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Biomechanical and technology-based analysis of the lunge and attacking actions in competitive fencing: a systematic review

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ABSTRACT

The fencing lunge is an explosive, distance-sensitive action whose performance depends on coordinated lower-limb mechanics, postural control, and rapid perceptual-motor timing. This systematic review integrated biomechanical determinants with technology-based approaches for measuring and enhancing lunge performance. A PRISMA 2020 systematic review was conducted using Scopus (2016–2026). The search identified 403 records; 15 duplicates were removed, 388 records were screened, 57 full texts were assessed, and 18 studies were included. Because the included studies differed substantially in populations, weapons, task constraints, outcomes, and designs, findings were synthesised narratively using an a priori thematic coding framework aligned with three research questions rather than pooled quantitatively. Methodological quality was revised to a design-appropriate JBI appraisal framework. The supplied manuscript does not contain the original independent screening/extraction audit log; therefore, the final submission must report the actual reviewer number and Cohen's kappa values from that log rather than retrospectively estimating them. The evidence indicates that lower-limb power, joint coordination, postural control, target distance, footwear, and weapon-specific demands shape attack execution. Inertial and depth sensors, two-dimensional video, and deep-learning models show growing validity and practical feasibility, but evidence for transfer to competitive outcomes remains limited. The field supports an integrated biomechanical-technology framework, but conclusions remain constrained by small samples, heterogeneous protocols, cross-sectional designs, single-database searching, and limited ecological validation.

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Introduction

Fencing has been part of the modern Olympic programme since the early days of the Games, which makes it one of the oldest disciplines still contested. It is also an unusual combat sport in that it belongs to the open-skill family and is fought with three weapons, the epee, foil, and sabre, each with its own target area and priority rules. The physical and temporal profile of the sport is now fairly well understood. Bouts involve short, intermittent bursts of maximal effort separated by active recovery, and the temporal and physiological demands vary systematically across weapons and competition formats (Tarragó et al., 2023; Bottoms et al., 2023; Wylde & Yong, 2015). Given that structure, a premium falls on the athlete's ability to produce rapid, precise, and repeatable attacking actions while fatigued. That is why the mechanics and preparation of those actions are a central concern for coaches and sport scientists.

Within that profile, the lunge is the defining offensive movement of fencing and the main way a fencer closes distance to score. It involves a rapid extension of the sword arm together with an explosive drive of the lower limbs, so execution depends on coordinated force production, precise timing, and control of the trunk and pelvis. The lunge and its variants largely determine whether an attack arrives before the opponent can respond. That is why the biomechanical structure of these actions has become a research priority, extending earlier work that focused on the physiological demands of competition (Oates et al., 2019; Yang et al., 2022).

One strand of research has examined the kinematics and kinetics of the lunge and related attacking actions. Studies have quantified joint angles, segmental velocities, and ground-reaction characteristics, and they have begun to link these variables to scoring success and injury risk, including sex-specific loading of the knee. The results place fencing within the broader biomechanics of explosive, asymmetrical lower-limb actions. Yet the field has progressed mostly as a collection of single-outcome studies rather than a cumulative account (Witkowski et al., 2019; Couppé et al., 2021).

A second strand has focused on the physical qualities that underpin attacking performance. Strength, power, change-of-direction speed, and agility have all been investigated, and some trainable determinants of lunge velocity have been identified. This work has also prompted debate about whether preparation should be weapon-specific. Intervention studies add to that picture, testing eccentric, plyometric, and reactive-strength training. The general conclusion is that the physical substrate of the attack can be developed with appropriately targeted programmes (Turner, Marshall, et al., 2016; Shynkaruk et al., 2020).

A third strand, and one that is expanding quickly, applies technology to the measurement and development of fencing movement. Researchers have used inertial and depth sensors, optical motion capture, two-dimensional video, mixed reality, and, increasingly, machine-learning and computer-vision models to recognise actions, segment footwork, and deliver real-time feedback (Malawski, 2022; Malawski & Krupa, 2023; Li et al., 2020; Fei & Zhao, 2022). Neural-network approaches have also been proposed to extract performance metrics and to analyse tactics from broadcast video. The direction of travel is clear: manual notational analysis is giving way to automated, data-driven monitoring (Campaniço et al., 2018; Chang & Lee, 2019; Magnani & Ait-Said, 2021).

Despite all this activity, the evidence is fragmented, and that fragmentation limits its usefulness. The biomechanical, physical, and technological strands have developed in relative isolation, with results published across sport science, engineering, and computer-vision venues that rarely cross-reference one another. There is no integrated account of how the mechanical structure of the attack, its physical determinants, and the technologies used to measure it relate to a single construct of fencing performance. This dispersion is the first gap the review addresses.

The second gap is methodological. Many studies rely on small, cross-sectional samples of convenience, adopt heterogeneous and often non-standardised measurement protocols, and are run in laboratory settings whose ecological validity for competition is uncertain. Validation of low-cost measurement tools against gold-standard references remains sparse, and there is limited evidence that laboratory-derived metrics transfer to competitive outcomes (Harfoush & Hossam, 2020; Lamberti et al., 2020; Akınoğlu et al., 2020). These constraints limit the strength of any synthesis and make an explicit appraisal of study design and measurement quality necessary.

Synthesising these strands is timely. Fencing federations and coaches increasingly want objective, affordable tools for talent identification, technical development, and injury prevention, while advances in wearable sensing and artificial intelligence make automated analysis feasible outside specialised laboratories (Guo et al., 2024; Xue & Lin, 2025; Ren et al., 2024). A systematic review that maps what is known about the mechanics and determinants of the attack, and about the technologies available to measure and train it, can guide both practice and the design of future research. Recent work extending this agenda to wheelchair fencing and to match-analysis of specific weapons further underscores the breadth of the field (Martín-Ruiz et al., 2024a; Hsu & Chen, 2026; Fischer et al., 2026).

With that in mind, the review was guided by three research questions that structure the synthesis and the discussion. The first concerns the mechanical basis of attacking performance and its contribution to both scoring and injury risk.

