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Biomechanical analysis of the human body in fitness athletes

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INTRODUCTION

Review question / Objective What are the biomechanical characteristics, methodological innovations, and key factors influencing resistance-exercise performance and safety (e.g., load, range of motion, sex, fatigue, asymmetry) among adult fitness and strength-trained populations as reported in studies from 2015–2025?

Rationale Multi-joint resistance exercises such as squats, deadlifts, Olympic lifts, and bench presses constitute the foundation of strength and conditioning programs and are now widely practiced beyond traditional weightlifting clubs, particularly within high-intensity functional training (HIFT) programs such as CrossFit®. These compound movements are highly effective for developing muscular strength, power, and metabolic conditioning but simultaneously impose considerable mechanical loads on the musculoskeletal system. When performed with

suboptimal technique or under fatigue, these loads can substantially elevate injury risk, emphasizing the importance of biomechanical understanding for both performance optimization and athlete safety.

Biomechanics provides a systematic framework for quantifying human movement by assessing kinematics, kinetics, and muscle activation. Such analyses elucidate how factors including external load, range of motion, fatigue, sex, and individual anthropometrics influence mechanical efficiency, stability, and neuromuscular control during resistance exercise. The resulting insights are essential for evidence-based coaching, technical feedback, rehabilitation, and injury prevention. Over the past decade, the field has undergone rapid technological and methodological advancement. Traditional laboratory-based systems—such as optical motion capture and force plates—have been complemented by wearable sensors, inertial measurement units (IMUs), and portable linear transducers. Concurrently, analytical methods such as statistical

parametric mapping and principal component analysis now allow researchers to examine complex, high-dimensional datasets, thereby extending biomechanical assessments from controlled laboratory settings to ecologically valid training environments.

Despite these advances, recent evidence syntheses remain scarce. Most earlier reviews predate 2015, focusing on single exercises, specific joints, or elite Olympic weightlifters, while overlooking the rapidly growing population of recreational and CrossFit participants performing similar lifts under varied conditions. Consequently, the literature does not yet provide a comprehensive or contemporary overview of how biomechanical principles apply across the spectrum of resistance-based disciplines practiced by modern fitness athletes. This knowledge gap limits the translation of biomechanical evidence into applied training and coaching contexts and constrains the development of strategies to mitigate injury risk or enhance performance in general fitness populations.

Given the expansion of functional training worldwide and the proliferation of new measurement technologies, an updated synthesis is warranted to clarify the biomechanical characteristics of commonly performed resistance exercises. A systematic review encompassing studies published from 2015 to 2025 allows for the inclusion of recent innovations in wearable technology and analytical modeling while capturing the diversity of training settings now represented in biomechanical research. By integrating findings across squats, deadlifts, Olympic lifts, bench presses, and CrossFit workouts, the present study seeks to identify consistent biomechanical patterns, methodological innovations, and emerging applications. Ultimately, such evidence can inform coaches, practitioners, and researchers on how modifiable factors, such as load intensity, range of motion, asymmetry, and fatigue, shape human movement, with direct implications for improving performance, safety, and the design of strength and conditioning programs.

Condition being studied The condition under investigation is the biomechanical demands and adaptations associated with resistance-based and functional fitness exercises, specifically, how mechanical loading, fatigue, and technical variations influence human movement patterns, performance, and injury risk in fitness and strength-trained populations.

This encompasses mechanical and neuromuscular stress experienced during multi-joint resistance exercises (e.g., squats, deadlifts, Olympic lifts, and bench presses) and high-intensity functional training (HIFT) tasks typical of CrossFit®. The review examines how modifiable factors such as load magnitude, range of motion, asymmetry, sex differences, and fatigue alter kinematics, kinetics, and muscle activation, thereby affecting movement efficiency, performance output, and musculoskeletal safety.

In essence, the study addresses the condition of mechanical strain and movement variability inherent to resistance and functional training—an area critical to understanding both performance optimization and injury prevention in athletic and recreational fitness contexts.

