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Review

A Systematic Review of the Biomechanical Studies on Shoulder Kinematics in Overhead Sporting Motions: Types of Analysis and Approaches

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Abstract: The shoulder is a unique and complex joint in the human body with three bones and four joints, which makes it the most unstable joint in the body due to the amount of motion. To improve approaches toward understanding the performance of overhead throwing movements, this systematic review summarizes the type of analysis related to shoulder biomechanics involving overhead sporting motions. A search of seven databases identified 33 eligible studies, which were subsequently scored using the Modified Coleman Methodology Score scale. A total of nine articles from badminton, seven from baseball, five from volleyball, five from tennis, three from cricket, and one from softball were reviewed. All 33 studies evaluated shoulder kinematics and 12 of them also investigated the forces and torques (kinetics). The most common methods used were 3D motion analysis (76%), digital video cameras (15%), electromagnetic tracking system (6%), and finally 3% used IMU sensors. Overall, shoulder external rotation during the back swing, internal rotation, and elbow extension during the forward acceleration phase were the strongest predictors of high velocity overhead throwing movement. The findings provide some useful insights and guidance to researchers in their future contribution to the existing body of literature on shoulder overhead throwing movement biomechanics.

Keywords: overhead throw; shoulder; biomechanics; kinematics; kinetics

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1. Introduction

Overhead sporting motions can be defined as any motion in which the upper arm and shoulder arc over the athlete's head to hit or propel an object towards the opponent [1]. This includes motions such as the badminton smash, tennis serve, cricket bowling, and the baseball pitch. According to Guinness World Records [2], the fastest projectile speeds in overhead sports recorded include 118.3 m·s^{-1} in the badminton post impact shuttlecock speed in a competition, 73.1 m·s^{-1} in the tennis serve, 44.8 m·s^{-1} in the cricket fast bowl, 44.7 m·s^{-1} in the baseball pitch, and 36.1 m·s^{-1} in the volleyball jump spike. Overhead motions in sport have both a speed and control/accuracy component to achieve success, both of which are reliant on appropriate shoulder movements. Unsurprisingly, shoulder injury rates are high in athletic populations with 18–61% of shoulder injury rates reported among the overhead throwing athletes [1,3], accounting for 12.0% and 13.1% of all high school and college sports injuries in the National Collegiate Athletic Association injury surveillance program [4].

During overhead throwing movements such as pitching in baseball, athletes typically utilize the stretch–shortening cycle with a larger hip–shoulder separation angle (X-factor) during the backswing, followed by trunk forward flexion, rapid shoulder internal rotation, elbow extension, and wrist flexion in a proximal–distal order during the arm acceleration phase to the instant of ball release/impact [5]. The pre-stretch of the active muscles stores elastic energy during eccentric loading and increases muscular force and power output during the final concentric phase of movement [6,7]. Consensus was met among the authors across the literature on the baseball pitch, tennis serve, volleyball spike, and badminton smash, whereby the major contribution to faster ball release/post-impact speed comes from shoulder internal/external rotation [8–13]. Another study reported that shoulder internal rotation contributes around 66% towards the development of racket head speed [14].

Previous studies have reported peak angular velocities as high as 2594°/s in volleyball jump spike [15], 2900°/s in tennis serve [16], 7148°/s in badminton jump smash [10], and 7200°/s in baseball pitching [17,18]. These high angular velocities suggest shoulder internal rotation is important to speed development in overhead sporting motions, although methodological differences mean caution should be taken when comparing across studies on different sporting movements.

The most common testing method for overhead movements is currently 3D motion analysis. Over the decades, the technology to accurately track human motion has developed exponentially and is widely applied in research and field settings. The approaches include capturing video with high-speed cameras, electromagnetic tracking, using wearable sensors such as inertial measurement unit (IMU), and infrared marker-based motion capture system. The evolution of automated marker-less 3D-tracking technology incorporating deep learning algorithms to solve computer vision problems is encouraging, but the accuracy is not well validated yet [19,20]. Three-dimensional motion capture in a laboratory with markers on the performer's body segments tracked using multiple cameras is currently the gold standard to track continuous human motion [21]. In many cases, the continuous movement data are reduced to a number of discrete values for statistical analysis, which excludes potentially valuable information [22]. More recently investigations have identified this limitation and have applied non-linear tools and advanced statistical methods (i.e., Statistical Parametric Mapping) in biomechanical analyses [11,23,24].

To execute even a basic shoulder movement, the muscles around the shoulder joint need to work together, synergistically to create a coordinated movement [25]. In addition to poor technique, muscular imbalance can potentially cause faulty shoulder mechanics, which has been linked to increased risk of shoulder injury [26–28]. The majority of biomechanical research on overhead sports has investigated the external biomechanical performance and injury-risk indicators [29]. The interpretation of the existing findings has some shortcomings as internal joint loadings are not determined [29]. Musculoskeletal modelling offers the potential to understand human movement through the prediction of the articular and tissue loading [30]. Over the years, efforts have been made to evaluate the sensitivity of musculoskeletal model predictions to lower limb muscle–tendon properties [31,32] and the body of knowledge on lower limb musculoskeletal modeling especially for gait analysis is well-documented [33]. However, little is known about the shoulders and upper limbs [33] and to the best of the authors' knowledge, almost all shoulder and upper limbs musculoskeletal modeling studies have a clinical context. Existing studies normally report external moments obtained through kinetic analysis to reflect joint loading [29,34,35]. The findings are limited as intrinsic forces such as muscle forces are not accounted for and therefore the calculated external joint moments do not necessarily represent the actual mechanical burdens imposed on the articular interfaces [36,37].

The aims of this systematic review were to critically review the published studies over the past 10 years that primarily investigated shoulder biomechanics during overhead sporting movements. This systematic review aimed to thoroughly assess the body of published studies spanning the last decade, focusing on shoulder biomechanics during overhead sporting movements. The primary objectives were to summarize the utilized biomechanical analysis approaches and the key findings related to sports, gender, level of experience, and the presence or absence of injury in these studies. The review also serves to identify a research gap in this area for future investigation. A better understanding of shoulder biomechanics will assist researchers and practitioners in planning their respective strategies for performance enhancement and/or injury prevention with greater specificity and transferability across overhead sports.

2. Materials and Methods

2.1. Search Strategy and Data Selection

This systematic review was conducted according to the Preferred Reporting Items for Systematic review and Meta-Analyses (PRISMA) guidelines. A literature search on relevant studies was performed by two co-authors using seven online databases: PubMed, Web of Science (Thomson Reuters, Toronto, ON, Canada), ScienceDirect (Elsevier, Amsterdam, The Netherlands), CINAHL® Complete (EBSCO), SPORTDiscus with Full Text (EBSCO, Ipswich, MA, USA), Scopus (Elsevier), and Google Scholar. The articles being reviewed were published between November 2011 and July 2022, peer-reviewed, and published in English. Following the initial study selection, the inclusion criteria were applied to each selected study. Each criterion was evaluated with a yes/no determination. In cases where there were discrepancies among the authors' evaluations, the article's ratings were shared and discussed collaboratively until a consensus was reached. There were no attempts made to contact the articles' authors to get any additional information. The set of keywords used in the searches were "biomechanics", "kinematics", "kinetics", "3D motion analysis", "shoulder", "musculoskeletal modelling", "overhead throwing", "overhead sports", and "overhead athletes". These search terms were combined with the two Boolean operators AND; OR. The same search strategy was applied to all selected online databases and duplicates were removed. The titles and abstracts were assessed for eligibility criteria while the full-text articles were retrieved and assessed for relevance. Finally, cross-referencing of the included articles was performed using the same inclusion and exclusion criteria for additional potential eligible studies.

