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What are the Individual Characteristics or Skills Associated with Baseball Batting Performance? A Scoping Review

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Abstract

Background In baseball, batting performance can be measured using game and advanced statistics as well as hitting metrics. To date, the core set of individual characteristics or skills associated with superior batting performance remains to be identified. The aim of this scoping review was to identify and classify the individual characteristics or skills associated with baseball batting performance indicators and describe the methods used to assess these individual characteristics or skills and batting performance indicators.

Methods A scoping review design was chosen to conduct a systematic literature search. Electronic searches of MEDLINE, SPORTDiscus, and PsycINFO databases were undertaken from inception to August 2024. Cross-sectional studies that investigated the relationship between batting performance indicators and individual characteristics or skills in male or female baseball batters were selected.

Results Twenty-two cross-sectional studies investigating potential individual characteristics or skills of baseball batting performance met the inclusion criteria. The primary baseball batting performance indicators were grouped into three categories: game statistics, advanced statistics and hitting metrics. Anthropometric measures (height, weight), physical fitness tests (1-RM bench and squat, grip strength, jumps, medicine ball throws, sprint, trunk flexibility, etc.), visual skills (visual acuity, contrast sensitivity, etc.), perceptual skills (anticipation, visual recognition, etc.) and visuomotor skills (eye-hand coordination, reaction time, etc.) were the individual characteristics or skills associated with either game statistics, advanced statistics or hitting metrics.

Conclusions Based on the studies included in this scoping review, the results show that several anthropometrics, physical, perceptual-cognitive, and visual skills were associated with superior game statistics, advanced statistics or hitting metrics. Greater height, weight, upper- and lower-body muscle strength, power, and speed, as well as oculomotor skills, visual system characteristics, anticipation, visual recognition, and visuomotor skills corresponded to better batting performance.

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Key Points

Batting performance in baseball can be measured by a variety of performance indicators, including game statistics (e.g., batting average, homeruns, on-base %), advanced statistics (e.g., hard-hit %, inside-zone contact %, outside-zone chase %) as well as hitting metrics (e.g., ball exit speed, swing speed, launch angle).

The most reported individual characteristics or skills categories associated with batting performance indicators are anthropometric measures and physical fitness tests, primarily focused on strength and power qualities in both the upper and lower body. In contrast, visual, perceptual, and visuomotor skills are less reported despite their important role in interceptive tasks such as batting in baseball.

Keywords Anthropometrics, Physical fitness tests, Athletic abilities, Perceptual skills, Visual skills

Background

A combination of different individual characteristics and skills is a crucial component characterizing elite baseball players [1–3]. These characteristics and skills often differentiate the less experienced players from the most elite ones [2, 4–6].

The fundamental technical requirements for a position player to learn in baseball can be separated into three categories such as baserunning, fielding, and batting. Batting is a critical skill that is now extensively tracked during practice and games using modern technologies [7]. Thus, when recruiting the best talent in a team or organization, batting performance statistics and metrics are used to assess players' offensive value [8].

In addition, batting in baseball is a complex interceptive motor skill that requires a high-level of visuomotor control influenced by batters' reaction time, eye-hand coordination, strategic decision-making, and anticipation to succeed against the pitcher [9–13]. In baseball, a swing can be broken down into several key phases: stepping, landing, swing and impact [14]. As a result, batters need to coordinate incoming visual and perceptual information with optimal motor coordination to make an accurate solid contact with the ball to increase their chance of success.

Several batting performance indicators have been used to assess in-game batting performance and can be classified into outcome-based game statistics (i.e. bases on ball, batting average, on-base %, runs batted in), advanced statistics that capture both decision-making tendencies and quality of bat-to-ball contact (i.e. fastball chase %, inside-zone swing %, hard-hit %) and hitting metrics related to ball flight and physics (i.e. ball exit speed, launch angle and swing speed) [7, 8]. Compared to traditional outcome-based game statistics, more advanced statistics metrics, such as players ability to swing at pitches in the zone compared to outside the zone, swing at fastballs instead of off-speed pitches, and their ability to produce a high percentage of hard-hit balls can offer deeper insights into a player's batting abilities and tendencies [15, 16]. With the emergence of new technologies in sport performance analysis, ball exit speed is now a commonly measured in-game metric, as higher ball exit speed is generally associated with greater chance to get hits [17]. Altogether, these statistics and metrics provide a comprehensive overview of a baseball player's offensive contributions.

Despite the importance of these offensive statistical measures and metrics, a comprehensive understanding of batting performance requires considering the broader context in which these numbers are produced. To date, much of the scientific research on factors associated with baseball performance has focused on pitching [1, 3, 18], but the need for a systematic assessment of the individual characteristics or skills associated with baseball batting performance seems just as important to cover and is currently lacking. Understanding the associations between batters' individual characteristics or skills with batting performance indicators will help coaches and trainers to create and adapt individualized training programs in the hope of enhancing players' offensive abilities resulting in increased performance at the plate. Therefore, the purpose of this study was to identify and classify the key individual characteristics or skills associated with batting performance indicators in baseball and describe the methods used to assess these individual characteristics or skills and batting performance indicators.

Methods

Study Design

A scoping review design was selected to address broad sport-performance research questions in a sport science subject that has been examined mostly through cross-sectional designs with several variables and research tools. This scoping review was conducted according to the Peters et al. [19] and Pham et al. [20] framework for scoping reviews.

Search strategy

Identifying the Research Question

This scoping review was conducted to answer the following research questions: what are the individual performance indicators of baseball batting performance, how are they measured, and what are the relationships

between the individual characteristics or skills and batting performance indicators?

Identifying Relevant Studies

The initial search strategy was conducted with the assistance of the university's librarian, with no restrictions on publication date, in October 2023 and updated in August 2024 in the following databases: MEDLINE, SPORTDiscus and PsycINFO. The search was organized around sport performance and baseball specific key terms (MeSH or non-MeSH) such as (baseball) AND (performance OR kinematics OR kinetics OR perceptual* OR vis* OR fitness test*) AND (bat* OR biomechanic OR hit*). Included studies references list were examined to identify potential additional sources. Endnote 20.6 was used for reference deduplication across the mentioned databases to ensure tracking the number of duplicates and to manage the search.