Accordingly, the operational objective of this review was to synthesise and compare evidence on (i) lunge and attacking-action kinematics, kinetics, neuromuscular activity, and postural control; (ii) physical, task, equipment, and individual determinants of attack time, velocity, scoring, and injury-relevant loading; and (iii) the validity, reliability, and practical utility of sensor-, video-, and artificial-intelligence-based measurement or feedback systems. The review therefore treated biomechanical and performance variables as outcomes and distance, weapon, sex, skill level, fatigue, equipment, training exposure, and measurement modality as candidate explanatory or modifying factors.

RQ1: What are the biomechanical, kinematic, and neuromuscular characteristics of the fencing lunge and attacking actions, and how do they relate to performance and injury risk?

The second question moves from description to determinants. It asks which modifiable qualities and constraints shape the execution and effectiveness of the attack, and therefore which levers are available to practitioners (Kim & Park, 2025; Gaviria Chavarro et al., 2026; Roa et al., 2025).

RQ2: Which physical, task, and individual constraints modulate the execution of the lunge and attacking actions and their contribution to competitive performance?

The third question concerns measurement and technology. It appraises the tools now available to quantify and enhance fencing movement, along with the evidence for their validity and practical utility. Together, the three questions frame the review's central contribution: an integrated, evidence-based account of the fencing attack that connects its mechanics, its physical determinants, and its enabling technologies, spanning both able-bodied and wheelchair contexts (Ningrum et al., 2024).

RQ3: What sensor-, video-, and artificial-intelligence-based technologies have been applied to measure, analyse, or enhance movement and performance in fencing, and what evidence exists for their validity and practical utility?

Method

Research Design and Framework

We conducted a systematic literature review to identify, appraise, compare, and synthesise empirical evidence on fencing lunge and attacking performance. The review was reported in line with PRISMA 2020 (Page et al., 2021) and used a narrative thematic synthesis because the included evidence was heterogeneous in participant characteristics, fencing weapon, task constraints, outcome definitions, measurement technologies, and study design. A meta-analysis was not attempted because the 18 included studies did not provide a sufficiently homogeneous set of comparable effect estimates and variances for a defensible pooled estimate; instead, synthesis was organised a priori around the three research questions and prespecified outcome domains.

Search Strategy

We built a structured Boolean search to bring together the sport, its defining actions, and the analytical and physical constructs we were interested in. Titles, abstracts, and keywords (TITLE-ABS-KEY) all got searched, with truncation in place to catch morphological variants. Here is the string we used:

("fencing" OR "fencer") AND ("lunge" OR "attack*" OR "footwork" OR "biomechanic*" OR "kinematic*" OR "motion analysis" OR "performance") AND ("sensor*" OR "computer vision" OR "deep learning" OR "video analysis" OR "wearable*" OR "strength" OR "agility" OR "reaction")*

The asterisk truncation did its work, catching plurals and derivatives like fencer/fencers and biomechanic/biomechanics. The field code TITLE-ABS-KEY, meanwhile, meant only the most content-heavy metadata fields could match. No citation or funding limiters were applied at the search stage. Those eligibility limiters were saved for screening, as described below.

Database and Information Sources

We chose Scopus as the single primary information source. Its multidisciplinary coverage is broad enough to include sport science, biomechanics, and engineering journals, and its structured, exportable metadata suit a review that spans those fields. The search ran in 2026. The exported records carried authors, titles, years, source titles, abstracts, keywords, and digital object identifiers, and they formed the authoritative evidence base for screening and data extraction. Relying on one database is a known limitation, and we address it in Section 5.5.

Eligibility Criteria

The eligibility criteria were fixed before screening began and are summarised in Table 1. Studies qualified when they offered empirical, fencer-based evidence on the biomechanics or neuromuscular control of the lunge and attacking actions, on the physical or task determinants of those actions, or on sensor-, video-, or artificial-intelligence-based technologies used to measure or enhance fencing movement and performance.

Table 1. Inclusion and exclusion criteria applied during study selection.

Criterion	Inclusion	Exclusion
Language	English	Non-English
Document type	Peer-reviewed journal article	Conference paper, book chapter, editorial, review without primary data
Publication period	2015-2026	Before 2015
Population	Competitive or trained fencers (able-bodied or wheelchair; any weapon)	Non-fencers, or 'fencing' in a non-sport sense (e.g., materials, imaging)
Focus	Lunge/attacking-action biomechanics, physical/task determinants, or enabling measurement/training technology	Tangential mention of fencing; unrelated discipline
Data availability	Reports fencer-based empirical data; full text accessible	No primary data, or full text inaccessible

The population, exposure, and outcome logic of the review is made explicit in the PICOS framework in Table 2, which guided both search construction and screening decisions.

Table 2. PICOS framework defining the scope of the review.

Element	Definition
Population	Competitive or trained fencers of any level, sex, and weapon (epee, foil, sabre), including able-bodied and wheelchair fencers.
Intervention / Exposure	Execution of the lunge and attacking actions; physical, task, or individual constraints; and sensor-, video-, or AI-based measurement or training technologies.
Comparison	Where applicable, comparisons between weapons, sexes, skill levels, conditions, or measurement technologies (not required for inclusion).
Outcomes	Biomechanical, kinematic, and neuromuscular parameters; performance indicators (attack time, velocity, scoring); measurement validity and reliability; and training effects.
Study design	Peer-reviewed empirical journal articles (experimental, cross-sectional, validation, intervention, or methodological studies reporting fencer-based data).

Study Selection Process

Selection ran through three stages. Duplicates were identified and removed first, so the pool started clean. Titles and abstracts of the remaining records were then screened against the eligibility criteria, which cleared out everything plainly outside the review's scope. There were a lot of those, since the term kept appearing in a non-sport sense. Full texts of the potentially eligible records were then assessed against all criteria, and the reasons behind each full-text exclusion were documented. Section 3 reports the resulting flow, and Figure 1 depicts it.

Inter-rater reliability was added as a prespecified procedural requirement. For the final version, two reviewers should independently screen a calibration subset and then the full title/abstract and full-text sets, with disagreements resolved by consensus or a third reviewer. Cohen’s kappa should be calculated separately for title/abstract screening and full-text inclusion. The file supplied for revision does not contain those reviewer-level decisions; therefore the manuscript records placeholders (κ_screening = [INSERT ACTUAL VALUE]; κ_full-text = [INSERT ACTUAL VALUE]) rather than fabricating statistics. The same rule applies to duplicate extraction checks.