2.2. Eligibility Criteria

Figure 1 describes the PRISMA flow chart for the study selection. The studies identified were then screened and eliminated for ineligibility. For inclusion, the studies were required to be (a) journal articles (not conference proceedings or review papers), (b) published in English from 2011 to 2022, (c) investigating overhead movements, and (d) using one or more of the following approaches: kinematics analysis, kinetics analysis, neuromuscular assessment, and musculoskeletal modeling. The studies were excluded if there was no full-text available and/or the participants were non-human.

2.3. Scientific Literature Quality Assessment

The quality of the studies used in the review were evaluated using a modified Coleman Methodology Score (MCMS). The Coleman Methodology Score was developed to grade the methodology of clinical studies on patellar and Achilles tendinopathy, hence not all score items were relevant as this systematic review was developed mainly based on observational and descriptive studies [38]. As a consequence, the Coleman Methodology Score was modified to combine the MCMS scoring items adapted by [38] (items 1 to 4) and [39] (items 4, 8, 9) and to remove the subcategories that duplicate or unfairly applicable to these studies (Table 1). The MCMS used in this study assessed the methodology with 13 criteria, giving a total maximum score of 100 points. The scores were reported in raw and percentage values. The authors had agreed to set the standard of acceptance on the quality of the studies at a score of 60 and above.

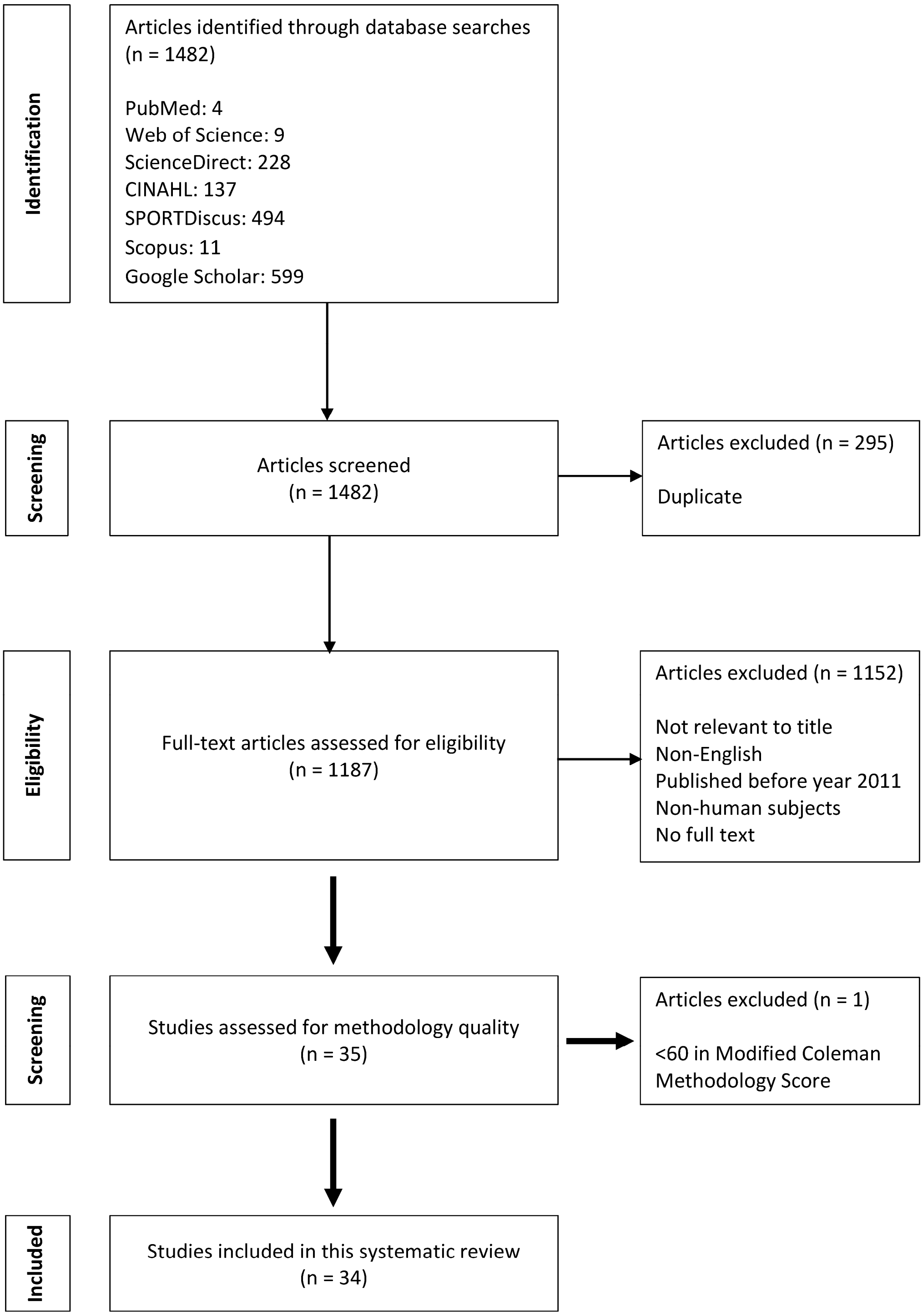

Figure 1. PRISMA flow chart for study selection.

Table 1. Modified Coleman Methodology score (MCMS).

No.	Items	Score
1	Inclusion criteria	-
	Not described	0
	Described without %	3
	Enrolment rate < 80%	6
	Enrolment rate > 80%	9
2	Power	-
	Not reported	0
	>80%, methods not described	3
	>80%, methods described	6
3	Significance threshold	-
	Not reported	0
	<0.05	3
	<0.01	6
4	Sample size	-
	Not stated/<20	0
	20–40	3
	41–60	6
	>60	9
5	Type of study	-
	Retrospective cohort study	0
	Prospective cohort study	10
	Randomized controlled trial	15
6	Outcome measures clearly defined	2
7	Timing of outcome assessment clearly stated	2
8	Use of outcome criteria that has reported reliability	3
9	General health measure included	3
10	Participants recruited	5
11	Investigator independent of trainer	4
12	Quantitative assessment	3
13	Completion of assessment by patients themselves with minimal investigator assistance	33
	TOTAL	100

2.4. Data Extraction

The retrieved studies were assessed systematically by the authors based on a predefined template. The template included the following parameters: (a) objectives, (b) design, (c) participant characteristics (age, sex, experience level, injury presence/absence), (d) type of biomechanical analysis approaches, (e) data collection equipment, (f) statistical analysis methods, and (g) key biomechanical findings. Consensus among the authors was reached on any controversy through detailed discussions.