Studies Selection and Screening

- Inclusion and exclusion criteria

To be included in the first step of article selection, studies had to be published in a peer-reviewed journal, written in either English or French, and report an association between an individual characteristic or skill and a batting performance indicator. The articles search was restricted to English and French articles, as these were the languages in which the research team had sufficient proficiency to ensure accurate screening and data extraction. Only cross-sectional studies focusing on male or female baseball batting performance were included in the review. All other sports were excluded. Studies involving injured players or players presenting with pain were also excluded. In baseball, batting performance indicators are outcome-based and mostly include game statistics (e.g. batting average, hits, slugging %, homeruns), advanced statistics related to decision-making and quality of bat-to-ball contact (e.g. zone-contact %, fastball chase %, inside-zone miss %, batting average on balls in play), and hitting metrics (e.g. swing speed, ball exit speed, launch angle, distance, hang time). To be included, studies needed to report on at least one of these performance indicators. The following study designs and publication types were excluded from the review: opinion and commentary papers, letters, editors' responses, conference abstracts, intervention studies, case reports and case series studies.

- Study screening

The article search was completed by one of the authors (M.T.). Record screening by title and abstract was conducted independently by two authors (M.T. and B.C.). Three categories were used to classify the studies. The studies were classified as either relevant, irrelevant, or possibly relevant studies. Then, studies were gathered in an Excel spreadsheet where the two authors compared their initial screening. If a disagreement occurred between the two authors, further review was conducted by both authors to decide whether a study should be included or not, and a third author (M.D.) was involved if the initial authors could not reach agreement. Studies' full texts judged relevant and possibly relevant by the authors were screened by two authors (M.T. and B.C.) to determine the final set of eligible studies to be included in this scoping review.

Data Extraction

To extract relevant data and information from the included studies, a data extraction table was created and included the following information: *author and year of publication, study objectives, study design, population, batting performance indicators, individual characteristics or skills, and results*. Data extraction was conducted by one reviewer (M.T) and double-checked by a second one (B.C.).

Results

A total of 1948 articles were identified in the literature, and 22 fulfilled the selection criteria. Figure 1 presents the schematic overview of the search methodology. All included studies were cross-sectional conducted with various types of design ranging from descriptive laboratory study to longitudinal observational study design. Populations across studies varied as two studies involved youth baseball players, three studies high school players, five studies college players, two studies amateur players while ten studies involved professional baseball players either from Minor League, Major League, or both. Only two studies included female baseball players (Fig. 2).

Batting Performance Indicators

Game Statistics

Ten studies reported on offensive game statistics and investigated their associations to batters' individual characteristics or skills. The selected statistics included: bases on ball (BB) [10, 21], batted ball outcomes (hit or no hit) [17], batting average (BA) [4, 21–26], homeruns (HR) [4, 6, 22, 27], on-base plus slugging (OPS) [4, 28], on-base % (OBP) [4, 10, 21, 24–26], runs batted in (RBI) [4, 24], runs scored (RS) [4, 28], singles [28] slugging (SLG) [4, 6, 10, 21, 24–26, 28], strikeouts (K) [10, 21, 25], total bases (TB) [6, 24], bases on ball-to-strikeouts ratio (BB/K) [21, 25] and weighted on-base average (wOBA) [28].