METHODS

Search strategy A comprehensive literature search was conducted according to the PRISMA 2020 guidelines across three major electronic databases: PubMed/MEDLINE, Scopus, and Web of Science. These databases were selected for their extensive coverage of biomedical, sports science, and biomechanical research. The search included peer-reviewed studies published between 1 January 2015 and 6 August 2025, ensuring the inclusion of recent technological and methodological advances in biomechanical analysis.

Reference lists of included studies and relevant reviews were manually screened to identify additional eligible publications not captured in the database search.

Only peer-reviewed original research articles written in English were included. Eligible studies were required to:

Involve adult participants (≥ 18 years) engaged in resistance or functional training activities;

Employ biomechanical instrumentation such as motion capture, force plates, electromyography, linear encoders, or wearable sensors; and

Report quantitative kinematic, kinetic, or neuromuscular outcomes related to the selected exercises.

Exclusion criteria were: reviews, theses, case reports, conference abstracts without full data, studies involving pathological or rehabilitative populations, and papers without accessible full texts.

Searches were performed independently by two reviewers, and all records were imported into reference management software for duplicate removal. Titles and abstracts were screened for relevance, followed by full-text evaluation according to predefined inclusion criteria. Discrepancies between reviewers were resolved through discussion or, if necessary, consultation with a third reviewer.

This systematic and transparent search approach ensured comprehensive coverage of the biomechanical literature related to multi-joint resistance and functional fitness exercises across the period of 2015–2025.

Participant or population The review focuses on adult participants (≥ 18 years) engaged in fitness-oriented or resistance-training activities that involve multi-joint exercises commonly performed in strength and conditioning programs. This includes individuals participating in CrossFit®, high-intensity functional training (HIFT), Olympic weightlifting, powerlifting, and traditional resistance training performed in gym or laboratory settings.

Eligible participants encompass a wide performance spectrum, ranging from recreationally trained individuals to competitive strength and fitness athletes. Studies involving both men and women were included, provided participants had prior experience with resistance or functional training exercises sufficient to ensure safe and technically competent performance during testing.

The review explicitly targets healthy, non-pathological populations, as the aim is to synthesize biomechanical data representative of typical training and competition conditions. Therefore, studies focusing on clinical, rehabilitative, pediatric, or elderly populations were excluded, as were those assessing patients with musculoskeletal, neurological, or metabolic disorders.

By concentrating on trained adult participants performing multi-joint resistance and functional exercises under varied loading, fatigue, and asymmetrical conditions, this review captures biomechanical evidence most relevant to practical strength and conditioning environments. The inclusion of both sexes and diverse training backgrounds also allows for the identification of sex-specific or experience-dependent biomechanical adaptations.

Intervention The intervention examined in this review is the application of biomechanical analysis techniques to assess multi-joint resistance and functional fitness exercises performed by adult fitness or strength-trained populations. These interventions involve controlled performance of exercises such as the squat, deadlift, bench press, Olympic lifts (snatch, clean), and CrossFit® workouts, under varying experimental conditions related to load intensity, range of motion, fatigue, and asymmetry.

Eligible studies must have employed objective biomechanical measurement tools to quantify human movement. These include, but are not limited to:

Motion capture systems (optical or infrared-based 3D kinematics),

Force plates and load cells (for kinetic analysis and ground reaction forces),

Surface electromyography (sEMG) (for muscle activation patterns),

Linear position transducers and velocity trackers (for load–velocity profiling), and

Wearable sensors such as inertial measurement units (IMUs) or in-shoe pressure systems (for field-based assessments).

The intervention is not a treatment or training program but a biomechanical assessment approach applied to exercise performance. It encompasses both laboratory-based and field-based analyses designed to evaluate how variations in external load, movement range, fatigue, or asymmetrical loading influence kinematic, kinetic, and neuromuscular outcomes during resistance training tasks.

Comparator The review includes studies that compare different exercise conditions or performance variations within the same population to determine how these factors influence biomechanical outcomes. The comparative interventions are not therapeutic treatments, but rather experimental or methodological manipulations applied to the target exercises.

Typical comparative conditions identified in the included studies involve:

Exercise variation: comparisons between different lifts (e.g., sumo vs. conventional deadlift, weighted push-up vs. bench press).