3. Results

3.1. Literature Search

The literature search across seven online databases resulted in a total of 1482 potential studies. During the screening phase, 295 duplicates were removed, and the remaining 1187 papers were examined and selected based on the eligibility criteria of this review. A total of 1152 articles failed to fulfil the eligibility criteria and were eliminated, yielding 34 journal articles. The excluded studies were not relevant to the topic of this review, not published in English from 2011 to 2022, no full text available, and/or were conference proceedings or review papers.

3.2. Study's Methodology Quality

All 34 eligible studies were scored using the MCMS scale. An average score of 69.5 (range: 58–82) was obtained, with 33 studies (97%) meeting the 60% criteria for methodological quality. The one excluded study failed to describe participant inclusion criteria, report power, alpha error, and had a small sample size of 8. Out of the 33 studies that were included in this review, only two of them performed a sample size calculation [29,40].

3.3. Sport

In this review, seven sports (Figure 2) were included, with badminton being the most studied sport in this context (nine papers, 27%), followed by baseball (eight, 24%), volleyball (five, 15%), tennis (five, 15%), cricket (three, 9%), handball (two, 6%) and one paper from softball. Meanwhile, one of the 33 studies investigated a non-athlete population. The majority of the 33 studies (79%) were evaluating performance factors (technique) while the remaining 21% focused on injury.

Figure 2. Illustration of overhead movement sports; (**a**) Badminton, (**b**) Baseball, (**c**) Volleyball, (**d**) Tennis, (**e**) Cricket, (**f**) Handball, (**g**) Softball, (**h**) Kayaking.

3.4. Participants' Characteristics

In total, there were 1083 participants involved in this review across 33 studies, with 519 (48%) of them accounted for by eight baseball studies. The number of participants in each study ranged from 5 [41] to 322 [42]. Only two studies performed priori power analysis with shoulder internal/external range of motion as the primary outcome with significance level set at 0.05. The minimum sample size suggested per group to achieve 70% power and 80% power are 12 [40] and 15 [43], respectively. With respect to sample characteristics, the majority of these studies targeted young adults with age ranging from 18 to 25 years (71%), male-only (53%), and elite-level athletes (74%), respectively.

3.5. Type of Biomechanical Analysis Approaches

All 33 studies included shoulder kinematics during overhead movements but only 12 of the studies (36%) investigated the forces and torques in relation to the motion (kinetics). Surprisingly, only one study analyzed the shoulder muscle activation patterns when performing shoulder overhead movements [41]. Meanwhile, [44] were the only authors who used a shoulder kinematics model with the simulation of the badminton overhead forehand smash.

3.6. Data Collection and Statistical Analysis Approaches

The most common biomechanical data collection method identified in this review was using retroreflective marker-based 3D motion analysis approach (76%). The remaining studies used digital video cameras (15%), electromagnetic tracking systems (6%), or IMU sensors (3%). Most of the studies used linear models or standard analytics methods whereby most often, discrete values at key instants were considered during the data analysis. There were three studies that utilized statistical parametric mapping (SPM) method in their analysis [11,23,24], which can identify the field regions that significantly co-vary while preserving the complexity of the biomechanical dataset over time.

4. Discussion

The primary findings (Table 2) based on the amalgamation of results in this systematic review were: (a) kinematic analysis is the most common approach used in biomechanical analyses with less attention given to kinetics, especially with the integration of muscle activation data and musculoskeletal modeling approach, (b) the majority of biomechanical data were collected using marker-based motion capture system and analyzed based on discrete information, and (c) current literature (Table 3) shows relatively consistent findings that the shoulder internal rotation and elbow extension angular velocities are important variables that contribute to a fast badminton smash, volleyball spike, baseball pitch (including maximum external rotation angle), and tennis serve (only shoulder internal rotation); while a fast cricket bowling speed is associated with a quicker run-up, straighter knee, and greater shoulder angle relative to the upper trunk during front foot contact. Overall, the contribution and importance of trunk rotations to the development of speed has been articulated, although there has been some inconsistency in the findings.

Table 2. Research designs of biomechanical studies on overhead throwing movement.

Authors & Year	Study Design	Participants	Objectives	Types of Biomechanical Analysis	Data Collection Equipment (Data Analysis Methods)
Badminton					
Ramasamy et al. (2022) [34]	Descriptive	N = 19 Male, elite players Age (21 ± 2)	to examine (i) forehand jump smash whole-body kinematics and GRF, (ii) relationships between technique and shuttlecock speed	A, B	Qualisys MCS (Pearson product moment correlation analysis, Kendall tau-b correlation, CI)
Ramasamy et al. (2021) [10]	Descriptive	N = 19 Male, elite players Age (21 ± 2)	to investigate the relationships between racket head speed and upper limb joint moments	A, B	Qualisys MCS (Pearson product moment correlation analysis, Kendall tau-b correlation, CI)

Table 2. *Cont.*

Authors & Year	Study Design	Participants	Objectives	Types of Biomechanical Analysis	Data Collection Equipment (Data Analysis Methods)
Rusdiana et al. (2021) [45]	Descriptive	N = 18 Male, elite players Age (24.4 ± 1.8)	to analyze the movement of overhead backhand and forehand smash techniques in badminton	A	Digital Video Cameras (one-way ANOVA)
Barnameher et al. (2021) [44]	Descriptive	N = 20 Professional players Age (24 ± 4)	to understand which model is best to simulate the badminton overhead forehand smash	A, B, D	VICON MCS (Multiple 3-way ANOVA)
Rusdiana et al. (2021) [45]	Observational	N = 26 Skilled group, n = 13 Unskilled group, n = 13 Male Age (19.4 ± 1.6)	to analyze the joint kinetics of the shoulders, elbows, and wrists of skilled and unskilled players when performing overhead standing smash in badminton	A, B	Digital Video Cameras (Mann–Whitney U test)
Rusdiana et al. (2021) [45]	Descriptive	N = 24 Male, skilled players Age (19.4 ± 1.6)	to analyze the movement of backhand and forehand smash stroke techniques in three dimensions using a kinematics approach in badminton	A	Digital Video Cameras (One-way ANOVA)
King et al. (2020) [22]	Observational	N = 18 Regional level, n = 9 National level, n = 4 International level, n = 5 Male Age (24.3 ± 7.1)	to identify full-body kinematic parameters that best explain the generation of post-impact shuttlecock velocities in the badminton jump smash	A	VICON MCS (Pearson product moment correlation analysis, CI, multiple linear regression analysis)
Rusdiana et al. (2020) [46]	Descriptive	N = 15 Male Age (19.4 ± 1.6)	to analyze the effect of fatigue on the kinematic variable movement changes during overhead jump smash in badminton	A	Digital Video Cameras (Paired sample *t*-test)
Zhang et al. (2016) [13]	Observational	N = 24 (17M 7F) Skilled group, n = 14 Novice group, n = 10 Age (Skilled: 23.2 ± 2.8, Novice: 24.3 ± 4.7)	to (i) quantitatively determine kinematic characteristics of the forehand smash and (ii) compare kinematic differences between novice and skilled players with a focus on trunk rotation	A	VICON MCS (Independent *t*-test, Pearson correlation coefficient)
Baseball					
Manzi et al. (2021) [42]	Descriptive	N = 322 Professional players Age (21.9 ± 2.1)	to determine the associations between shoulder abduction and external rotation to throwing arm kinetics	A, B	Raptor-E MCS (ANOVA, two-sample *t*-test, linear regression correlation coefficient)
Lin et al. (2020) [43]	Observational	N = 30 GIRD group, n = 15 Non-GRID group, n = 15 Male, Top-tier players Age (GIRD: 18.4 ± 2.5, non-GIRD: 17.8 ± 2.3)	to investigate whether GIRD causes a change in the pitching dynamics of senior league and collegiate pitchers with a longer pitching history	A	Cortex MCS (Mann–Whitney U test, ICC, priori G*Power analysis)
Reinold et al. (2018) [47]	Experimental	N = 38 Experimental group, n = 19 Control group, n = 19 Male Age (13–18 years)	to (i) determine the effectiveness of a 6-week weighted ball training program on enhancing pitch velocity and (ii) quantify the effects on shoulder and elbow biomechanics	A	IMU (2-way Repeated measures ANOVA)