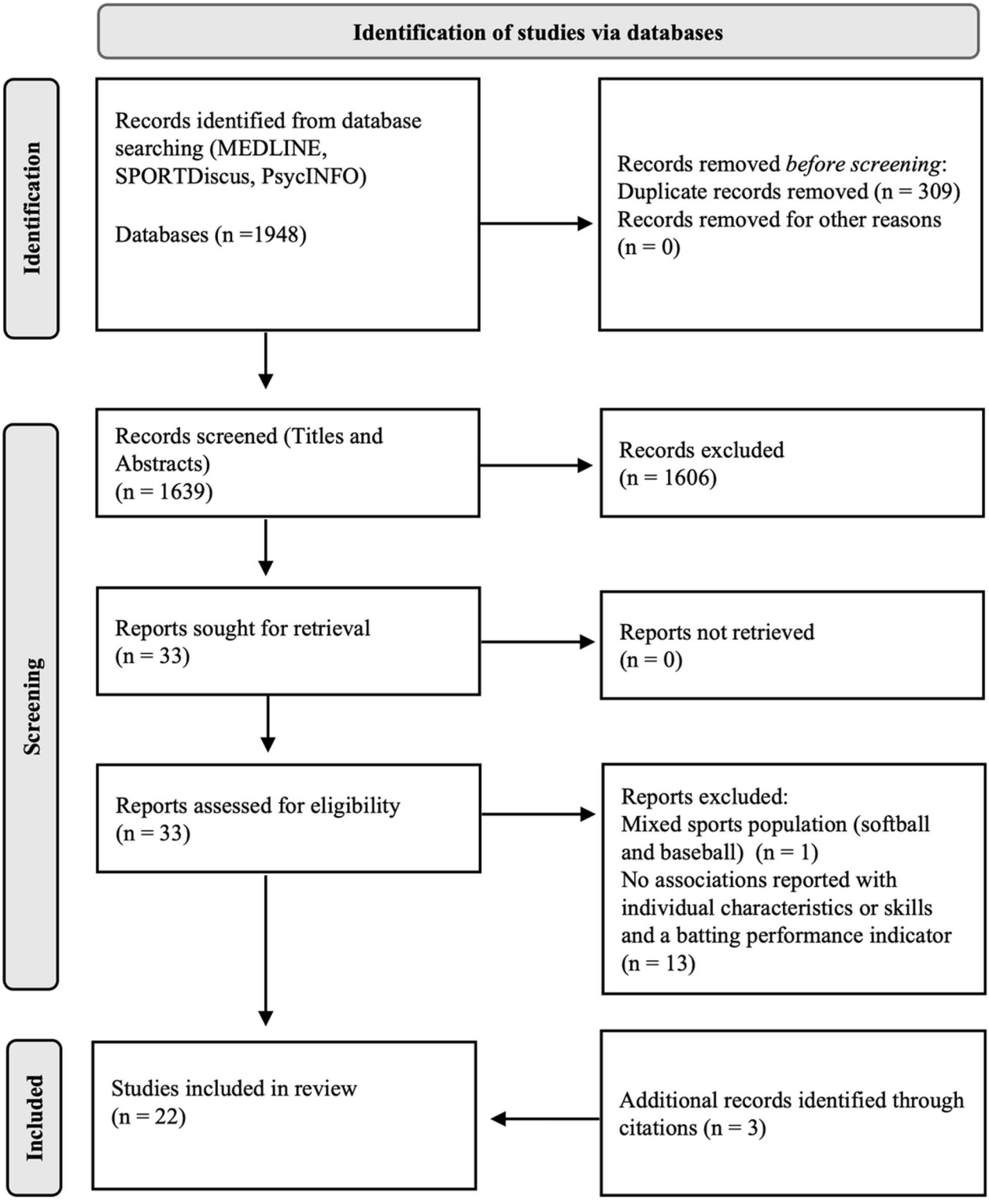

Fig. 1 Flow diagram of the search methodology

Advanced Statistics

Five studies reported on advanced statistics and investigated their associations to batters' individual characteristics or skills. The selected advanced statistics included: at bats per base on ball (BB per AB) [15, 16], fastball chase % [15, 16], hit rate (total number of hits/30) [11] hard-hit % at 95 miles per hour + (HHP) [29], inside-zone swing % [15, 16], inside-zone miss % [13], inside-zone fastball

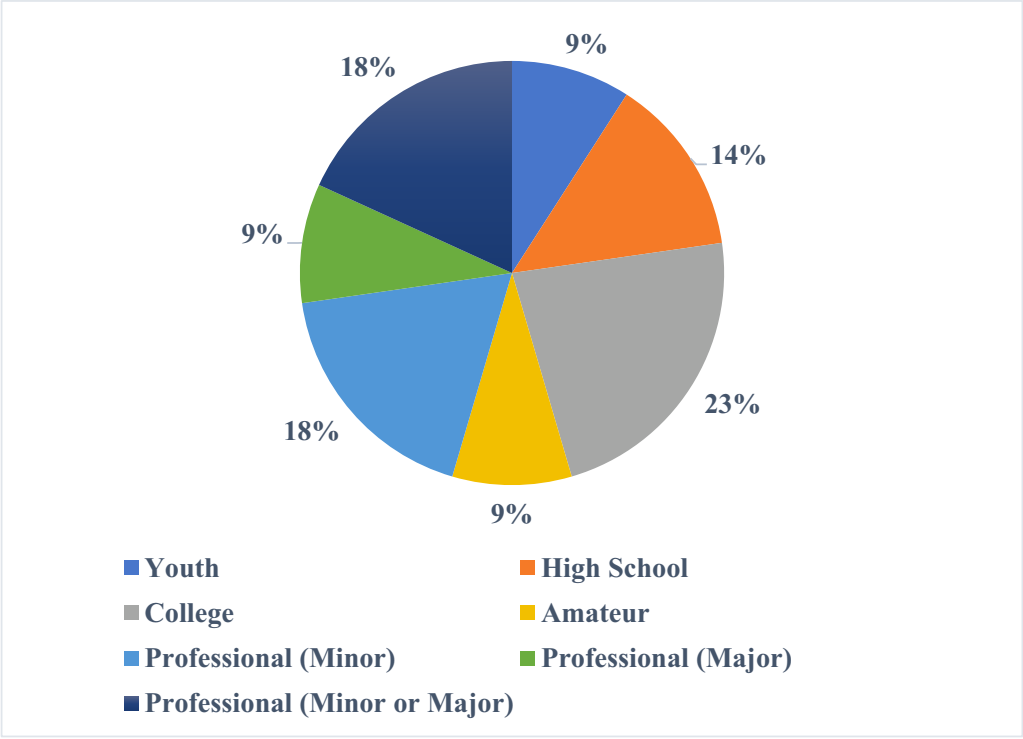

Fig. 2 Distribution of samples across studies

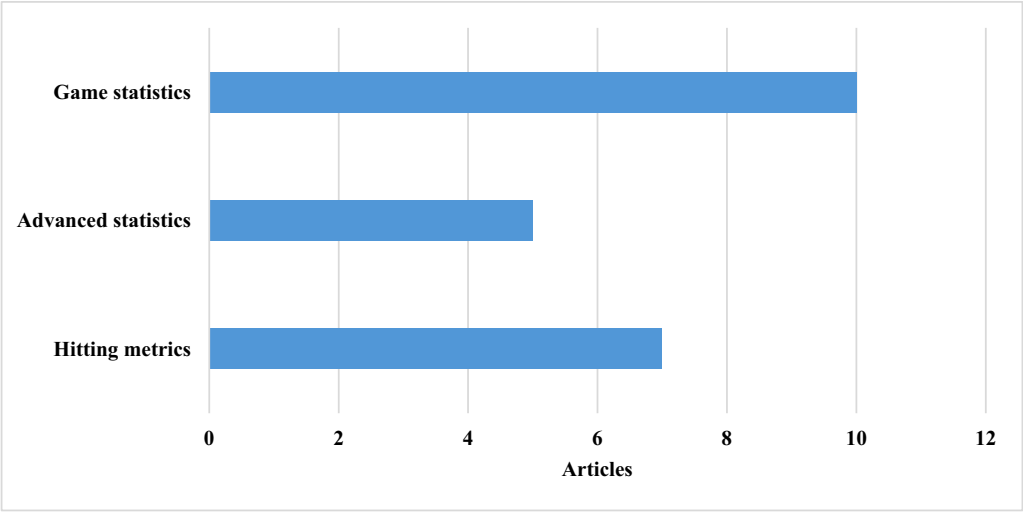

Fig. 3 Distribution of batting performance indicators across studies

swing % [15, 16], outside-zone chase % [13, 15, 16] and zone contact % (ZCP) [29].

