer, tri-axial gyroscope, and/or tri-axial magnetometer (MEMS technology). These sensors quantify physical signals such as acceleration, angular velocity, and magnetic field intensity.
Scope: Includes sensors used for feedback, performance monitoring, or methodological validation (e.g., algorithm development for stroke phase segmentation).

Comparator Reference methods or criterion measures used for verification and validity assessment.
Examples: Synchronized video-based analysis systems (e.g., high-speed cameras), instrumented speedometers (e.g., Swim-Spektro), or other gold-standard biomechanical measurement tools.
Note: Observational studies describing performance profiles without a direct comparator group are also included if they provide quantitative performance outcomes derived from IMUs.

Study designs to be included Peer-reviewed full-text empirical studies, including validation studies, observational studies, and intervention designs.Excluded: Conference proceedings/ abstracts, theses, dissertations, editorials, narrative reviews, and duplicate publications using the same dataset without additional relevant outcomes.

Eligibility criteria
1. Participants: High-level/professional swimmers (elite cohorts).
2. Intervention: Wearable inertial sensors (IMUs) for performance analysis.
3. Outcomes: Reporting kinematic/kinetic variables relevant to free-swimming and/or start/turn/finish phases.
4. Study Type: Peer-reviewed articles in English (2020-2026).
5. Specific Exclusions: Hardware design papers focusing solely on sensor fabrication without swimmer performance data; studies on non-competitive populations.

Information sources Electronic databases (Web of Science, EBSCOhost, IEEE, PubMed) and manual search of reference lists.

Main outcome(s)
1. Kinematic Variables: Velocity proxies (average speed, intracyle velocity variation), acceleration profiles (peak acceleration), and angular velocity.
2. Temporal-Spatial Parameters: Stroke count, stroke rate/frequency, stroke length (distance per stroke), and lap times.
3. Phase Segmentation: Identification and timing of specific swimming phases (start, glide, swim, turn, finish) based on inertial signal patterns.
4. Validity Metrics: Agreement statistics between IMU data and reference standards, including Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Intraclass Correlation Coefficient (ICC), and Bland-Altman limits of agreement.

Quality assessment / Risk of bias analysis Tool: COSMIN (COnsensus-based Standards for the selection of health Measurement INstruments) Risk of Bias checklist.
Rationale: Since the included studies primarily evaluate the measurement properties (validity, reliability) of IMU-derived outcomes, the COSMIN checklist is the most appropriate tool, as opposed to tools designed for interventions (e.g., Cochrane RoB) or observational studies (e.g., STROBE).
Process: Assessment will be performed independently by two authors.

Strategy of data synthesis Synthesis Type: Structured narrative synthesis.
Justification for No Meta-analysis: Due to the expected high heterogeneity in sensor devices (different manufacturers, specifications), sensor placements (sacrum vs. wrist vs. head), sampling rates (ranging from 30Hz to 500Hz), and data processing algorithms across studies, a quantitative meta-analysis is not feasible or methodologically sound.
Plan: Studies will be qualitatively synthesized and grouped by (i) swimming phase (start, free-swim, turn, finish) and (ii) outcome family (velocity, stroke/ kick count, phase segmentation, coordination). Methodological patterns and consistency of findings will be summarized within these groups.

Subgroup analysis Analysis will be stratified by (i) swimming phase (start, free-swimming, turn, finish) and (ii) sensor placement location (e.g., sacrum vs. extremities) to evaluate how these factors influence measurement accuracy and application utility.

Sensitivity analysis Qualitative sensitivity analysis will be performed by giving greater interpretive weight to studies employing stronger reference standards (e.g., gold-standard synchronized video) and those with lower risk of bias ratings.

Language restriction English.

Country(ies) involved Poland, China, Portugal.

Keywords Swimming; Inertial Sensor; Accelerometer; Gyroscope; Stroke Analysis; Microelectromechanical System; Human Motion MeasurementPoland, China, Portugal.

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