Table 2. *Cont.*

Authors & Year	Study Design	Participants	Objectives	Types of Biomechanical Analysis	Data Collection Equipment (Data Analysis Methods)
Marsh et al. (2018) [8]	Experimental (single-group design)	N = 17 Professional players Age (19.9 ± 1.3)	to evaluate the effects of a six-week training period on shoulder external rotation, elbow valgus stress, pitching velocity, and kinematics	A, B	Prime 13 MCS (Paired *t*-test)
Scarborough et al. (2018) [48]	Observational	N = 22 High school level, n = 5 College level, n = 11 Professional level, n = 6 Age (High school: 16.8 ± 1.6, College: 20.9 ± 1.9, Professional: 24.3 ± 1.5)	to investigate the kinematic sequence through analyses of the peak angular velocity of pelvis, trunk, arm, forearm and hand during the execution of the fastball pitch	A	VICON MCS (One-way ANOVA, MANOVA)
Kobayashi et al. (2016) [49]	Descriptive	N = 42 Male, Skilled Age (8–12 years)	to investigate joint kinetics of the throwing arms and role of trunk motion in skilled elementary school boys during an overarm distance throw	A, B	Digital Video Cameras (Kruskal–Wallis test, Mann–Whitney U test)
Roach & Lieberman (2014) [18]	Descriptive	N = 21 Male, Skilled Age (19–23 years)	to examine how the upper body contributes to power generation during throwing	A, B	VICON MCS (Repeated measure ANOVA, MANOVA, paired *t*-test)
Hurd & Kaufman (2012) [50]	Descriptive	N = 27 Male, Competitive players Age (16 ± 1.1)	to evaluate (i) the relationships between clinical measures of shoulder rotation and strength and (ii) pitching biomechanics in baseball pitchers	A, B	3D MCS (Linear regression analysis)
Volleyball					
Fuchs et al. (2019) [51]	Observational	N = 30 Male group, n = 15 Female group, n = 15 Elite players Age (M: 22.7 ± 4.3, F: 19.9 ± 3.5)	to determine (i) the relationship between primary variables and jump height, (ii) the interaction of secondary variables, and (iii) sex differences in the primary attributes of volleyball spike jumping	A, B, C	VICON MCS (MANOVA, mixed ANOVA repeated measure, effect size, multivariate regression analysis, Pearson's product moment correlation coefficient)
Serrien et al. (2018) [52]	Observational	N = 16 Male group, n = 8 Female group, n = 8 Elite players Age (14–18 years)	to examine changes in elite youth volleyball players' performance, proximal-to-distal sequencing and coordination variability of the spike motion between the start and after one year of a talent development program	A	VICON MCS (Two-way ANOVA, post-hoc paired sample *t*-test, Pearson correlation coefficient)
Serrien et al. (2016) [11]	Observational	N = 37 Adolescent group, n = 18 (8M 10F) Youth group, n = 19 (8M 11F) Elite players Age (Adolescent, M: 23.33 ± 2.78, F: 24.23 ± 2.01; Youth, M: 15.05 ± 0.76, F: 15.19 ± 0.54)	to analyze differences in the spike kinematics of the pelvis, trunk and spike arm shoulder and elbow between male and female top level and junior elite volleyball players	A	VICON MCS (SPM-1D ANOVA, multiple MANOVA)

Table 2. *Cont.*

Authors & Year	Study Design	Participants	Objectives	Types of Biomechanical Analysis	Data Collection Equipment (Data Analysis Methods)
Seminati et al. (2015) [40]	Observational	N = 21 Male group, n = 11 Female group, n = 10 National players Age (M: 22.1 ± 5.8, F: 22.8 ± 7.5)	to assess whether the TT or AT spiking technique presented advantages from an injury prevention perspective, while maintaining athlete performance	A	VICON MCS (Paired t test, one-way ANOVA repeated measure, Pearson's correlation coefficient
Mitchinson et al. (2013) [9]	Observational	N = 24 Injured group, n = 13 Uninjured group, n = 11 Male, Elite players Age (Injured: 23.5 ± 6.8, Uninjured: 25.5 ± 7)	to quantify differences in upper arm and trunk kinematics during the spike between elite volleyball players with and without a recent history of recurrent shoulder overuse injury	A	VICON MCS (Linear mixed model analyses, independent *t*-test)
Tennis					
Gillet et al. (2018) [53]	Observational	N = 28 Male, Competitive players Age (12.1 ± 2.5)	to investigate how a history of dominant shoulder problems affects humerothoracic and scapulothoracic 3D kinematics in adolescent competitive players	A	trakSTAR Electromagnetic Sensors (Chi-squared test, student *t*-test)
Ladermann et al. (2016) [54]	Descriptive	N = 10 (9M 1F) Intermediate/ex-professional players Age (39.7 ± 8.9)	to evaluate the different types of impingements and stability during tennis movements	A	VICON MCS, MRI
Whiteside et al. (2014) [55]	Experimental	N = 11 Female, elite players Age (14.6 ± 0.7)	to identify the effects of swing weight on serving arm mechanics, racquet kinematics, impact location, and ball speed in the tennis serve	A	VICON MCS (Repeated measures ANOVA, effect size)
Whiteside et al. (2013) [56]	Observational	N = 11 Pre-pubescent, n = 5 Pubescent, n = 5 Adult, n = 1 Female, elite players Age (Pre-pubescent: 10.6 ± 0.6, Pubescent: 14.8 ± 0.5, Adult: 26.7)	to compare the body, racquet and ball kinematics characterising successful serves and service faults, missed into the net, in two groups of elite junior female players and one professional female tennis player	A	VICON MCS (Mixed-model ANOVA)
Creveaux et al. (2013) [41]	Experimental	N = 5 Male, international players Age (25 ± 4)	to investigate the effects of the three different rackets on shoulder joint kinetics during tennis serves	A, B, C	Eagle MCS (Friedman test, Wilcoxon rank test)
Cricket					
Dutton et al. (2020) [23]	Observational	N = 15 Elite group, n = 8 Amateur group, n = 7 Male Age (22 ± 3.4)	to describe stationary overhead throwing biomechanics in South African cricketers, considering playing level, and relative to baseball	A, B	VICON MCS (SPM-1D ANOVA, Coefficient of variance)
Felton et al. (2018) [57]	Observational	N = 40 Male group, n = 20 Female group, n = 20 Elite players Age (M: 20.1 ± 2.6, F: 19.9 ± 3.2)	to investigate ball release speed and performance kinematics between elite male and female cricket fast bowlers	A	VICON MCS (ANOVA, ICC, Student *t*-test, Mann–Whitney U test, Effect size)