Hitting Metrics

Seven studies reported on hitting metrics and their associations to batters' individual characteristics or skills. The selected hitting metrics included: batted ball distance [12, 17], ball exit speed [2, 12, 17, 30], hang time [17], launch angle [17] and swing speed [30–33] (Fig. 3).

Individual Characteristics or Skills Associated With Batting Performance Indicators

Anthropometric Measures

Eight studies [2, 4, 6, 12, 17, 22, 29, 33] reported on anthropometric measures associated with batting performance indicators in male baseball players across competitive levels, including youth athletes (6–15 years), high school players (grades 7–12), collegiate athletes (Division I and summer leagues), and professional players (Major League Baseball (MLB) and Minor League), as well as

one study on Japanese female professional players. Positive relationships were found between height and batted ball outcomes (hit or no hit) [17], exit speed [2, 12], swing speed [33], HHP [29] and ZCP [29]. No associations were reported for height and BA [22], SLG [6] and swing speed [33]. Regarding weight, seven studies [2, 6, 12, 17, 22, 29, 33] focused on the association between weight and batting performance indicators. Exit speed [2, 12] and HHP [29] were all positively associated with weight whereas ZCP [29] was negatively associated. Mixed results were found for HR, as Hamburg et al. [22] reported a positive association with weight and Hoffman et al. [6] reported no association. Three studies [4, 22, 24] investigated associations between body mass index (BMI) and batting performance indicators. One the one hand, Crotin et al. [4] found positive associations with BA, HR, OBP, OPS, RBI, RS, and SLG and Hamburg et al. [22] with HR. On the other hand, Watanabe et al. [24] found no associations between BMI and BA, OBP, OPS, SLG, RBI in and TB. Hoffman et al. [6] was the only study reporting associations with body fat % and lean body mass and found no associations with HR, SLG and TB.

Additional details regarding the sample characteristics and the tools used to assess the relationship between anthropometric measures and the batting performance indicators are available in the supplementary materials section (supplementary materials).

Physical Fitness Tests

Nine studies [2, 6, 24, 26, 29–33] reported on physical fitness tests associated with batting performance indicators in youth players (6–15 years), high school athletes, collegiate players (Division I, Division III, and Appalachian League), professional organizational athletes and MLB players, and Japanese female professional athletes. To facilitate the reporting of studies' results, the physical fitness tests were grouped into their respective physical qualities such as muscle strength, muscle power, speed, muscle endurance, muscle flexibility, balance, and coordination. Figure 4 presents the physical fitness tests' physical qualities studies' distribution.

Muscle Strength

Two studies [26, 32] used 1-repetition maximum (RM) protocols, respectively bench press and squat exercise protocols, to assess their relationship with swing speed, AVG, OBP and SLG. Miyaguchi et al. [32] found that 1-RM bench press was positively associated with swing speed when considering absolute value, but not when looking with respect to kilogram/bodyweight value. Papadakis et al. [26] found positive associations between 1-RM squat with AVG and OBP, but not SLG. Six studies [2, 6, 24, 26, 29, 33] investigated muscle strength with the use of a dynamometer with protocols of grip strength [2, 6, 24, 26, 29], back strength [2] and lower extremity muscle torque in abduction, adduction and internal rotation for the pivot and step legs of the batting stance [33]. Positive associations were found between grip strength and HR, SLG and TB in Hoffman et al. [6]. Papadakis et al. [26] found positive associations between grip strength and AVG and OBP but not SLG. On the one hand, Nakata et al. [2] found a positive association in their total sample between right arm and left arm grip strength and ball exit speed. On the other hand, Watanabe et al. [24] found no