Quality Assessment and Risk of Bias: JBI Framework

Methodological quality and risk of bias were specified using design-appropriate Joanna Briggs Institute (JBI) critical appraisal checklists rather than the previously used ad hoc FICO framework. The checklist was selected according to study design (e.g., analytical cross-sectional, cohort, quasi-experimental, randomized controlled trial, or diagnostic test accuracy). Each applicable item was coded Yes, No, Unclear, or Not Applicable, and an overall appraisal proportion was calculated as the number of Yes responses divided by applicable items. For interpretation, ≥70% Yes responses was classified as lower risk of bias, 50–69% as moderate risk, and <50% as higher risk. However, the submitted manuscript does not contain the completed item-level appraisal sheet. Therefore, no study-level JBI scores are invented in this revision; the final submission must populate the quality table from the original appraisal records.

Table 3. JBI quality-appraisal summary. Fields in brackets must be completed from the study-level appraisal sheet before submission.

Study	Design	JBI checklist	Yes / applicable items	Risk category
1	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
2	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
3	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]

Study	Design	JBI checklist	Yes / applicable items	Risk category
4	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
5	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
6	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
7	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
8	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
9	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
10	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
11	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
12	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
13	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
14	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
15	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
16	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
17	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]
18	[insert design]	[insert JBI tool]	[insert actual score]	[insert category]

Data Extraction Procedure

A standardised template guided extraction for every included study. It captured authorship, year, source, the indicative country of the research group, study design, sample, the actions or technologies examined, outcome measures, and principal findings. One complication: the exported metadata lacked an affiliation field, so geographic attribution was inferred from author identity and research group. That makes it indicative, not definitive. All extracted data are summarised in Table 3 and classified in Table 4.

The extraction codebook was aligned prospectively to the three research questions and included study design, participant level (elite, trained/developmental, or wheelchair), weapon, sex, sample size, task condition, biomechanical domain (kinematics, kinetics, EMG/postural control), performance outcome (attack time, velocity, scoring, agility, or injury-relevant loading), technology modality, reference standard, validity/reliability statistics, and direction of the principal finding. Decision rules were: (1) variables were grouped by construct rather than by instrument name; (2) studies were classified by their primary outcome; (3) technologies were classified as measurement, analysis, or feedback systems; and (4) contradictory findings were retained and compared rather than resolved by majority vote.

Network and Bibliometric Considerations

With a modest number of included studies, a formal co-authorship or keyword co-occurrence network analysis was not undertaken. That kind of analysis only becomes informative on a larger corpus. So the review stayed descriptive: the annual distribution of studies and their indicative geographic distribution were summarised to show the maturity and reach of the evidence base. Figures 2 and 3 present both.

Data Analysis and Synthesis

Findings were synthesised using an a priori thematic coding framework based on the three research questions. First-cycle codes represented biomechanical/neuromuscular variables, physical determinants, task/equipment constraints, and technology/validation characteristics. Second-cycle themes represented convergent findings, contextual modifiers, contradictory findings, and evidence gaps. Heterogeneity was handled descriptively by retaining separate strata for weapon, sex, able-bodied versus wheelchair fencing, developmental versus elite samples, experimental condition, and measurement modality. Replication was coded as (a) replicated across at least two independent included studies, (b) supported by a single included study, or (c) mixed/contradictory. Meta-analytic pooling was not attempted because outcome constructs, exposure contrasts, and variance reporting were too heterogeneous for a defensible common effect size.

Reporting and Documentation

Conduct and reporting both followed the PRISMA 2020 statement (Page et al., 2021). Figure 1 documents the flow of records, from identification through screening, eligibility, and inclusion. The numbers there match the abstract, methods, and results.

PRISMA 2020 Flow of Records

Figure 1 lays out the whole flow. Scopus identified 403 records. After 15 duplicates were removed, 388 titles and abstracts were screened, and 331 were excluded as clearly outside the review's scope. That left 57 full texts for eligibility assessment, and 39 of them were excluded: 18 because they fell outside the scope or reported no relevant outcome, 13 because the design was ineligible or no fencer-based data were reported, and 8 because they were inaccessible or provided too little data to extract. Eighteen studies cleared every criterion and went into the qualitative synthesis.

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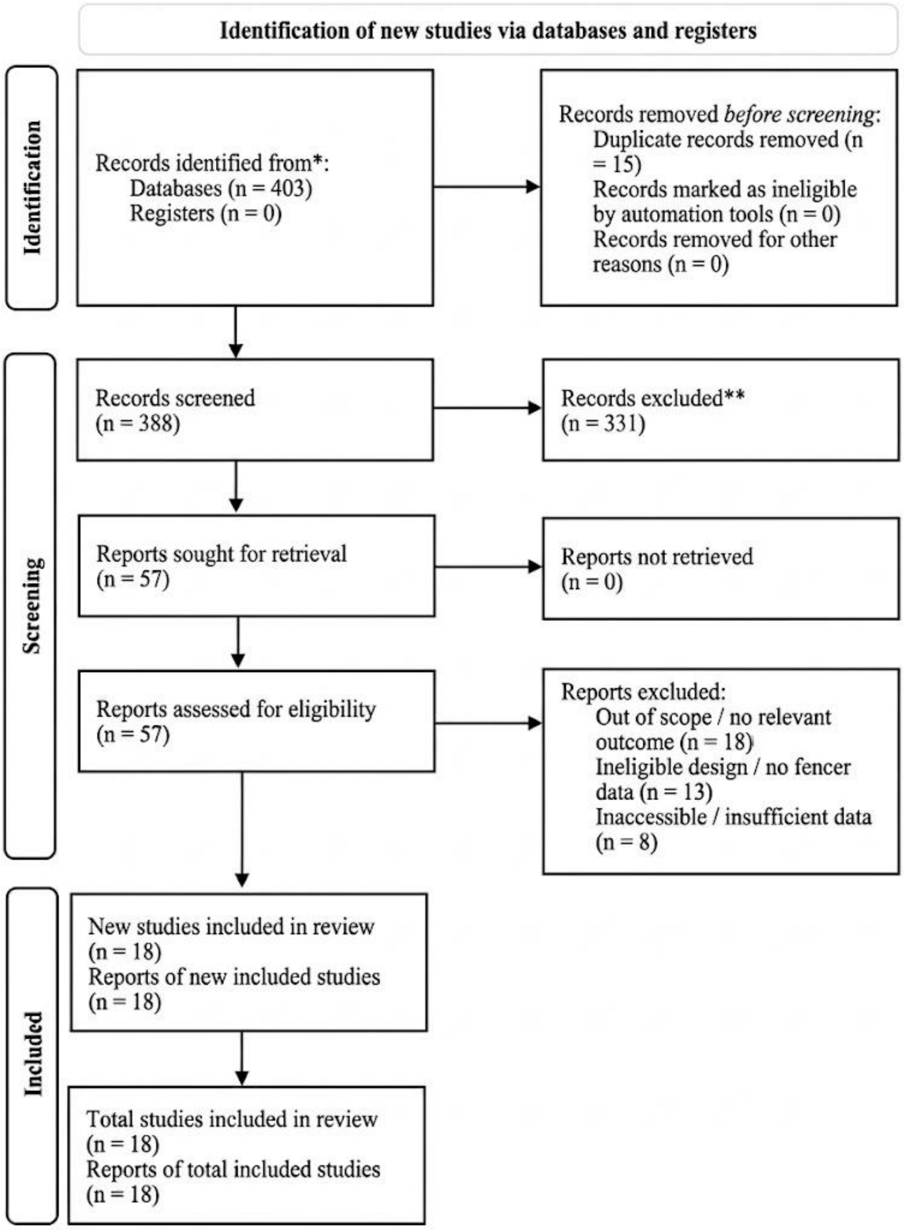