Table 2. *Cont.*

Authors & Year	Study Design	Participants	Objectives	Types of Biomechanical Analysis	Data Collection Equipment (Data Analysis Methods)
Worthington et al. (2013) [12]	Descriptive	N = 20 Male, Elite players Age (20.1 ± 2.6)	to identify the key kinematic parameters of a fast bowler's technique that can predict bowling speed	A	VICON MCS (ANOVA, ICC, forward stepwise linear regression)
Handball					
Serrien et al. (2015) [24]	Observational	N = 20 Male group, n = 10 Female group, n = 10 Semi-professional players Age (M: 25.4 ± 4, F: 23.7 ± 2.7)	to examine differences in ball release speed and throwing kinematics between male and female team-handball players in a standing throw with run-up	A	VICON MCS (Mixed model ANOVA, effect size, SPM-1D 2way ANOVA, two-sample SPM test)
Van Den Tillaar & Cabri (2012) [58]	Observational	N = 22 Male group, n = 11 Female group, n = 11 Elite players Age (M: 23.6 ± 5.2, F: 20.3 ± 1.8)	to compare the throwing performance (throwing velocity) and the kinematics of the upper extremity, trunk and lower extremity movements in overarm throwing in team handball between elite male and female team handball players	A	Qualisys MCS (Student *t*-test)
Softball					
Bordelon et al. (2022) [59]	Descriptive	N = 61 Female, Elite players Age (19.9 ± 1.9)	to determine the association of peak elbow flexion during the acceleration phase of the pitch with peak shoulder distraction force and ball velocity	A, B	MotionMonitor xGen Electromagnetic Tracking System (Linear regression analysis, bivariate correlation analysis)

Note. The table above presents the summary of research designs of the 34 included studies. A = kinematic analysis; AT = alternative technique; B = kinetic analysis; C = neuromuscular assessment (EMG data); CI = confidence interval; D = musculoskeletal modeling; EMG = electromyography; F = female; GIRD = glenohumeral internal rotation deficit; GRF = ground reaction force; IMU = inertial measurement unit; M = male; MCS = motion capture system; MRI = magnetic resonance imaging; N = total number; n = number; TT = traditional technique.

Table 3. Summary of shoulder and key upper body biomechanical findings on overhead throwing movement.

Authors & Year	Shoulder and Key Upper Body Biomechanical Findings
Badminton	
Ramasamy et al. (2022) [34]	• High racket head speed can be strongly predicted by greater shoulder IR moment • Peak moment on shoulder IR, backwards plane of elevation, and wrist extension correlate with racket head speed
Ramasamy et al. (2021) [10]	• Average peak shoulder IR angular velocity during forward swing to contact is 5040°/s (range 3773–7148°/s) • Greater shoulder IR, less shoulder elevation, and elbow extension angles at contact significantly correlated with greater smash speed

Table 3. *Cont.*

Authors & Year	Shoulder and Key Upper Body Biomechanical Findings
Rusdiana et al. (2021) [45]	• Shuttlecock speed is greater in forehand smash than that of backhand smash • Greater shoulder ER (p = 0.042) and wrist extension (p = 0.041) angles, and greater shoulder IR (p = 0.038), elbow extension (p = 0.022), and forearm supination (p = 0.037) angular velocities were demonstrated by forehand smash compared to backhand smash • Shoulder IR and elbow extension angular velocities and wrist extension angle are the main contributions to upper limb motion in both forehand and backhand smash techniques
Barnameher et al. (2021) [44]	• Kinematic model that modeled the joint between the scapula and the trunk by a contact ellipsoid (M4) displayed lowest marker error in various speeds, therefore reported as the best model among four tested models • No significant differences observed among various speeds indicating the model selection do not depend on the movement speeds
Rusdiana et al. (2021) [45]	• Skilled players exhibited greater shoulder IR torque, smaller shoulder inferior force, anterior force, shoulder horizontal abduction torque, elbow anterior force, and wrist flexion torque compared to unskilled players
Rusdiana et al. (2021) [45]	• Shoulder IR and elbow extension angular velocities and forearm supination contribute significantly to shuttlecock speed in both forehand and backhand smash
King et al. (2020) [22]	• Greater racket head speed, peak wrist joint center linear velocity, shoulder IR at SC, shorter duration for acceleration phase and more negative X-factor at ER were associated with greater shuttlecock speed
Rusdiana et al. (2020) [46]	• Shuttlecock velocity in jumping smash is greater in non-fatigue condition compared to fatigue • Decrease in shoulder IR velocity, wrist extension, and forearm supination reduce the shuttlecock velocity under fatigue condition during overhead jump smash
Zhang et al. (2016) [13]	• Due to their use of 28% greater trunk rotation, 2 times greater shoulder IR, 30% more elbow extension, 170% more wrist flexion, and pre-lengthening of the pectoralis major 38% more than the novice, the skilled players was able to generate higher smash speed compared to the novice
Baseball	
Manzi et al. (2021) [42]	• Pitchers who achieved greater MER had significantly greater ball velocity • Professional baseball pitchers with increased shoulder abduction at BR and ER at MER were associated with increased superior translation (3.7%, 2.3% BW/10° increase, respectively) and distraction forces (11.7%, 5.9% BW/10° increase, respectively) in the shoulder, potentially placing them at increased risk of shoulder injury • Pitchers can consider decreasing shoulder abduction at later stages of the pitching motion to approximately 80° to minimize shoulder superior force, with no impact on ball velocity
Lin et al. (2020) [43]	• GIRD group demonstrated higher shoulder IR torque and inferior force during cocking and acceleration phases, as well as smaller shoulder ER and greater shoulder horizontal adduction at the instant of BR compared to the group without GIRD
Reinold et al. (2018) [47]	• Significant increase of 4.3° shoulder ER PROM was found in the training group (p = 0.01) after 6 weeks and this variable correlates to pitch velocity as well as increased shoulder and elbow forces • Weighted baseball training programs may be effective at enhancing pitch velocity but may also increase injury rates