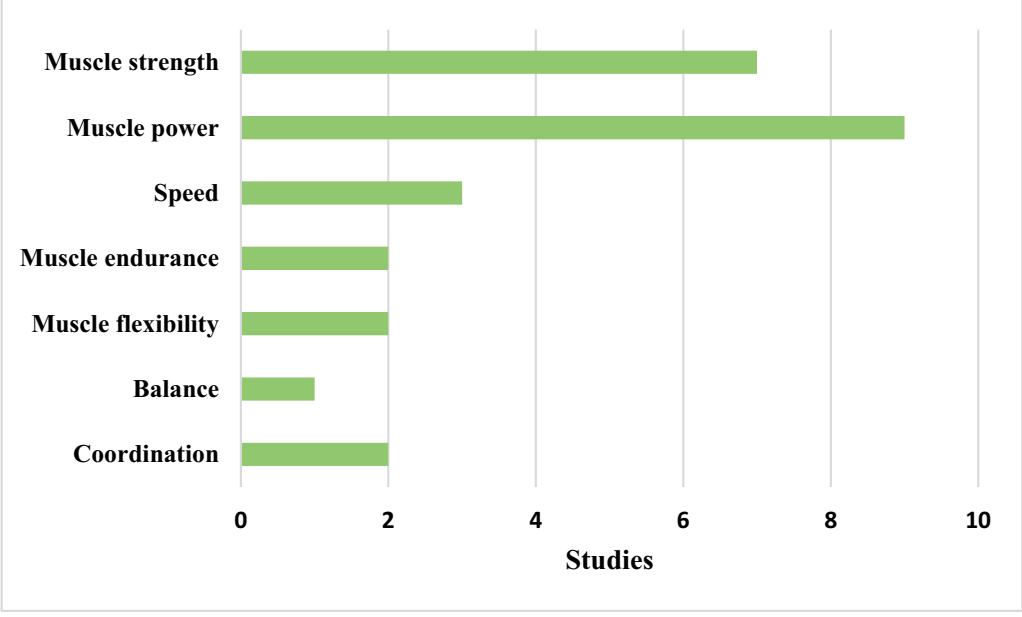

Fig. 4 Physical fitness tests' physical qualities

association between grip strength and TB, SLG, BA, RBI, OBP and OPS in Japanese female baseball players. Finally, grip strength was found to be positively associated with HHP for the dominant and non-dominant arm grip strength, but not for ZCP for the latter two in Kohn et al. [29]. Regarding back strength, Nakata et al. [2] found a positive association with ball exit speed whereas Watanabe et al. [24] found no associations with game statistics in Japanese female baseball players. Lower extremity muscle torque protocols showed that internal rotation torque was positively associated with swing speed in the Tee-ball division for the pivot leg and for the step leg in all subjects and the Tee-ball division in Tsutsui et al. [33]. Two studies [24, 32] used an isokinetic machine to assess the associations between muscle strength protocols to swing speed [32] and offensive statistics such as TB, SLG, BA, RBI, OBP and OPS [24]. Miyaguchi et al. [32] investigated the isokinetic chest press protocol using 3 different speeds (0.4 m/s, 0.8 m/s and 1.2 m/s) in absolute and relative value (kilogram/bodyweight) to assess its relationship to swing speed. The results showed that the 0.4 m/s, 0.8 m/s and the 1.2 m/s absolute values were all positively correlated to swing speed whereas only the 1.2 m/s protocol in relative value was found to be associated with swing speed. Watanabe et al. [24] investigated the association between isokinetic knee extension and knee flexion protocol and found no association with offensive statistics of TB, SLG, BA, RBI, OBP and OPS.

Muscle Power

Nine studies [2, 6, 24, 26, 28–30, 32, 33] reported on muscle power tests' associations with batting performance indicators. Five studies [6, 24, 26, 28, 29] used the countermovement jump protocol to find associations with batting performance indicators. Only countermovement jump height was found to be positively associated with offensive statistics such as BA, SLG, TB, and OPS in Watanabe et al.[24]. Other jump protocols such as the broad jump [2, 24, 30] and the lateral to medial jump [2] were also investigated and only broad jump was found to be positively associated with TB, SLG, BA, RBI, OPS [24] and exit speed [2]. In relation to upper-body power, one study investigated the associations with bench press absolute and relative (kilogram/bodyweight) peak power and swing speed and found a positive association in absolute peak power but not in relative [32]. Another study used the backward overhead medicine ball throw protocol for distance and found that it predicted swing speed in the study total sample and major division samples but not for the Tee-ball division sample. Finally, Taniyama et al. [30] explored the relationship between rotational medicine ball throw and exit speed and swing speed and found positive associations for both batting performance indicators.

Speed

Three studies [2, 6, 29] reported on speed tests and their associations with batting performance indicators. Hoffman et al. [6] found that the 10-yard sprint was negatively associated with TB whereas Nakata et al. [2] found a negative association with ball exit speed. Kohn et al. [29] used the 30-yard sprint and found no association with either hard-hit % or zone contact %.

Muscle Endurance

Two studies [2, 31] examined the association between muscle endurance tests and batting performance indicators. Lin et al. [31] found that static flexors endurance, dynamic flexors/extensors ratio and static flexors/extensors ratio were negatively associated with swing speed. Nakata et al. [21] explored sit-ups protocol association with exit speed and found a positive association.

Muscle Flexibility

Two studies [2, 24] reported on muscle flexibility assessments and its link to batting performance indicators. Watanabe et al. [24] explored the association between stride-leg and pivot-leg straight-leg raise flexibility and reported no association with TB, SLG, BA, RBI, OBP and OPS. Nakata et al. [2] examined trunk flexibility association with ball exit speed and reported a positive association with exit speed.

Balance

Only Tsutsui et al. [33] investigated a balance protocol with swing speed and found that only pivot-leg modified star excursion balance test (SEBT) was a predictor of swing speed in their major division sample group.

Coordination

Two studies [2, 6] reported on coordination tests associations with batting performance indicators. Hoffman et al. [6] found no association between the pro-agility test and HR, SLG and TB whereas Nakata et al. [2] found side steps protocol to be positively associated with ball exit speed.

Additional details regarding the sample characteristics and the tools used to assess the relationship between the physical fitness tests and the batting performance indicators are available in the supplementary materials section (supplementary materials).

Visual Skills

Four studies [10, 11, 13, 16] reported on visual skills tests associated with batting performance indicators in male and female athletes from the Hong Kong national team and baseball athletes across multiple levels. Chen et al. [11] found that a 12-element ocular-tracking index including latency, open-loop acceleration, steady-state

gain, proportion smooth, saccadic rate, saccade amplitude, saccade dispersion, direction noise, noise asymmetry, direction anisotropy, speed noise and speed responsiveness was positively associated with male and female baseball players' hit rate in players of different years of experience ranging from 3 to 10 and more years. Liu et al. [13] used quantitative eye-tracking tasks to investigate their relationship with advanced statistics. Among these eye-tracking tasks, general oculomotor speed was found to be an individual predictor of inside-zone swing %, smooth pursuit accuracy was found to be an individual predictor of outside-zone swing % and general processing speed was found to be an individual predictor of outside-zone swing % and inside-zone swing %. Both Burris et al. [10] and Liu et al. [13] investigated visual clarity and contrast sensitivity assessment baseball performance indicators. Burris et al. [10] found no relationship between OBP, BB%, K% and SLG and visual clarity but found that contrast sensitivity was an individual predictor of K%. Liu et al. [13] found no associations for either visual clarity or contrast sensitivity with outside-zone swing %, inside-zone swing %, and inside-zone miss %. Laby et al. [16] found associations between its enhanced vision testing system core score and inside-zone swing %, inside-zone fastball swing %, outside-zone chase %, fastball chase % and BB per AB. Burris et al. [10] found that depth perception was an individual predictor of BB% but not for OBP, K% and SLG.

Additional details regarding the sample characteristics and the tools used to assess the relationship between visual skills and the batting performance indicators are available in the supplementary materials section (supplementary materials).