Load intensity: analyses across multiple relative loads (e.g., 60%, 80%, 100% of 1RM) to evaluate load-dependent kinematic or kinetic adaptations.

Range of motion (ROM): full vs. partial movement execution to assess its effect on sticking points, joint angles, and barbell velocity.

Asymmetrical or unilateral loading: graded differences in load distribution between limbs to study interlimb activation and compensatory mechanisms.

Fatigue conditions: pre- versus post-fatigue assessments within workouts (e.g., CrossFit® sessions performed to volitional failure).

Sex comparisons: male versus female participants to identify normalization effects when controlling for fat-free mass.

Equipment or footwear modifications: for example, heel wedges vs. barefoot squats or lifting shoes vs. standard footwear.

These comparative interventions enable analysis of how technical, mechanical, and physiological variations alter movement mechanics, muscle activation, and force production during resistance and functional training.

Study designs to be included To address the objective of this review, eligible studies include original, peer-reviewed empirical research employing quantitative biomechanical analyses of multi-joint resistance or functional fitness exercises. Given the experimental and measurement-focused nature of biomechanics research, a range of observational and experimental study designs are included to capture diverse methodological approaches. Specifically, the following study types are eligible: Cross-sectional studies, providing between-condition or between-group comparisons of biomechanical variables during specific exercises.

Eligibility criteria In addition to the criteria defined by the PICOS framework, several supplementary parameters were applied to ensure methodological consistency, data quality, and relevance to the study objectives.

Additional Inclusion Criteria

Language: Only studies published in English were included to ensure accurate interpretation of biomechanical terminology and methodological reporting.

Publication Type: Only peer-reviewed full-text journal articles were eligible to guarantee scientific rigor and accessibility of complete methodological details.

Time Frame: Studies published between 1 January 2015 and 6 August 2025 were included to capture the most recent developments in biomechanical measurement and analytical techniques (e.g., wearable sensors, advanced motion analysis).

Instrumentation Requirements: Eligible studies must have employed objective biomechanical tools, such as motion capture systems, force plates, electromyography, linear position transducers, or inertial measurement units (IMUs), to quantify kinematic, kinetic, or muscle activation outcomes.

Exercise Type: Studies must have analyzed multi-joint resistance or functional fitness exercises, including but not limited to squats, deadlifts, Olympic lifts (snatch, clean), bench presses, or CrossFit® workouts performed under typical training conditions.

Information sources To ensure a comprehensive and methodologically rigorous identification of relevant studies, multiple information sources will be systematically searched and reviewed. The search strategy will encompass electronic databases, manual reference screening, and, where necessary, direct contact with study authors to obtain additional information or clarify missing data.

Electronic Databases

Three major academic databases will serve as the primary sources of information: PubMed/MEDLINE, Scopus, and Web of Science. These databases were selected due to their extensive coverage of biomedical, sports science, and biomechanical literature, and their inclusion of journals publishing experimental research in exercise physiology, strength and conditioning, and biomechanics.

The search will include peer-reviewed articles published between 1 January 2015 and 6 August 2025, ensuring the inclusion of recent studies that reflect advances in measurement technology (e.g., wearable sensors, inertial measurement units) and analytical techniques (e.g., statistical parametric mapping, principal component analysis). Searches will be limited to articles published in English.

Each database will be queried using combinations of controlled vocabulary and free-text terms related to three core domains:

Population: “athlete,” “fitness,” “high-intensity functional training,” “CrossFit.”

Biomechanical analysis: “biomechanics,” “kinematics,” “kinetics,” “electromyography,” “force plate,” “wearable sensors.”

Exercise type: “squat,” “deadlift,” “bench press,” “powerlifting,” “weightlifting,” “snatch,” “clean.”

Boolean operators (AND/OR) will be used to connect these concept groups. The final Boolean syntax will be adapted for the indexing structure of each database to maximize sensitivity and specificity.

Supplementary Sources

To identify additional eligible studies not captured by the database searches, the reference lists of all included papers and relevant systematic reviews will be manually screened. This backward citation tracking will help locate studies published in specialized journals or those not yet indexed in major databases at the time of the initial search.