Table 3. *Cont.*

Authors & Year	Shoulder and Key Upper Body Biomechanical Findings
Marsh et al. (2018) [8]	• Maximum shoulder adduction torque significantly increases during the arm cocking phase after 6 weeks of weight-implemented training • When sub-groups were created based on velocity, the velocity increase group had significant increases in shoulder IR and elbow extension angular velocities as well higher maximum shoulder superior force in the deceleration phase • The velocity decrease group exhibited higher maximum shoulder adduction torque at arm cocking and lower elbow anterior force, compressive force, flexion torque, and shoulder compressive force during arm deceleration phase
Scarborough et al. (2018) [48]	• The majority of the pitchers demonstrated variability in kinematic sequence selection, performing 2–3 patterns • The most commonly performed kinematic sequence was similar to the proximal–distal sequence, but with the hand peaking prior to the forearm segment
Kobayashi et al. (2016) [49]	• Throwing distance and ball velocity significantly increased with an increase in the school grade • The elbow extension angular velocity, positive joint torque power of elbow extension, and shoulder internal rotation before ball release increased with the school grade
Roach & Lieberman (2014) [18]	• Hip rotators account for most of the torso rotation power and work produced during throwing • The pectoralis major contributes to energy absorption (negative work) at the shoulder during the cocking phase and helps power elbow extension • Lack of positive work produced by the wrist and elbow during either the cocking or acceleration phases shown that kinetic power transfers from proximal to distal segments
Hurd & Kaufman (2012) [50]	• Positive relationship between shoulder IR strength and peak shoulder ER moment (p = 0.181) and negative relationship between shoulder ER motion with peak shoulder IR moment (p = 0.25) and peak elbow adduction moment (p = 0.16) found indicated the existence of relationship between clinical measures of shoulder external-rotation motion and internal-rotator strength and upper extremity pitching biomechanics
Volleyball	
Fuchs et al. (2019) [51]	• Males demonstrated greater torso incline angle and later timing of maximal shoulder flexion angular velocity (mean: 64%) compared to females (mean: 57.6%) during the volleyball spike jump • Non-dominant shoulder velocity was positively correlated with upper body incline angle
Serrien et al. (2018) [52]	• Significant differences were observed between young elite male and female during volleyball jump spike in the timing of joint motions despite both showing typical proximal–distal sequencing behavior
Serrien et al. (2016) [11]	• Top-level male players exhibited a significantly higher elbow extension velocity (until 16 ms later), higher shoulder IR velocity (until 28 ms later), greater shoulder horizontal adduction (20 ms until the end), and higher elbow flexion velocity (40–52 ms) after ball impact compared to their female counterparts • Top-level players demonstrated higher trunk lateral tilt velocity (400–396 ms), higher shoulder ER angle (284–228 ms), higher trunk velocity in sagittal plane (184–128 ms), greater elbow extension (36–4 ms), and earlier onset of forward trunk rotation before ball impact compared to junior players • Male players had a little backward tilting motion (292–256 ms) with its velocity close-to-zero °/s (296–272 ms) before ball impact while the female players demonstrated close-to-zero and negative velocity at the respective time frames, indicating that female could be utilizing a later onset of trunk backward-tilt before ball impact

Table 3. *Cont.*

Authors & Year	Shoulder and Key Upper Body Biomechanical Findings
Seminati et al. (2015) [40]	• Maximal shoulder flexion (most dangerous maneuvers during spike movement) was significantly reduced in AT both for female and male athletes (on average by 108), while horizontal abduction angular amplitude (on average 158) although was found to be higher, exceeded the coronal/scapular plane for just a few frames of the movement, considered less dangerous for impingement • AT demonstrated significantly higher shoulder IR and ER angular velocities coupled with faster spike-hand and ball velocity than TT, indicating that this technique will not compensate the spike performance
Mitchinson et al. (2013) [9]	• Players demonstrated more trunk rotation ($p = 0.015$) towards the target at the instant of ball–hand impact with their upper arm positioned further in front of their trunk (0.016) and greater range of shoulder rotation velocity ($p = 0.011$) in cross-court spike compared to performing down-the-line spike • No kinematic differences were detected between the injured and uninjured groups
Tennis	
Gillet et al. (2017) [60]	• The dominant IROM (ES = 1.234, $p = 0.003$) and TAM (ES = 0.867, $p = 0.01$) was significantly lower for the HSP group than for the NHSP group • Adolescent tennis players with HSP exhibited less humeral abduction (ES = 1.262, $p = 0.001$) and external rotation (ES = 0.771, $p = 0.05$) and more scapular upward rotation (ES = 0.845, $p = 0.021$) at the end of the cocking phase of a serve than those with NHSP
Ladermann et al. (2016) [54]	• Dynamic and precise motion analysis of the entire kinematic chain of the shoulder is possible through a non-invasive method of investigation (optical motion capture and MRI) • At rest, the humeral head was slightly anteriorly translated. When flexion began, posterior translation was noted until 70° followed by a return to a more anterior translation • At late cocking stage of serve, glenohumeral translation was observed from anterior (flat serve, mean: 34%; kick serve, mean: 34%) and superior (flat serve, mean: 12%; kick serve, mean: 13%) • During the deceleration stage of the serve, anterior and superior translation varied from 8% to 57% and from 5% to 34%, respectively • Towards the end stage of the serve, anterior translation was slightly more intense (flat serve, mean: 46%; kick serve, mean: 42%), while superior translation remained low (flat serve, mean: 3%; kick serve, mean: 0%)
Whiteside et al. (2014) [55]	• Peak shoulder IR and wrist flexion angular velocities and acceleration were affected when racket swing weight was increased above a self-selected value and contributed to reduced swing speed and shift in impact location
Whiteside et al. (2013) [56]	• No significant differences in body kinematics or ball and racket kinematics at impact between successful and unsuccessful tennis serve of all age groups
Creveaux et al. (2013) [41]	• Using a light racket with high polar moment resulted in greater shoulder joint power and IR/ER peak moments, lesser activity in latissimus dorsi (during acceleration phase), and lesser activity in biceps brachii muscles (during follow through) compared to using a heavier racket with high twist weight and swing weight
Cricket	
Dutton et al. (2020) [23]	• Amateur cricketers demonstrated smaller elbow flexion angles between 2 and 14% of the throwing cycle ($p = 0.01$) compared to the elite cricketers • At MER, amateur cricketers exhibited greater shoulder ($p = 0.021$) and elbow compression ($p = 0.043$), as well as greater shoulder superior force ($p = 0.022$) than the elite cricketers