Perceptual Skills

Four studies [10, 13, 21, 25] included articles' reported on perceptual skills tests associated with batting performance indicators in male collegiate Division athletes and professional baseball athletes from different levels. In their study, Muller et al. [21] found a positive association between overall pitch type combination and temporal occlusion applied at front foot impact and BA but not for OBP, SLG, K and BB/K ratio. They also found positive associations between fastball/changeup combination and temporal occlusion applied at ball release with OBP, and BB but not for BA, SLG, K and BB/K ratio. No associations were found for overall pitch type combination and temporal occlusion applied at shoulder square, and ball release as well as fastball/changeup combination applied at front foot impact and shoulder square. Morris-Binelli et al. [25] also used an anticipation skill task with temporal occlusion applied at the point of ball release (R), 80 ms after ball release (R + 2) and 200 ms after ball release (R + 5). The authors found a positive relationship for combined pitch type and location prediction accuracy at R + 2 and SLG, for pitch location prediction accuracy at R + 2 and SLG and for pitch type prediction accuracy at R + 5 and OBP and BB/K ratio [25]. A negative relationship was found for pitch type prediction accuracy and R + 5 and K% [25]. Perception span association with batting performance indicators was investigated by Burris et al. [10] and Liu et al. [13]. Burris et al. [10] found no association with outside-zone swing %, inside-zone swing % and inside-zone miss % compared to Liu et al. [13] who found that perception span is a predictor of OBP, K% and SLG but not BB%. Finally, Reichow et al. [23] used a visual recognition tachischopic test to assess its relationship with BA and found a positive association.

Additional details regarding the sample characteristics and the tools used to assess the relationship between perceptual skills and the batting performance indicators are available in the supplementary materials section (supplementary materials).

Visuomotor Skills

Four studies [10, 11, 13, 15] reported on visuomotor skills assessments associated with batting performance indicators in male and female athletes from the Hong Kong national team and baseball athletes across multiple levels. Chen et al. [11] found that a 3-element manual-control index including RMS error, gain and phase lag was positively associated with batted ball outcome (hit rate) in male and female baseball players of the Hong Kong national team of varied years of experience ranging from 3 to 10 and more years of experience. Near-far quickness was also found to be an individual predictor of game statistics of K% but not of OBP, BB% and SLG in Burris et al. [10]. No result was found between near-far quickness and advanced statistics such as outside-zone swing %, inside-zone swing % and inside-zone miss % in Liu et al. [13]. The same authors investigated the reaction time assessment and respectively found that it is an individual predictor of BB% [10] but not OBP, K% and SLG but was not associated with advanced statistics of outside-zone swing %, inside-zone swing% and inside-zone miss % [13]. In addition, Liu et al. [13] found no result between these advanced statistics and multiple object tracking assessment. In their study, Burris et al. [10] found that the target capture assessment was shown to be an individual predictor of K% but not of OBP, BB% and SLG and the eye-hand coordination assessment an individual predictor of BB% and K% but not OBP and SLG. Finally, Laby et al. [15] investigated the relationship between a proactive eye-hand visuomotor reaction task with advanced statistics and found positive associations with outside-zone chase %, fastball chase %, inside-zone swing %, inside-zone fastball swing %, and BB per AB in professional baseball players.

Additional details regarding the sample characteristics and the tools used to assess the relationship between visuomotor skills and the batting performance indicators are available in the supplementary materials section (supplementary materials).

Discussion

The individual characteristics or skills associated with baseball batting performance were identified and classified to better understand the research methods and tools used by researchers to study their associations with baseball batting performance. Most studies focused on older amateur, college or professional baseball players (77%) while younger baseball players were least studied (23%). The physical fitness tests (n = 9) and anthropometric measurements (n = 8) were the two most investigated categories of individuals' characteristics or skills related to either game statistics, advanced statistics or hitting metrics.

Anthropometric Measures

Only height and weight were found to be associated with game statistics [22], advanced statistics [29] and hitting metrics [2, 12, 17, 33] whereas conflicting results were found for BMI and game statistics [4, 6, 22, 24]. These anthropometric measures also seem important to track over time to assess the evolution of players' profiles as suggested by Crotin et al.'s [34] results. Their study investigated height, weight, and BMI changes over time in MLB professional baseball players over three separate decades (1970, 1990, 2010) and found significant differences and greater weight, height, and BMI over time among the top offensive statistics league leaders. The same observation seems true in younger large groups of amateur baseball athletes. Tremblay et al. [3] found that, in male and female baseball players aged 10–22 years, height, weight and BMI were different between the under-13 (U13), U15, U18 and U21 age categories as older players were taller, heavier and had greater BMI. Even though the study investigated the association between these measurements and pitching velocity and not batting performance, in these age groups, players often take on other positions on the field and hit as well. Altogether, these results highlight the need to assess and track anthropometric measures changes over time in baseball batters because of their associations to batting performance.

Physical Fitness Tests

Greater performance on six muscle strength tests was found to be associated with better batting performance: 1-RM bench and squat protocols [26, 32], grip strength [2, 6, 24, 26, 29], lower extremity muscle torque [33] and isokinetic chest press [32]. Conflicting results were found in back strength where in young male baseball players, an association was found with ball exit speed [2] whereas in Japanese female players, no association was found with game statistics [24]. These results could be explained by the specificity of the task where back strength and ball exit speed relate more to physical output whereas game statistics are influenced by multiple factors such as the other team defense and in-game decision-making. Greater performance on five muscle power tests namely countermovement jump [6, 24, 29], broad jump [24], bench press peak power [32], overhead medicine ball throw [33] and rotational medicine ball throw [30] was found to be associated with superior batting performance. The physical qualities of speed, muscle flexibility, balance and coordination had one test each associated with superior batting performance, which were, respectively, the 10-yard sprint [2, 6], sit-ups protocol [2], trunk flexibility [2], pivot-leg SEBT balance protocol [33] and the side steps protocol [2]. The number of studies focusing on strength (n = 8) and power (n = 9) underscores the importance given to physical qualities in baseball research by sports science researchers. Spaniol [35] proposed a baseball-specific test battery to evaluate baseball players' strength and weaknesses composed of physiological, athletic, and sport-specific skills that could be predictors of successful baseball performance. The included assessments were similar to those for this review, i.e. muscle strength, leg power, flexibility, rotational power, agility and running speed [35]. The author also suggested ball exit speed and swing speed as batting performance indicators to track in baseball batters. Based on our systematic results, there is an agreement between our results and Spaniol's proposed Baseball Athletic Test (BAT) battery for the assessment of baseball players' performance in relation to batting performance. Finally, our results are also similar to those of Kohmura et al. [36] in which coaches subjectively rated the batting ability of college baseball players in an attempt to develop a baseball-specific battery of tests for college baseball players. They found associations between subjective players' batting ability evaluation and back strength, medicine ball throw, standing long jump and the change of direction T-test.