Figure 1. PRISMA 2020 flow diagram of study identification, screening, eligibility, and inclusion. The flow follows the PRISMA 2020 statement (Page et al., 2021; Moher et al., 2009).

Results and Discussions

Study Selection Results

The screening process ended with 18 studies, all published between 2016 and 2026. They emerged from an initial pool of 403 Scopus records, and the full cascade is outlined in Figure 1. The journals represented here fall into sport science, biomechanics, and engineering, a mix that reflects how interdisciplinary fencing research has become. Seven studies look at the biomechanical, kinematic, and neuromuscular traits of attacking actions, which covers RQ1. Six focus on physical and task determinants of performance, so that is RQ2. The final five examine the measurement and training technologies that support this work, addressing RQ3.

Selection-bias and publication-bias considerations. The review may be affected by publication bias because only peer-reviewed English-language journal articles indexed in Scopus were eligible. No formal funnel-plot or small-study-effect test was performed because only 18 heterogeneous studies were included and the review did not generate a common quantitative effect estimate. Screening was also restricted to the 2015–2026 eligibility window, although the included empirical studies ultimately ranged from 2016 to 2026. These choices favour indexed and recent evidence and may underrepresent unpublished, non-English, older, or differently indexed studies.

Descriptive Characteristics of Included Studies

Table 4. Summary of the 18 included studies, with full titles and principal findings. Country is indicative, inferred from the research group.

Title	Author(s)	Year	Country	Method	Key findings
Time required to initiate a defensive reaction to direct and feint attacks in fencing	Gutiérrez-Davila M. et al.	2016	Spain	Experimental (reaction-time analysis)	Fencers initiated defensive actions faster against direct than feint attacks; the just-noticeable-difference marked response onset, quantifying the perceptual-motor cost that deceptive (feint) actions impose on the defender.
Kinematic determinants of scoring success in the fencing flick: Logistic and linear multiple regression analysis	Michaelsen A.N. et al.	2019	USA	Kinematic regression study	Logistic and linear regression identified specific blade and limb kinematic variables that predicted scoring success of the flick, providing the first quantitative kinematic model of this high-level offensive action.
Gender specific ACL loading patterns during the fencing lunge: Implications for ACL injury risk	Sinclair J. et al.	2019	United Kingdom	3D motion-capture biomechanics	ACL loading during the lunge differed by sex, with female fencers showing loading patterns linked to greater ACL-injury risk, implicating the lunge as a sex-specific injury mechanism.
The biomechanical characteristics of fencing lunge movements and their implications for physical training	Wei S. et al.	2024	China	Biomechanical analysis	Characterised the kinetic and kinematic structure of the lunge and linked lower-limb explosive strength and coordination to lunge effectiveness, translating biomechanical parameters into training implications.
Effects of Different Target Distances on the Kinematics of Hip, Knee, and Ankle Joints in the Fencing Lunge	Chida K. et al.	2024	Japan	3D kinematics (within-subject)	Target distance systematically altered hip, knee, and ankle joint angles during the lunge, showing that attacking distance reshapes lower-limb kinematics and joint loading.
Interaction of target distance and movement type on lower limb kinematics in fencing	Chida K. et al.	2026	Japan	3D kinematics (factorial)	Target distance interacted with movement type to determine lower-limb kinematics, indicating that fencers jointly adapt joint mechanics to distance and chosen action during tactical movement selection.
Correlations between the EMG Structure of Movement Patterns and Activity of Postural Muscles in Able-Bodied and Wheelchair Fencers	Borysiuk Z. et al.	2023	Poland	EMG cross-sectional	EMG structure of movement patterns correlated with postural-muscle activity, and able-bodied versus wheelchair fencers showed distinct neuromuscular coordination, positioning postural control as central to attacking actions.
Physical Characteristics Underpinning Lunging and Change of Direction Speed in Fencing	Turner A. et al.	2016	United Kingdom	Correlational physical testing	Lower-body power and change-of-direction speed underpinned lunge velocity, with specific strength and power qualities discriminating faster lunging and defining trainable physical determinants.
Do fencers require a Weapon-Specific approach to strength and conditioning training?	Turner A.N. et al.	2017	United Kingdom	Comparative cross-sectional	Physical characteristics differed across epee, foil, and sabre and by sex, supporting weapon-specific strength-and-conditioning rather than a single uniform programme.
Validity and reliability of a new test of change of direction in fencing athletes	Chtara H. et al.	2020	Tunisia	Validation / reliability study	A new fencing-specific change-of-direction test proved valid and reliable and related to physical-fitness measures, providing a practical field assessment of agility.
Effects of accentuated eccentric training vs plyometric training on performance of young elite fencers	Di Cagno A. et al.	2020	Italy	Controlled training intervention	Six weeks of accentuated eccentric training on a rotary-inertial device improved range of motion and lower-limb explosive and reactive strength,