Furthermore, forward citation tracking using tools such as Google Scholar and Web of Science will be conducted to identify newer studies citing key references already included in the review.

Contact with Authors

When essential data are missing, unclear, or only partially reported, corresponding authors of the included studies will be contacted by email to request clarifications or supplementary information (e.g., sample characteristics, measurement protocols, or specific outcome values). If no response is obtained after two follow-up attempts, the available information will be analyzed as reported in the published text.

Grey Literature and Trial Registers

Given the methodological focus on biomechanical analyses rather than intervention trials, grey literature (such as theses, dissertations, and conference abstracts) and trial registers will not be primary information sources. Only peer-reviewed, full-text journal articles will be included to ensure methodological transparency and replicability of biomechanical procedures.

This multi-source strategy—integrating major databases, manual reference screening, and author correspondence—ensures comprehensive coverage of the relevant biomechanical literature

from 2015–2025, while maintaining a focus on data quality, reproducibility, and applicability to strength and functional fitness contexts.

Main outcome(s) The primary outcomes of this systematic review are the biomechanical characteristics of multi-joint resistance and functional fitness exercises, as reported in studies conducted between 2015 and 2025. Specifically, the review aims to synthesize quantitative evidence describing kinematic, kinetic, and electromyographic (EMG) variables measured during exercises such as the squat, deadlift, bench press, Olympic lifts (snatch, clean), and CrossFit® workouts.

Most eligible studies employ cross-sectional or repeated-measures designs, assessing acute biomechanical outcomes within single testing sessions rather than over longitudinal timeframes. Where applicable, effect measures (e.g., mean differences, standardized effect sizes, correlation coefficients, or normalized values to body mass or fat-free mass) will be extracted and summarized narratively due to expected methodological heterogeneity.

Primary Outcomes:

Kinematic variables: joint angles, angular velocities, displacement trajectories, barbell path, and range of motion throughout the movement cycle.

Kinetic variables: ground reaction forces, joint moments, impulse, rate of force development, and mechanical power output.

Neuromuscular activation: surface EMG amplitude, timing, and activation patterns of prime movers and stabilizing muscles.

Additional outcome(s) Performance-related indicators, including barbell velocity, repetition maxima, or load–velocity relationships.

Fatigue-induced biomechanical adaptations, such as changes in movement strategy or joint coordination patterns over time or across repetitions.

Comparative factors, including sex differences, asymmetrical loading effects, and the influence of equipment (e.g., heel wedges, lifting shoes, wearable sensors).

Methodological outcomes, evaluating the reliability and ecological validity of emerging biomechanical

technologies (e.g., inertial measurement units or in-shoe force sensors).

Quality assessment / Risk of bias analysis The methodological quality and risk of bias of all included studies will be evaluated using a modified Downs and Black checklist (Downs & Black, 1998), adapted for observational and experimental biomechanical research. This tool was selected for its applicability to both cross-sectional and intervention-type designs and its ability to assess multiple domains of methodological rigor beyond simple reporting criteria.

The checklist evaluates four key dimensions of study quality:

Reporting quality – assesses the clarity and completeness of descriptions regarding objectives, participants, interventions, outcomes, and main findings. This ensures transparency and replicability of biomechanical methods and results.

External validity – examines the generalizability of findings by evaluating whether the participants, settings, and measurement conditions reflect real-world resistance or functional training contexts.

Internal validity (bias and confounding) – considers methodological safeguards against bias, including participant selection, control of confounding variables (e.g., load normalization, sex, fatigue), reliability of instrumentation, and standardization of protocols.

Statistical power and data analysis – evaluates whether studies report adequate sample size justification, effect sizes, or statistical precision, and whether analyses are appropriate for the type and distribution of biomechanical data.

Each item will be scored as “yes” (1 point), “no” (0 points), or “unclear” (0 points). Total scores will be expressed as a percentage of the maximum possible score, and studies will be classified according to their overall methodological quality:

Low risk of bias: $\geq 70\%$

Moderate risk of bias: 50–69%

High risk of bias: $< 50\%$

Two reviewers will independently assess each study's quality. Disagreements will be resolved through discussion, and if necessary, a third reviewer will adjudicate unresolved discrepancies. Inter-rater agreement will be quantified using

Cohen's kappa coefficient to ensure reliability of the quality assessment process.