Table 3. *Cont.*

Authors & Year	Shoulder and Key Upper Body Biomechanical Findings
Felton et al. (2018) [57]	• At BFC, female bowlers exhibited less flexed front hip angles and less extended upper trunk angles • At BR, females exhibited more front-on pelvis and shoulder orientations, more flexed upper trunk angles, and more delayed bowling arm circumduction • Female bowlers exhibited more pelvis rotation between BFC and BR than the males • Male bowlers spent significantly more time between BFC and FFC, but less time between FFC and BR compared to female bowlers • Female bowlers adopted a technique more akin to throwing where ball speed is contributed to by both the whole-body angular momentum and the large rotator muscles used to rotate the pelvis and torso segments about the longitudinal axis to generate greater ball speed
Worthington et al. (2013) [12]	• Shoulder angle at BR explained 30% of the variation in release speed was the best individual predictor whereby a larger shoulder angle relative to the upper trunk was associated with faster release speed • The best four-parameter regression equation explained 74% of variation in release speed suggests that having a quicker run-up, maintaining a straighter knee and greater shoulder angle throughout the FFC phase, and performing greater upper trunk flexion up to BR are the four key aspects to fast bowling technique
Handball	
Serrien et al. (2015) [24]	• Male showed a higher elbow extension velocity (500–432 ms, 300–272 ms), higher shoulder horizontal abduction angle (216–212 ms, 180–176 ms), and higher shoulder ER velocity at 140 ms prior to BR compared to their female counterparts • Male players showed more activity in the transverse plane while female players showed more activity in the sagittal plane • Male players presented a greater outward pelvis rotation (500–484 ms), greater lateral pelvis tilt (500–256 ms) and greater backward pelvis rotation (228–48 ms) before BR and greater pelvis inward rotation (36–200 ms) after BR • Male exhibited higher pelvis lateral tilt velocity (304–188 ms) and higher pelvis forward tilt velocity (100–28 ms) before BR with both the peak velocities located closer to BR
Van Den Tillaar & Cabri (2012) [58]	• Elite male demonstrated significant higher ball release velocity and maximal linear velocities of the endpoints of wrist and hand compared to their female counterparts • At BR, male exhibited larger maximal shoulder abduction and elbow flexion angle • No significant gender differences for maximal angular velocities of different joint movements
Softball	
Bordelon et al. (2022) [59]	• Peak elbow flexion did not influence ball velocity or peak shoulder distraction force during the acceleration phase of a windmill softball pitch. • Significant and positive relationship between ball velocity and peak shoulder distraction force were found

Note. The table above presents the summary of shoulder and key upper body biomechanics during overhead throw movement reported by the 34 included studies. AT = alternative technique; BFC = back foot contact; BR = ball release; BW = body weight; ES = effect size; FFC = front foot contact; GIRD = glenohumeral internal rotation deficit; HSP = history of shoulder pain; IR = internal rotation; IROM = passive internal rotation range of motion; ER = external rotation; MER = maximal external rotation; MRI = magnetic resonance imaging; NHSP = no history of shoulder pain; PROM = passive range of motion; ROM = range of motion; SC = shuttlecock contact; TAM = total arc of motion; TT = traditional technique.

4.1. Type of Biomechanical Analysis Approaches

Thirty-five percent of the studies reviewed used inverse kinematics to obtain the force data at the joints of interest in order to investigate the indicators that lead to higher movement speed and performance [8,10,18,23,34,42,45,49–51] and/or to examine the amount of forces incurred from the joints when executing the tasks from an injury risk perspective [23,41,42,45,59]. For example, [10] identified greater shoulder internal rotation moment as a strong predictor of higher racket head speed (r = 0.737); this was supported by [45] who found greater shoulder internal rotation moment in the skilled vs. novice players (p = 0.016). Ref. [42] identified a positive association between shoulder abduction at ball release and shoulder distraction force, recommending that pitchers consider reducing shoulder abduction at the later stages of the pitching motion to approximately 80° to minimize shoulder superior force, with no impact on ball velocity. Meanwhile, all reviewed studies utilized kinematic analysis to identify the technique differences that contribute to different movement speed and performance, with six studies comparing between genders [11,24,51,52,57,58], two compared between age groups [49,56], four comparing between sport-experience level [11,13,23,45,61], and three comparing between injured and non-injured athletes [9,43,60].

Biomechanics dwells in the structure, function, and motion of the mechanical aspects of biological systems; therefore, the biomechanics and neural control of the muscular system are interrelated. Neurological and biomechanical management of human movement need to coordinate in order to execute a defined task [62]. Hence, integrating EMG information with kinematics and kinetics analyses, as well as considering the physical properties of the muscles and connective tissues through musculoskeletal modeling helps researchers better understand joint loading during sporting movements [29]. Nevertheless, only 1 of the 33 studies collected EMG data at the shoulder, whereby the results suggested different shoulder muscular activation patterns when using different types of racket during the tennis flat serve [41]. Meanwhile, there was only one study that used a kinematic modeling approach to simulate the shoulder movement during the badminton overhead forehand smash [44]. The authors proposed the best shoulder kinematic model is one where the joint between the scapula and the trunk is modeled by a contact ellipsoid although no significant difference was found across various smash speeds showing that the selection of model did not depend on the speed of the movement. However, more investigations are needed to consolidate those findings. The lack of studies exploring muscle activation and musculoskeletal modeling data could be due to the complexity of equipment set-up and data collection concerning the high-speed nature of the overhead movement typically performed in these sports, as well the complexity of the shoulder joint anatomy and the movement biomechanics, suggesting the existence of a large knowledge gap in analyzing the shoulder biomechanics during overhead movements. Accordingly, the authors hope to draw more research attention onto these areas in order to add to the body of knowledge, narrowing the gap, and eventually benefit practitioners in formulating performance enhancement and injury prevention strategies.

4.2. Data Collection and Statistical Analysis Approaches

Overhead throwing movements involve high rotational velocities and complex and increased joint kinetics at the shoulder, the combination of which makes it ideal for the utilization of 3D motion capture for analysis [19]. The most commonly used data collection method was infrared marker-based motion capture systems (Table 2). There are limitations as the process requires attachment of many markers correctly and firmly on the human body, this is time-consuming and requires skilled operators to collect accurate data. Due to the nature of overhead sporting motions (mostly performed at high speed), bandages or tapes were often used to minimize the number of markers falling off which could cause a diversion from their normal motion—reducing the ecological validity. Although markers are tracked accurately, skin artifact and wobbling mass movement can compromise the quality of data collected [44]. Fortunately, a handful of investigations have shown that marker-based motion capture is the current gold standard in motion analysis based on validation and high accuracy [21]. Meanwhile, the post-data processing can be very complex and tedious due to the segment definitions and mathematical constraints on the complex shoulder joint anatomy at different positions.

An alternative method used in tracking overhead sporting movements that is cheaper and easier to set up is based on wearable sensors such as IMU. These are a small and lightweight system embedded with 3D accelerometers, gyroscopes, and magnetometers, which make IMU more accessible and quicker in terms of gathering and processing the kinetic and kinematic data [63,64]. Despite IMU proving comparable to the gold standard accuracy of motion capture in certain circumstances, there is a phenomenon called IMU drift that stems from continuously integrated noise errors, and in turn could cause absolute IMU measurement error to increase over time [65,66]. However, if continuous integration can be avoided or a consistent reference (i.e., position or velocity) can be used, this error can be avoided.