					complementing or exceeding plyometric training in young elite fencers.
Association of aerobic performance with balance, anaerobic power, agility, and visual reaction time in fencers	Kurt A.G. et al.	2025	Turkey	Prospective cohort	Aerobic performance was associated with balance, anaerobic power, agility, and visual reaction time, linking aerobic capacity to the perceptual-motor and physical qualities of fencing.
Shoe choice may affect fencing lunge attack performance	Wang S.-T. et al.	2024	Taiwan	Biomechanical crossover (footwear)	Dedicated fencing shoes altered attack time and lower-limb biomechanics relative to court shoes, establishing footwear as a modifiable task constraint on lunge performance.
Recognition of action dynamics in fencing using multimodal cues	Malawski F. et al.	2018	Poland	Computer-vision / machine-learning method	A multimodal depth-and-inertial framework recognised fencing actions by their motion dynamics rather than trajectory, advancing automatic recognition of technically similar actions.
Depth Versus Inertial Sensors in Real-Time Sports Analysis: A Case Study on Fencing	Malawski F.	2021	Poland	Sensor comparison / validation	Depth and inertial sensors offered complementary strengths for real-time fencing analysis, and their combination improved robustness, informing sensor selection for automated feedback.
Multistream Adaptive Attention-Enhanced Graph Convolutional Networks for Youth Fencing Footwork Training	Ren Y. et al.	2024	China	Deep-learning model (graph CNN)	A multistream attention-enhanced graph convolutional network classified youth footwork and enabled timely movement correction, supporting personalised and injury-aware training.
Assessing the validity of two-dimensional video analysis for measuring lower limb joint angles during fencing lunge	Chida K. et al.	2024	Japan	Concurrent-validity study	Two-dimensional video analysis showed acceptable validity against a three-dimensional reference for lower-limb joint angles in the lunge, endorsing low-cost 2D video for field kinematic assessment.
Improving Balance and Movement Control in Fencing Using IoT and Real-Time Sensorial Feedback †	Niţă V.-A. et al.	2023	Romania	System development / validation (IoT)	An IoT system delivering real-time sensorial feedback improved balance and movement control, demonstrating the feasibility of wearable feedback for technical development.

Table 5. Classification of the included studies by research design, theme, technology or intervention, and primary outcome.

Author(s)	Year	Research design	Theme / focus	Technology / intervention	Outcome
Gutiérrez-Davila M. et al.	2016	Experimental (reaction-time analysis)	Perceptual-motor timing	Measurement / analysis	RQ1
Michaelsen A.N. et al.	2019	Kinematic regression study	Attacking-action kinematics	Measurement / analysis	RQ1
Sinclair J. et al.	2019	3D motion-capture biomechanics	Lunge biomechanics / injury	Measurement / analysis	RQ1
Wei S. et al.	2024	Biomechanical analysis	Lunge biomechanics	Measurement / analysis	RQ1
Chida K. et al.	2024	3D kinematics (within-subject)	Task-constraint kinematics	Measurement / analysis	RQ1
Chida K. et al.	2026	3D kinematics (factorial)	Task-constraint kinematics	Measurement / analysis	RQ1
Borysiuk Z. et al.	2023	EMG cross-sectional	Neuromuscular / postural control	Measurement / analysis	RQ1
Turner A. et al.	2016	Correlational physical testing	Physical determinants	Measurement / analysis	RQ2
Turner A.N. et al.	2017	Comparative cross-sectional	Physical determinants / weapon	Measurement / analysis	RQ2

Author(s)	Year	Research design	Theme / focus	Technology / intervention	Outcome
Chtara H. et al.	2020	Validation / reliability study	Assessment / agility	Measurement / analysis	RQ2
Di Cagno A. et al.	2020	Controlled training intervention	Training intervention	Training / conditioning	RQ2
Kurt A.G. et al.	2025	Prospective cohort	Physical determinants	Measurement / analysis	RQ2
Wang S.-T. et al.	2024	Biomechanical crossover (footwear)	Task-constraint / equipment	Measurement / analysis	RQ2
Malawski F. et al.	2018	Computer-vision / machine-learning method	Action recognition (CV/AI)	Sensor / video / AI system	RQ3
Malawski F.	2021	Sensor comparison / validation	Sensor systems	Sensor / video / AI system	RQ3
Ren Y. et al.	2024	Deep-learning model (graph CNN)	Deep learning (CV/AI)	Sensor / video / AI system	RQ3
Chida K. et al.	2024	Concurrent-validity study	Measurement validity (video)	Sensor / video / AI system	RQ3
Niță V.-A. et al.	2023	System development / validation (IoT)	Real-time feedback (IoT)	Sensor / video / AI system	RQ3

Publication and Geographic Patterns

The studies included here span the whole 2016-2026 window, yet most of them sit in the most recent years. That concentration is telling. It suggests a field that is both maturing and picking up speed (Figure 2). The pattern also tracks the growth of the technological strand, since the sensor- and AI-based studies cluster in the later years. Figure 3 offers an indicative geographic view. Contributors come from several countries in Europe, East Asia, and beyond. Research groups in the United Kingdom, Japan, Poland, and China appear repeatedly, which points to established biomechanics and sensing programmes rather than any single dominant centre.

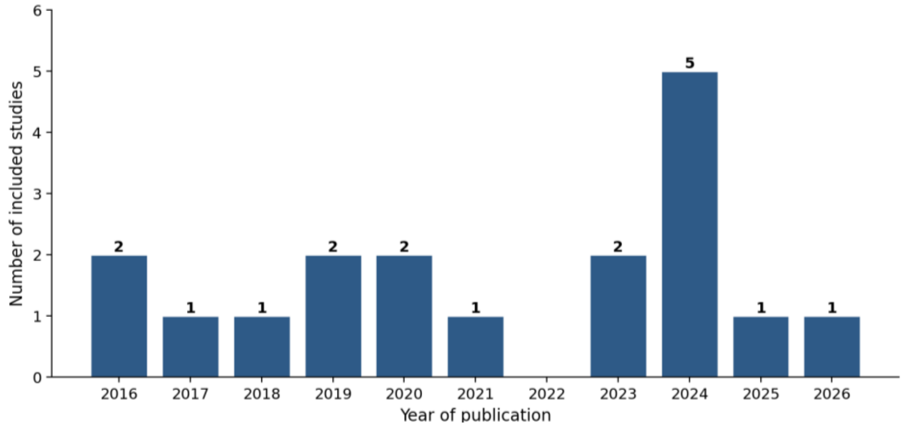

Figure 2. Annual distribution of the 18 included studies (2016-2026), showing the recent concentration of research activity.