Strategy of data synthesis The data analysis will follow a structured, transparent, and reproducible approach designed to synthesize biomechanical evidence across diverse study designs and exercise modalities. Given the heterogeneity of the included studies—encompassing different participant populations, instruments, and outcome measures—a narrative synthesis will be prioritized over quantitative meta-analysis. The primary objective is to identify consistent biomechanical patterns, methodological innovations, and sources of variability influencing performance and injury risk during resistance and functional fitness exercises.

Data Preparation and Extraction

Two independent reviewers will extract all relevant data using a standardized template. Extracted variables will include:

Study characteristics: year, design, country, and sample size.

Participant details: sex distribution, age, training experience, and sport background.

Exercise/task characteristics: exercise type (e.g., squat, deadlift, bench press, Olympic lifts, CrossFit® tasks), loading conditions (e.g., $\%1RM$), and experimental manipulations (e.g., asymmetry, fatigue, footwear, range of motion).

Instrumentation and biomechanical measures: motion capture, force plates, electromyography (EMG), inertial measurement units (IMUs), or linear encoders.

Quantitative results: mean and standard deviation of kinematic, kinetic, and EMG variables, as well as reported effect sizes, correlation coefficients, or p-values.

Disagreements during data extraction will be resolved through discussion or adjudication by a third reviewer. When essential data are missing or unclear, corresponding authors will be contacted for clarification.

Quantitative Synthesis

Whenever comparable outcome metrics are reported across studies (e.g., barbell velocity, joint moments, EMG amplitude), results will be summarized descriptively using ranges, means, and normalized values (e.g., to body mass or fat-free mass). Where possible, effect measures such

as mean differences, standardized effect sizes (Cohen's *d*), or correlation coefficients will be extracted or calculated from available statistics. These values will be presented in summary tables to facilitate inter-study comparison.

Narrative Synthesis

Given expected methodological diversity, results will be analyzed thematically and organized into major exercise categories:

Squat,

Deadlift,

Bench press,

Olympic lifts (snatch, clean), and

CrossFit or high-intensity functional training (HIFT).

Within each category, findings will be compared according to experimental manipulations such as load intensity, range of motion, fatigue status, asymmetrical loading, sex differences, and equipment variation. The synthesis will highlight consistencies in kinematic, kinetic, and neuromuscular patterns as well as contradictions or gaps requiring further investigation.

Integration with Quality Assessment

Study quality, assessed via the modified Downs and Black checklist, will inform interpretation of results. Greater analytical emphasis will be given to studies classified as low risk of bias ($\geq 70\%$), while findings from moderate- or high-risk studies will be discussed with appropriate caution. Methodological limitations—including small sample sizes, lack of normalization procedures, or inadequate control of confounding variables—will be explicitly considered when drawing conclusions.

Presentation of Findings

Data will be visualized in summary tables and figures, detailing study characteristics, biomechanical outcomes, and methodological trends. Where applicable, flowcharts and conceptual diagrams will illustrate the relationships among exercise type, mechanical load, and observed biomechanical adaptations.

This mixed descriptive–narrative analytic strategy will provide a comprehensive synthesis of biomechanical evidence across resistance and functional fitness modalities, enabling identification of the most influential mechanical determinants of

performance and injury prevention in trained adult populations.

Subgroup analysis Given the diversity of exercises, participant characteristics, and biomechanical variables reported in the included studies, subgroup analyses will be conducted to explore patterns and potential sources of heterogeneity. These analyses will allow a more nuanced interpretation of biomechanical adaptations and performance outcomes under different experimental or population-specific conditions.

Subgroup comparisons will be performed at the narrative synthesis level, as the variability in measurement protocols and reporting formats is expected to preclude a formal quantitative meta-analysis. Nevertheless, wherever sufficient data consistency exists, effect estimates or normalized mean differences will be compared across subgroups to identify meaningful trends.