Visual Skills

Chen et al. [11] and Liu et al. [13] were the only studies using quantitative eye-tracking apparatus respectively *Eyelink 1000* and the *RightEye test battery*. In Chen et al. [11], a greater ocular-tracking index performance was found to be associated with a better hit rate in a mixed male and female Japanese amateur baseball player's sample. Liu et al. [13] found that general oculomotor speed, latency and processing speed, auto refraction, smooth pursuit accuracy, cardinal reaction time and dynamic visual acuity were oculomotor abilities associated with

batting performance in professional baseball players. Greater visual clarity, contrast sensitivity, and depth perception were found to be associated with batting performance indicators and were all measured by the *Senaptec Sensory Station* in Burris et al. [10] and Liu et al. [13]. Finally, Laby et al. [16] found that an enhanced vision score composed of visual acuity and contrast sensitivity measure was found to be associated with batting performance in a Minor League cohort of baseball players.

Perceptual Skills

Greater visual recognition and visual anticipation skills task as well as perception span are associated with increased baseball batting performance. In two studies, Muller et al. [21] and Morris-Binelli et al. [25] investigated the visual anticipation of professional minor league baseball batters and found associations with game statistics in video-simulation temporal occlusion test requiring ball-strike assessments across different pitch type combinations (i.e. fastball/changeup/curveball) and at different phases of the pitcher motion (i.e. at front foot impact, at ball release/after ball release). The relevance of visual anticipation is high in baseball as batters are subject to extremely short temporal constraints to decide whether to swing or not at the ball based on contextual information [37]. Compared to Muller et al. [21] and Morris-Binelli et al. [25], Reichow et al. [23] investigated another important perceptual skill associated with batting performance in visual recognition accuracy using a tachiscopic task. The authors mentioned that this kind of evaluation assesses both the speed and the span of visual recognition. Their results showed an association between the task and batting average in batters and showed that the top five batters in their sample were the top scorers on the tachiscopic test. Finally, a perception span task was used by Burris et al. [10] and Liu et al. [13] to be investigate professional baseball players. Only Burris et al. [10] found perception span executed on the *Senaptec Sensory Station* to be an individual predictor of K% and SLG. The study defines the perception span task as the ability to remember and recreate visual patterns.

Visuomotor Skills

Chen et al. [11] results showed an association between a 3-element manual-control index and hit rate in a mixed male and female Japanese baseball players' sample. Their results also showed that the association between the index and hit rate was greater in more experienced players than less experienced ones. Greater eye-hand coordination, defined as the measure of the speed in which batters can make visually-guided hand responses to rapidly changing targets, and greater target capture, defined as the speed at which batters can shift attention and recognize peripheral targets, were found to be predictors of K% and SLG in professional baseball players in Burris et al. [10]. A standard reaction time assessment was also found as a predictor BB % in this study [10]. Overall, Burris et al. [10] and Liu et al. [13] used most of the same *Senaptec Sensory Station* sensorimotor tasks, but their results differed. Again, this can be partially explained by the choice of batting performance indicators such as outcome-based game statistics compared to advanced statistics related more to decision-making. Game statistics are influenced by the other team's defense, field conditions and external factors whereas the advanced statistics used in Liu et al. [13] are based on players' decision-making and take into account each decision whether to swing at the ball or not. Finally, Laby showed that a pro-active reaction time assessment was also found associated with advanced statistics based on athletes' decision-making such as outside-zone chase %, fastball chase %, inside-zone swing %, and inside-zone fastball swing %.

Evidence Gaps and Future Directions

Based on this scoping review results, several gaps were identified and could lead to deeper investigations in the field of baseball batting performance research. First, the variety of batting performance indicators used to assess their relationships to individual characteristics or skills makes it difficult to draw clear conclusions. We divided the batting performance indicators into game statistics, advanced statistics and hitting metrics to separate the indicators more logically. It is the authors' opinion that advanced statistics mostly relating to players' decision making (i.e. inside-zone swing %, outside-zone swing %, fastball chase %) are less influenced by external factors beyond a player's control such as other team defenders, weather or field conditions and should be prioritized in future investigations regarding batting performance research to remove external influence on the batting outcome measured. The second evidence gap identified through the data extraction phase was the very small representation of the female athlete population in baseball batting performance research. Only two out of twenty-two studies included were interested in associations between individual characteristics and skill and batting performance indicators in female athletes. One used a professional Japanese female athlete sample only [24] and one used a mixed male and female Japanese athletes sample [11]. Future studies should use female baseball player only samples to investigate individual characteristics and skills associated with baseball batting performance to better generalize results and to understand the differences compared with their male counterparts within the sport. Furthermore, evidence on visual and perceptual skills is inconsistent. While oculomotor control and basic visual acuity have shown some associations, other constructs such as contrast sensitivity, multiple object