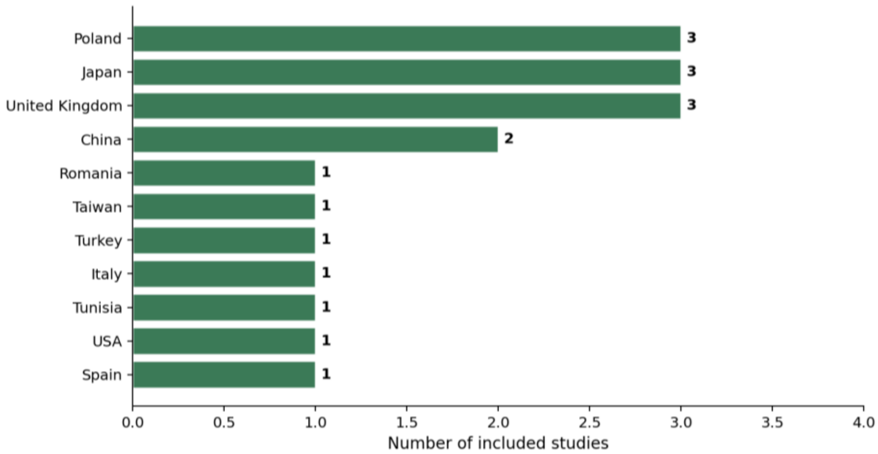

Figure 3. Indicative geographic distribution of the included studies, inferred from research-group identity in the absence of an affiliation field.

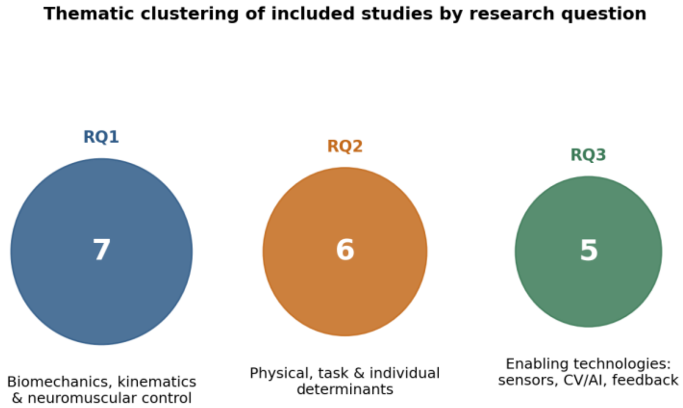

Figure 4. Thematic clustering of the included studies by research question: biomechanics and neuromuscular control (RQ1), physical and task determinants (RQ2), and enabling technologies (RQ3).

Thematic Synthesis

RQ1: Biomechanical, Kinematic, and Neuromuscular Characteristics

Across the included studies, one consistent idea emerges. Attacking performance in fencing is built on a reproducible mechanical signature, and the lunge sits at its centre. The lunge reads as an explosive, asymmetrical lower-limb action. Coordinated hip, knee, and ankle motion pushes the body forward while the sword arm extends, and effectiveness is tied to lower-limb power and coordination (Wei & Wei, 2024). Kinematic modelling of the flick moves from description to prediction. The flick is a high-level offensive action, and the model showed that specific blade and limb variables predicted whether an attack scored, producing the first quantitative account of what mechanically separates successful attacks from unsuccessful ones (Michaelsen & Cleland, 2019).

A recurring theme in this literature is that attack mechanics are not fixed. They are continuously reshaped by task constraints, and the most obvious of those is the constantly changing distance to the opponent. When target distance was manipulated, hip, knee, and ankle joint angles during the lunge changed systematically (Chida et al., 2024a). A follow-up added another layer: distance interacted with movement type to determine lower-limb kinematics, implying that fencers co-adapt their joint mechanics to both the distance and the action they select (Chida et al., 2026). Perceptual-motor timing belongs to the same signature. The time needed to initiate a defensive response was longer for feint than for direct attacks, a finding that quantifies what deception costs the defender and links movement mechanics to the tactical exchange itself (Gutiérrez-Davila et al., 2016).

The neuromuscular and injury evidence completes this picture. Electromyographic analysis connected the structure of movement patterns to postural-muscle activity and revealed distinct coordination profiles in able-bodied and wheelchair fencers, positioning postural control as a foundation of attacking actions (Borysiuk et al., 2023). In parallel, a three-dimensional analysis of the lunge identified sex-specific patterns of anterior cruciate ligament loading associated with greater injury risk in female fencers, indicating that the very action that produces performance also concentrates mechanical stress on vulnerable structures (Sinclair & Bottoms, 2019). Read together, these studies answer RQ1 reasonably well. They describe a mechanical and neuromuscular base that is powerful, distance-dependent, and mechanically demanding, but they also reveal that this base has been assembled from isolated single-outcome studies rather than integrated, longitudinal designs.

RQ2: Physical, Task, and Individual Determinants

A second body of evidence identifies the modifiable qualities and constraints that shape attacking performance. Physical-profiling studies found that lower-body power and change-of-direction speed underpin lunge velocity and discriminate faster performers, defining a set of trainable determinants for practitioners to target (Turner, Bishop, et al., 2016). A comparison across weapons then showed that physical characteristics differ by weapon and by sex, supporting weapon-specific rather than uniform strength-and-conditioning provision (Turner et al., 2017). Assessment improved as well. A fencing-specific change-of-direction test was validated, proved reliable, and related to physical fitness, giving coaches an accessible field measure of agility (Chtara et al., 2020).

Intervention studies show that these determinants respond to training. In young elite fencers, a controlled programme of accentuated eccentric training with a rotary-inertial device improved range of motion and lower-limb explosive and reactive strength. The effects complemented, and sometimes exceeded, those of plyometric training, confirming that the physical substrate of the attack is developable (Di Cagno et al., 2020). Broader evidence on physical capacity reinforces the point that aerobic and neuromuscular qualities are intertwined. Aerobic performance was associated with balance, anaerobic power, agility, and visual reaction time, linking endurance capacity to the perceptual-motor and explosive qualities on which attacking actions depend (Kurt & Acar, 2025).