On the other hand, the emerging marker-less 3D tracking technology could potentially ease the lab and field settings. However, the accuracy of these systems is not yet well validated. Ref. [19] identified similar baseball pitching kinematics between marker-based and marker-less motion capture system but variations still exist in the results between the two systems due to different methods in defining joint center locations. While a variety of 3D tracking technologies besides motion capture system are now commercially available, the preference of different approaches often depends on (but is not limited to) the testing objectives, cost, time consumed, complexity in the set-up, operator dependency, portability of the devices, and the ecological validity.

Most studies reviewed in this paper relied on the investigation of joint kinematics at discrete time points (i.e., key instants, peak and summary values) and used standard analytic (linear) methods. However, overhead sporting motions consist of a continuous time series of kinematic data, therefore motion analysis based on discrete data may neglect potential valuable information throughout the entire movement. The discrete value itself does not represent the complete description of a single variable over time nor taking spatiotemporal confounding effect into consideration [67]. In the last decade, Statistical Parametric Mapping (SPM) has been used within the biomechanics and human movement science community for uni/multivariate time series data (i.e., kinematics and kinetics) [68,69]. This method is advantageous for biomechanical analysis as it allows full-field non-direct hypotheses tests and visualization of the statistical results over time series [70]. Consequently, the field regions that significantly co-vary can be identified objectively, potentially facilitating better data interpretation. For instance, Fuchs detected specific differences in the shoulder orientation and angular velocity throughout the entire spike motion between male and female volleyball players [51], illustrating the different mechanisms used in generating high speed movement. However, only 12% of the studies in this review paper utilized SPM method in their analysis indicated the wide knowledge gap between the collected and analyzed shoulder biomechanics data during overhead throwing movements.

4.3. Shoulder Biomechanics during Overhead Sporting Motions

Shoulder joint moments perform an important role in producing high joint angular velocities for any rapid overhead movement. As such, one common biomechanical predictor of faster overhead motions was identified (demonstrated by higher post-impact ball/shuttlecock speed, ball release speed, and racket head speed) in the badminton smash, baseball pitch, and volleyball spike, namely shoulder internal rotation angular velocities during acceleration phase to the instant of contact/release [10,11,40,42,43,45,50,55]. Current literature (Table 3) shows consistent findings on shoulder biomechanics during overhead sporting motions across various sports with a larger external rotation along with sequential forward shoulder movement enabling faster extension from proximal to distal segments.

Consensus was met among the authors wherein the pre-stretch of the upper body demonstrated by maximal shoulder ER and abduction angle during the backswing stores elastic energy that facilitates a greater shoulder internal rotation moment during the forward acceleration phase [71]. Inversely, the literature also shows that achieving greater peak shoulder ER at the end of backswing movement and abduction angles at ball release were associated with increased superior translation and distraction force at the shoulder joint [42]. Comparison based on gender, sports experience level, and presence of injury shows agreement in that significant differences exist in the biomechanical predictors mentioned and the speed of the particular overhead movement, with the male, elite/skilled, and injury-free individuals being more dominant than their respective counterparts. Adding to that, amateur performers consistently demonstrated higher compression and distraction force at the shoulder joint compared to professional players when performing overhead tasks [23]. Ref. [56] reported no kinematic difference detected between successful and unsuccessful tennis serves among 11 female elite players. Meanwhile, significantly different timing of segments or joint motions were reported between genders [40,51,52,57,58] and experience levels [11,22,45], indicating the employment of different optimal strategies, but overall exhibiting similar movement patterns.

Overhead athletes with disabled throwing shoulder (DTS) often exhibit consistent alteration in glenohumeral rotation, which has been identified as the factor most strongly associated with shoulder pain and injury [72,73]. Even though having greater shoulder flexibility and mobility allows the athletes to have advantages by performing overhead movements with greater range of motion, they are also carrying the risk of overuse injury due to the nature of having pathomechanics [74]. This repetitive movement can potentially cause increased load on anterior shoulder with corresponding internal impingement [74]. Glenohumeral internal rotation (GIR) has been identified critically as key to normal force development in overhead throwing motion and, when altered beyond certain level, it changes the glenohumeral kinematics and it is implicated in shoulder injury [72]. The need to scrutinize shoulder metrics as a basis for determining which athletes should undergo preventive measures warrants scrutiny. The primary objective of assessing shoulder parameters in sports involving overhead movements should focus on appraising the present condition of the shoulder, gauging enhancements in performance, or establishing normative benchmarks to achieve before resuming play post-injury [75].

In addition, the only study that analyzed the shoulder muscle activation patterns among the included papers, ref. [41] suggests that racket specifications are critical for coaches who train players with shoulder pain and upper limb injuries. The authors found that during tennis serves, the latissimus dorsi (during acceleration phase) and biceps brachii muscles (during follow through) were less activated when using low mass, high balance, and polar moment racket compared to a high mass, swing and twist weight racket. It is important to understand the adaptation of muscles activity and recruitment patterns in response to the corresponding movement biomechanics; yet, the shoulder, in particular, remains under-researched specifically in rapid overhead throwing movements.

5. Limitations

There are some shortcomings within this systematic review. First, the majority of the included studies involved small sample sizes and did not report statistical power, with a few studies reported being underpowered. Second, the majority of the studies were conducted in laboratories; therefore, it is unclear how the testing methodologies and environment impacted ecological validity. This review only considered publications in English language; therefore, there may be other relevant papers that have been missed. Despite the target movement of interest in the reviewed studies all falling under the term “overhead sporting movements”, the disparities in the execution technique nature of the sports, athletes’ demographics, and physiques across various sports may result in bias and less meaningful conclusions considering that the interpretation of overhead throwing biomechanics was being generalized. While it is acknowledged that other joints play important roles in overhead movements (Table 3), this review focused on shoulder movements and their relationship to performance. The exclusion of information related to other joints does not diminish the importance of their contributions but rather reflects the specific scope of this review.

6. Conclusions and Recommendations

The studies included in this review focused on analyzing the 3D biomechanics of the shoulder during overhead movements in various sports. The findings consistently indicated the following:

- Shoulder external rotation angle during the backswing and the internal rotation velocity during the acceleration phase were strong predictors of high speeds in overhead throwing movements.
- Shoulder abduction and flexion angles at contact/release, as well as maximum external rotation angle, may be associated with an increased risk of shoulder injuries.

This information can help the athletes and coaches understand the key role of shoulder positioning in generating greater speeds in overhead sporting motions. and guide their training strategies accordingly. Kinematic analysis was the most employed approach in the studies reviewed. However, the authors emphasize the need for further investigations into the corresponding muscle activations and recruitment patterns to better understand the biomechanics of overhead throwing movements. They also highlight the importance of exploring shoulder musculoskeletal modeling in this context. Despite the limitations mentioned, the authors encourage future well-designed studies to address the gaps identified in this review and further advance the understanding of shoulder biomechanics during overhead throwing movements.

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