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# From Novice to Expert: How Expertise Shapes Motor Variability in Sports Biomechanics—a Scoping Review

Emile Marineau[1,2] | Julien Ducas[2,3] | Janny Mathieu[1,2] | Alvaro De Pano Rodriguez[2,3] | Martin Descarreaux[2,3] | Jacques Abboud[2,3]

[1]Department of Anatomy, Université du Québec à Trois-Rivières, Trois-Rivières, Canada | [2]Groupe de recherche sur les affections neuromusculosquelettiques de l'Université du Québec à Trois-Rivières, Trois-Rivières, Canada | [3]Department of Physical Activity Sciences, Université du Québec à Trois-Rivières, Trois-Rivières, Canada

**Correspondence:** Jacques Abboud (jacques.abboud@uqtr.ca)

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## ABSTRACT

With expertise, athletes develop motor strategies that enhance sports performance or reduce functional costs. Motor variability is known as a relevant way to characterize these strategies in athletes with different levels of expertise. The aim of this scoping review is to gather and discuss the latest advances in the impact of expertise on motor variability during sports-related tasks. A search encompassing three databases, Medline, SportDiscus, and Academic Search Complete, was performed. Our research methodology included three core themes: motor variability, laboratory instruments, and sports. Motor variability metrics (e.g., standard deviation and approximate entropy) and laboratory instruments (e.g., motion capture system, EMG, and force plate) were compiled. Athletes' expertise was defined by the time of deliberate practice, the performance results, or the level in which they performed. Overall, 48 of the 59 included studies determined that higher-skilled athletes had lesser motor variability than lower-skilled athletes. This difference in motor variability between skill levels was present within individual athletes (intra-individual) and between athletes (inter-individual). This result was independent of the criteria used to define expertise, the type of instrumentation used, and the metrics used to quantify motor variability.

## 1 | Introduction

What is an expert? For many years, researchers have tried to answer this question. One of the widely recognized definitions of expertise is the 10000 h of deliberate practice rule of Ericsson [1]. More recently, some theories have put into perspective the importance of deliberate practice and looked into the common factor among experts [2–5]. Therefore, many definitions are used to characterize experts. For example, expertise might be based on past achievements such as holding national records or achieving personal bests (PBs), the competitive level at which the athlete has competed (international vs. national vs. regional competition level), or the duration of deliberate practice. Nowadays, no consensus has been reached on how to define an expert.

In sports, as an athlete acquires expertise, its sensorimotor system will adapt to enhance performance or reduce functional costs [6, 7]. Motor variability (MV) is often used to quantify such adaptations. MV refers to the variations that emerge in motor performance across multiple repetitions of the same task [8]. MV has been associated with motor redundancy, which is the abundance of elements beyond the requisite for task resolution. This redundancy offers multiple strategies for a given motor task [8]. Various motor control theories have tried to explain how MV impacts motor performance. For instance, the uncontrolled manifold hypothesis suggests that the nervous system regulates movement by differentiating between variability that is relevant to the task and variability that is not [9]. With practice, task-relevant variability tends to decrease, as the athletes fine-tune their motor skills, while task-irrelevant variability remains constant [10].

According to optimal feedback control theory, practice-related changes may also be relevant to motor performance. Optimal performance is attained through a feedback control law that continuously resolves redundancy. This law uses all available information to select the most appropriate action for the given circumstances, reducing relevant variability [11]. This theory also suggests that movements are planned to optimize both performance and functional cost [11]. Moreover, it has been suggested that MV can contribute to the functioning and learning mechanisms of the sensorimotor system [12]. In sum, MV changes as the sensorimotor system explore new motor strategies through trial-and-error, strengthening approaches that lead to the achievement of the goal [10]. Therefore, expert athletes may exhibit lower levels of variability in task-relevant dimensions due to their learned refined motor skills and increased ability to select and execute optimal movement patterns.

Among sporting tasks, MV can be classified into three distinct types [13]. The first, strategic MV, refers to different methods or techniques chosen to realize task objectives (e.g., fast ball or curved ball in baseball). The second, execution MV, involves slight variations or adjustments across repetitions of the same method or technique (e.g., two fast balls thrown by a baseball pitcher with slightly different kinematic and/or muscle recruitment). The third, outcome MV, arises from variations in the results or outcomes of a specific action or movement (e.g., pitching a strike or a ball) [13]. This review explores the execution of MV. To assess the execution MV, one can quantify variability in movement timing, in the kinetic components or kinematic components of movement patterns, such as the center of mass displacement or joint angles and velocities. Moreover, electromyography can be used to assess execution MV by analyzing muscle activity and recruitment patterns in different regions within the same muscle or between different muscles [14].

A review by Bartlett, Wheat, and Robins [15] explored the importance of MV in sports performance. The authors summarized the findings of three studies involving javelin throwing, basketball shooting, and locomotion, and concluded that even elite athletes showed some level of variability in their movement patterns. However, they did not compare these elite athletes with novice athletes. They underline the need to investigate individual variability to complement group-focused research designs and to determine whether MV benefits or hampers sports motor performance [15].