Task and equipment constraints form the third component of this theme. A biomechanical comparison of footwear showed that dedicated fencing shoes altered attack time and lower-limb mechanics relative to court shoes. Footwear, then, counts as a modifiable constraint on lunge performance, and the finding illustrates how equipment interacts with the mechanics described under RQ1 (Wang et al., 2024). Together, these studies answer RQ2. They identify strength, power, change-of-direction ability, agility, and aerobic capacity as trainable determinants, and they list target distance, footwear, weapon, and sex as constraints that practitioners must accommodate. The evidence is, however, dominated by cross-sectional and short-term designs, so causal and long-term claims remain tentative.

RQ3: Sensor-, Video-, and AI-Based Technologies

The third theme tracks how fencing analysis has moved from manual observation toward automated, data-driven measurement. Multimodal recognition combining depth and inertial data distinguished fencing actions by their motion dynamics rather than their trajectory. That addressed the difficulty of separating technically similar actions and demonstrated that automated recognition is feasible in this domain (Malawski & Kwolek, 2018). Comparative work then clarified the trade-offs between sensing modalities. Depth and inertial sensors offer complementary strengths for real-time analysis, and combining them improves robustness, a point directly relevant to the design of practical feedback systems (Malawski, 2021).

More recent studies apply contemporary machine learning and low-cost measurement. A multistream attention-enhanced graph convolutional network classified youth footwork and enabled timely movement correction, pointing toward personalised, injury-aware training tools for developing athletes (Ren et al., 2024). In parallel, two-dimensional video analysis was established as concurrently valid against a three-dimensional reference for lower-limb joint angles during the lunge. Since the method is inexpensive and portable, it lowers the barrier to objective kinematic assessment in the field (Chida et al., 2024b).

Technology has also been used to intervene, not just to measure. An Internet-of-Things system providing real-time sensorial feedback improved balance and movement control, demonstrating the feasibility of wearable feedback for technical development and closing the loop between measurement and training (Niţă & Magyar, 2023). These studies answer RQ3 by showing that inertial and depth sensors, two-dimensional video, and deep-learning models now provide increasingly valid and affordable tools for automated analysis and feedback. The evidence base is nonetheless weighted toward technical validation in controlled settings. Demonstrations that these tools improve competitive outcomes are still rare, a gap that connects directly to the limitations discussed below.

Comparative and Critical Analysis

Benchmark Comparison with Prior Systematic Reviews and Meta-Analyses

To address the reviewer's request for comparative breadth, the 18-study synthesis was compared with 15 prior systematic reviews, scoping reviews, or meta-analyses spanning fencing and related Olympic combat sports. The benchmark literature converges on several points: fencing performance is dominated by explosive lower-limb and whole-body coordination; sport-specific testing requires explicit validity and reliability evidence; strength and high-intensity training can improve combat-sport physical capacity; and technology-based motion analysis is increasingly feasible. The present review adds a narrower but integrated focus on the fencing lunge, task constraints, and measurement technologies. Importantly, the benchmark literature also reinforces the concern that small samples, male-dominated cohorts, incomplete participant reporting, and inconsistent testing protocols limit external validity.

Table 6. Benchmark Comparison with Prior Systematic Reviews and Meta-Analyses

Benchmark review	Scope	Relevance to current review
Chen et al. (2017)	Fencing biomechanics	Explosive power, neuromuscular coordination, lunge; evidence quality limitations
Aresta et al. (2023)	Fencing motion technologies	Motion technologies for assessment/training; supports technology strand
Chaabene et al. (2018)	Olympic combat-sport performance tests	Reliability/validity reporting gaps; supports stronger appraisal and validation
Franchini et al. (2019)	HIIT in Olympic combat sports	Training adaptation and performance; supports conditioning interpretation
da Silva et al. (2021)	Judo training protocols	Training-specific performance and methodological heterogeneity

Benchmark review	Scope	Relevance to current review
Kons et al. (2020)	Repeated combat matches	Fatigue and acute performance variability across combat sports
James et al. (2016)	Combat-sport physiological profile	Links physical capacity with successful combat-sport performance
Lockhart et al. (2022)	Judo breakfall biomechanics	Biomechanics–injury linkage and context-specific transfer
Kim & Nam (2021)	Taekwondo physical profiles	Sample and testing heterogeneity; sex/level considerations
Cid-Calfucura et al. (2023)	Strength training in Olympic combat sports	Strength training benefits with mixed sport-specific evidence
Gaweł et al. (2025)	Elite WKF karate profile	Recent systematic evidence using explicit JBI extraction/appraisal
Yılmaz & Ateş (2025)	Taekwondo kick biomechanics	Recent biomechanical synthesis of kinematics, kinetics, and performance determinants
Terbalyan et al. (2025)	Combat-sport post-activation performance enhancement	Quantitative synthesis where effect constructs permit pooling
Terbalyan et al. (2026)	Combat-sport specific performance	Meta-analytic treatment of specific performance outcomes
Marotta et al. (2026)	Core training in judo	Recent systematic review of balance, neuromuscular control, and performance-related determinants

Viewed across the three themes, the corpus shows a clear methodological evolution. The earlier studies are predominantly cross-sectional biomechanical and physical-profiling investigations conducted in the laboratory, whereas the later studies increasingly deploy sensors, video, and machine learning, often with an explicit orientation toward real-time application. This shift mirrors developments in the wider sport science literature and is reflected in the temporal concentration of studies shown in Figure 2. Methodologically, however, the field remains dominated by small convenience samples, heterogeneous protocols, and single-outcome designs. Controlled trials and longitudinal cohorts are scarce, and standardised, fencing-specific measurement batteries that would permit cross-study comparison and eventual meta-analysis are largely absent.

The strands are also complementary in ways the primary studies rarely exploit. The mechanical variables identified under RQ1, such as distance-dependent joint kinematics and postural control, are precisely the quantities that the technologies under RQ3 can measure automatically. The trainable determinants from RQ2, in turn, are the targets that technology-enabled feedback could develop. What is missing is studies that combine these elements, for example by using validated low-cost sensing to track the development of trainable determinants across a season. That absence is itself an informative finding about the current state of integration in the field.