The following subgroup dimensions will be examined:

Exercise Type

Studies will be grouped by the primary task analyzed: squat, deadlift, bench press, Olympic lifts (snatch or clean), and CrossFit®/HIFT workouts.

This distinction enables the identification of exercise-specific biomechanical determinants, such as joint loading patterns or movement strategies unique to each lift.

Load Intensity and Range of Motion (ROM)

Comparisons across relative intensities (e.g., 60%, 80%, 100% 1RM) will be used to evaluate load-dependent changes in kinematics, kinetics, and muscle activation.

Studies manipulating ROM (full vs. partial movement) will be analyzed separately to determine their influence on sticking-point mechanics, barbell velocity, and force production.

Sex Differences

Studies including both male and female participants will be analyzed to explore differences in absolute versus normalized biomechanical outcomes (e.g., power output, velocity, EMG amplitude normalized to fat-free mass).

This will clarify whether observed disparities are primarily due to morphological factors or neuromuscular control strategies.

Fatigue Status

Data from pre-fatigue and post-fatigue conditions will be compared to identify compensatory biomechanical strategies and movement deviations associated with exhaustion, particularly in high-intensity functional training settings.

Asymmetry and Unilateral Loading

Subgroups will be defined based on the magnitude of load asymmetry (e.g., 0%, 2–4%, ≥6%), enabling assessment of thresholds beyond which interlimb imbalance compromises performance or increases compensatory activation.

Measurement Context and Technology

Laboratory-based studies using traditional motion capture and force plates will be contrasted with field-based studies employing wearable sensors (e.g., IMUs, in-shoe force systems) to evaluate ecological validity and technological reliability.

The outcomes of these subgroup analyses will be synthesized narratively and summarized in comparative tables. This approach will facilitate identification of context-dependent biomechanical adaptations, helping to explain variability across studies and to generate hypotheses for future longitudinal or interventional research.

Sensitivity analysis A sensitivity analysis will be conducted to assess the robustness and reliability of the review's findings, particularly regarding the influence of methodological quality, sample characteristics, and data reporting practices on the overall synthesis. Given the expected heterogeneity in study designs and outcome measures, this analysis will be performed primarily through qualitative comparison rather than statistical re-analysis.

The following strategies will be implemented:

Quality-Based Sensitivity Assessment

Studies will be stratified according to their methodological quality, as determined by the modified Downs and Black checklist.

Findings from studies classified as low risk of bias (≥70%) will be compared with those from moderate (50–69%) and high-risk (<50%) studies

to evaluate whether conclusions are driven by lower-quality evidence.

If key biomechanical relationships (e.g., load-velocity or sex differences) remain consistent across quality levels, confidence in the robustness of the evidence will be strengthened.

Sample and Design Sensitivity

Analyses will examine whether findings differ between small-sample studies ($n < 15$) and larger-sample studies ($n \geq 15$), recognizing that small samples are more susceptible to statistical noise and reduced generalizability.

The influence of study design (cross-sectional vs. repeated-measures) on reported biomechanical outcomes will also be explored.

Instrumentation and Measurement Sensitivity

Results derived from laboratory-based instrumentation (e.g., motion capture, force plates) will be compared with those from field-based systems (e.g., IMUs, wearable sensors) to assess whether methodological differences systematically affect outcome estimates such as joint moments or barbell velocity.

Data Reporting and Normalization

Studies that normalize biomechanical data to body mass, limb length, or fat-free mass will be contrasted with those reporting absolute values to determine whether normalization procedures affect interpretability or sex comparisons.

The outcomes of these sensitivity analyses will be summarized narratively and integrated into the discussion. This approach will allow the identification of potential biases, methodological dependencies, or context-specific limitations, thereby enhancing the transparency, reliability, and interpretive validity of the review's conclusions.

Language restriction English.

Country(ies) involved This systematic review is being conducted through a multi-national collaboration involving researchers from Portugal, Cuba, and Brazil, reflecting an international effort to synthesize biomechanical evidence within the field of strength.

Keywords Biomechanics; Resistance Training; CrossFit; Kinematics; Kinetics; Functional Fitness.

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