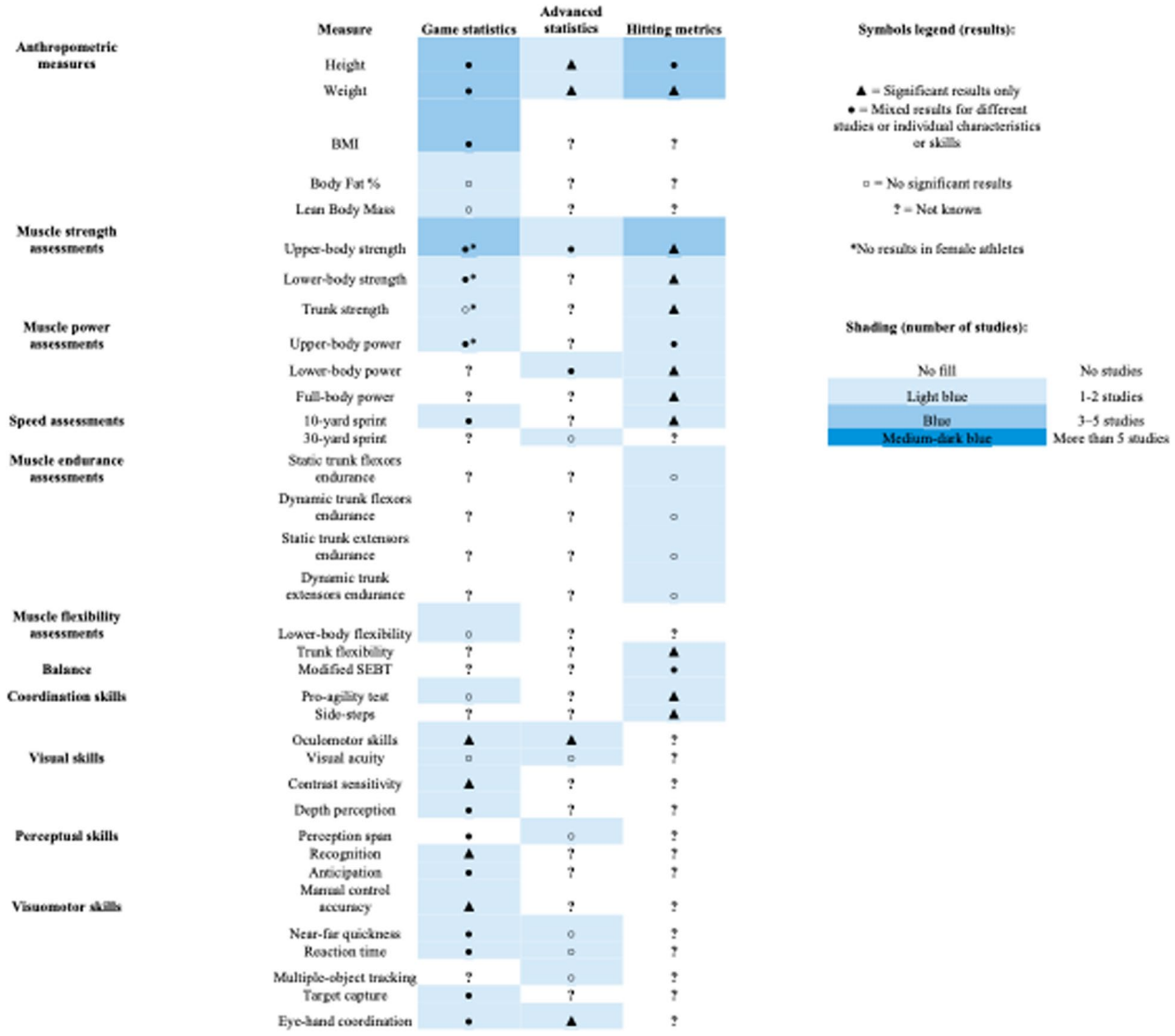

Fig. 5 Presents a systematic map of individual characteristics or skills associated with baseball batting performance

tracking, and anticipation skills relationships with baseball batting remain unknown. Also, this scoping review did not assess the risk of bias of the different studies, and the data extraction highlighted validity and reliability concerns regarding the visual, perceptual and visuomotor skill tools used in the studies of these fields of research, with sometimes only brief commercial descriptions of the tools provided to justify their use. Validity and reliability studies are needed to better understand and justify the selection of these tools to investigate their associations with batting performance in the future. For other research gaps, see Fig. 5.

From a practical perspective, the findings of this review provide an overview of batting performance that coaches, practitioners, and sports scientists can use to guide player development. Training programs should aim at the development of muscular strength, power and speed, and perceptual-cognitive skills such as visual recognition, anticipation and visuomotor skills. A combination of vision training and oculomotor exercises with strength and conditioning may enhance batting performance indicators (game statistics, advanced statistics and hitting metrics) by improving physical abilities, pitch recognition and decision-making (for further information on sport vision performance, see reviews [38–41]). The integration of these priorities into player development programs aligns with the growing accessibility of advanced measurements tools in sports (e.g., ball-tracking and eye-tracking technologies) enabling accurate monitoring of the performance changes. Altogether, the evidence from this review offers a foundation for applied practice and future intervention studies that should aim at investigating causal relationships and training intervention design to improve the individual characteristics and skills

related to batting performance. Finally, more studies are needed to better understand the different individual characteristics or skills based on athlete level of skill and competition level.

Limitations

The first limitation that should be considered is that only studies published in the English and French (although no French publications were identified) were included in this review. Another limitation concerns the variety of batting performance indicators used in the original studies to investigate their relationships with individual characteristics or skills. Such variety limits the conclusion of the review on which individual characteristics or skills are the most relevant to baseball batting performance.

Conclusion

To conclude, game statistics, advanced statistics and hitting metrics were the batting indicators used to assess their relationships with individual characteristics or skills of baseball batters in the studies included in this scoping review. Anthropometric measures and physical fitness tests were the most reported categories of individual characteristics or skills compared to visual, perceptual and visuomotor skills categories. Based on the included studies' results, we conclude that anthropometric measures such as height and weight, physical fitness tests including mostly upper-body and lower-body strength and power measures, visual skills assessing oculomotor abilities and physical characteristics of the visual system, perceptual skills of anticipation and visual recognition and finally visuomotor skills including visual perception combined with a motor response are important individual characteristics or skills that are associated with superior batting performance. Future research should investigate how the changes in these individual characteristics and skills are related to the changes in baseball batting performance indicators over time to better guide training intervention and optimize batters' performance.

Abbreviations

BA	Batting average
BB	Bases on ball
BMI	Body Mass Index
HR	Homeruns
OPS	On-base plus slugging
OBP	On-base percentage
RBI	Runs batted in
RS	Runs scored
SLG	Slugging
K	Strikeouts
TB	Total bases
BB/K	Bases on ball per strikeouts ratio
wOBA	Weighted on base average
BB per AB	Bases on ball per at bats
HHP	Hard hit percentage
MLB	Major league baseball
SEBT	Modified star excursion balance test
ZCP	Zone contact percentage
RM	Repetition maximal
R	Release
BAT	Baseball athletic test

Supplementary Information

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Supplementary Material 1.

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MT designed the search strategy whereas the selection process was carried out by MT and BC. MT, BC, JA, and MD wrote the manuscript. All authors read and approved the final version.

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Competing interests

The authors declare having no competing interest.

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