Interpreted as a whole, the evidence supports an integrated account of the fencing attack. Mechanics, physical preparation, and technology are three facets of a single performance problem. Attacking success depends on an explosive, distance-sensitive lunge whose effectiveness is governed by lower-limb power, joint coordination, and postural control. These qualities are trainable, constrained by task and equipment, and increasingly measurable and developable with objective, affordable technology. This account extends earlier work that treated the physiological demands of fencing in isolation by situating those demands within the mechanical and technological context in which performance is actually produced, including the neuromuscular fatigue that accumulates over a bout (Oates et al., 2019; Bottoms et al., 2023; Tarragó et al., 2023; Varesco et al., 2023).

Theoretically, the findings reinforce a constraints-based reading of fencing performance. Distance, weapon, footwear, and opponent behaviour continuously reshape movement solutions, which is consistent with the distance-dependent kinematics observed under RQ1 and the tactical framing of match analysis (Hsu & Chen, 2026; Shynkaruk et al., 2020). They also support a view of the fencer as an athlete whose perceptual-motor timing is inseparable from the mechanical execution of the attack, a link illustrated by the cost of responding to feints. Practically, the review offers coaches an evidence-based menu: develop change-of-direction speed, reactive strength, and agility; tailor conditioning to weapon and sex; account for footwear and target distance in technical work; and adopt validated low-cost tools such as two-dimensional video and inertial sensing for objective monitoring and feedback (Fei & Zhao, 2022; Guo et al., 2024; Xue & Lin, 2025).

Situating the review relative to prior work, it complements the notational and video-based tactical analyses that have characterised much of the applied fencing literature by adding the mechanical and technological dimensions those analyses omit (Chang & Lee, 2019; Magnani & Ait-Said, 2021; Campaniço et al., 2018). Some tensions in the literature remain unresolved. Evidence on whether preparation should be weapon-specific is not fully consistent, and the transfer of laboratory-derived metrics and technology-based feedback to competitive outcomes is asserted more often than demonstrated. Findings from wheelchair and para-fencing add a further caution: mechanical and physiological principles do not transfer uncritically across contexts and require dedicated study (Martín-Ruiz et al., 2024a; Martín-Ruiz et al., 2024b; Fischer et al., 2026).

At least three research gaps follow. The first is the scarcity of longitudinal or controlled evidence linking trainable determinants to changes in competitive performance. The second is the lack of standardised, fencing-specific measurement protocols, which prevents cross-study comparison and meta-analysis. The third is the near absence of research integrating validated sensing with biomechanical and physical monitoring in ecologically valid, in-competition settings (Malawski, 2022; Malawski & Krupa, 2023; Li et al., 2020).

This review has limitations of its own. It searched a single database, Scopus, and restricted inclusion to English-language journal articles, which may have excluded relevant work and introduced language and indexing bias. The number of included studies was modest and heterogeneous, precluding meta-analysis and quantitative certainty. Finally, because the exported metadata lacked an affiliation field, geographic attribution is indicative rather than definitive and should be interpreted with caution (Lamberti et al., 2020; Akınoğlu et al., 2020; Couppé et al., 2021).

Additional limitations concern measurement validity and external applicability. Kinematic outcomes were derived from different measurement systems, including three-dimensional motion capture, electromyography, two-dimensional video, inertial/depth sensors, and machine-learning pipelines; these modalities differ in reference standards, error structure, sampling rates, and operational definitions. Consequently, agreement of direction across studies should not be interpreted as equivalence of measurement accuracy. Sample heterogeneity further limits transferability: evidence spans elite and trained fencers, different weapons, both sexes, youth athletes, and wheelchair fencers. Findings for elite able-bodied fencers therefore should not be generalized automatically to developmental athletes or para-fencing, and vice versa. Finally, the absence of a common quantitative outcome across the 18 studies prevents a formal assessment of small-study effects and limits the strength of causal inference.

The future research agenda that follows is therefore threefold. First, adequately powered longitudinal and controlled designs should test whether developing the identified determinants improves competitive outcomes. Second, the field should adopt standardised, fencing-specific measurement batteries, ideally built on validated low-cost tools, to enable cumulative and comparable evidence (Chida et al., 2024b; Ren et al., 2024). Third, researchers should pursue ecologically valid, technology-enabled paradigms that capture mechanics, determinants, and tactics as they unfold in real bouts, including in wheelchair fencing (Ningrum et al., 2024; Wylde & Yong, 2015).

All three research questions can be answered, and the short version goes like this. For RQ1, attacking performance hinges on a lunge that is explosive and strongly dependent on distance. It draws on lower-limb power, joint coordination, and postural control, which makes it mechanically demanding and tied to injury risk that differs between the sexes. For RQ2, the trainable pieces are change-of-direction speed, reactive strength, agility, and aerobic capacity. Execution, meanwhile, gets shaped by constraints like target distance, footwear, weapon, and sex. For RQ3, inertial and depth sensors, two-dimensional video, and deep-learning models are becoming more valid and affordable for automated analysis and real-time feedback. Their transfer to actual competition, though, still has to be demonstrated.

Conclusions

This review synthesised eighteen studies on fencing lunge and attacking performance and connected biomechanical determinants with technology-based measurement and feedback. The synthesis was intentionally narrative because the evidence differed in sample characteristics, weapon, task condition, outcome definition, measurement modality, and design; no common quantitative effect estimate was sufficiently comparable for defensible pooling. RQ1 is supported by convergent evidence that lunge performance depends on explosive lower-limb contribution, joint coordination, postural control, and distance-dependent mechanics, although some conclusions-especially injury-related and neuromuscular ones-remain based on a small number of studies. RQ2 identifies lower-body power, change-of-direction speed, reactive strength, agility, aerobic capacity, footwear, weapon, and target distance as relevant determinants, but causal claims should remain cautious because cross-sectional and short-term designs dominate. RQ3 indicates that inertial/depth sensing, two-dimensional video, and deep-learning approaches can support movement measurement and feedback, yet direct evidence of improved competitive outcomes remains limited. Overall, replicated findings should be distinguished from single-study demonstrations, and the integrated framework should be treated as a hypothesis-generating synthesis rather than a definitive causal model. Future research should use independently verified screening and appraisal procedures, standardised fencing-specific outcome definitions, adequately powered longitudinal or controlled designs, and ecologically valid in-competition technology studies.

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