The ability to tailor movements and muscle activity to meet evolving demands appears to be a key characteristic that distinguishes expert athletes from their peers [15–17]. In the last two decades, new studies on expertise and MV using more accurate tools and assessment methods deserve consideration. Thus, the objective of this review is to gather and discuss the latest advances presented in the literature on the impact of experience on MV during sports-related tasks.

## 2 | Methods

### 2.1 | Search Strategy

This systematic scoping review was conducted according to the framework developed by Arksey and O'Malley & Levac, Colquhoun, and O'Brien [18, 19]. This framework included the following steps:

1. identifying the research question,
2. identifying relevant studies,
3. study selection,
4. charting the data,
5. collecting, summarizing, and reporting the results,
6. optional consultation.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyzes extension for Scoping Reviews (PRISMA-ScR) guidelines were also used for reporting the results [20]. With the help of a librarian (CL), database searches were performed by EM. The search strategy consisted of using index terms and keywords in EBSCO (Medline), SportDiscus, and Academic Search Complete (ASC) search engine. Initially, three main themes were combined for the search: “Motor Variability,” “Sports,” and “Instruments.” The “Instrument” theme was more specified with terms such as “Electromyography,” “Kinematic,” and “kinetic.” The detailed search equation for each database is available in the supplemental data file. Initial searches in the databases were performed on September 15, 2022. During the review process, frequent updates of the search strategy were performed.

### 2.2 | Study Selection

First, Endnote software (Version X9, Clarivate Analytics, London, UK) was used to remove duplicates. Second, Rayyan software [21] was used to perform the initial article selection. Three independent reviewers (EM, JD, and JM) completed the title and abstract screening. In the event of disagreement, the assessors conducted a further review and open discussions to decide whether a study should be included or not. The initial literature search revealed 24 788 studies. Details of the search and inclusion process are shown in the PRISMA flow chart (Figure 1).

Details of the inclusion criteria are presented in Table 1. Only studies assessing specific sports tasks were included. For example, the comparison of countermovement jump kinematics in soccer players of different skill levels would not have been included, since countermovement jump is not a specific task performed during a soccer game. However, kicking the ball or running with a soccer ball would have been included.

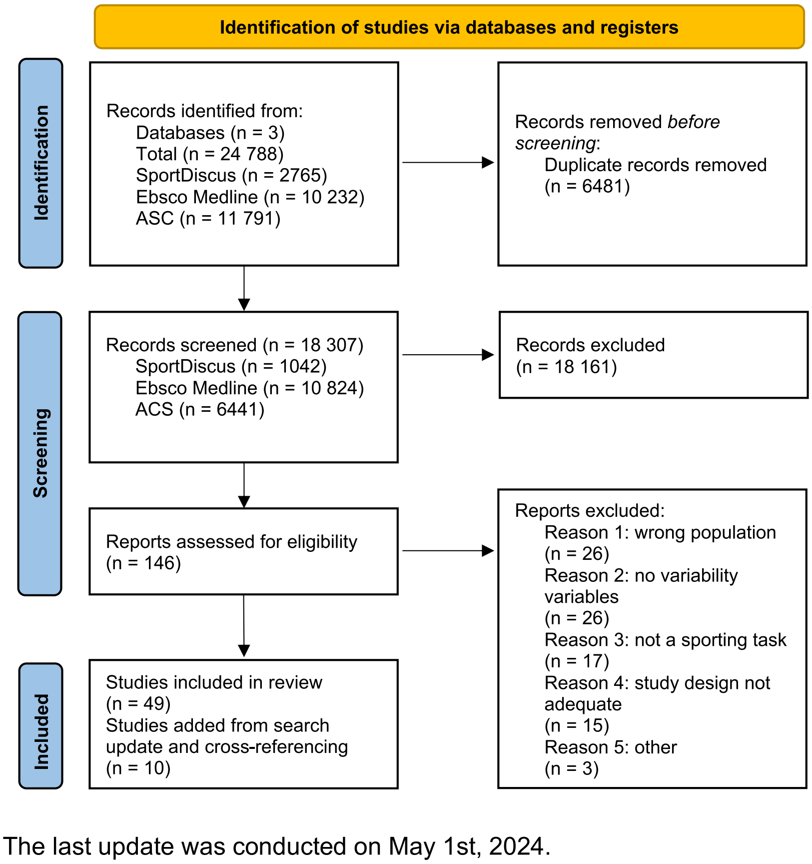


**FIGURE 1** | PRISMA flowchart illustrating the different phases of the search and selection of studies. Abbreviation: PRISMA, preferred reporting items for systematic reviews and meta-analyses.

**TABLE 1** | Inclusion criterion.

| Criterion | Description |
|---|---|
| Publication type | Empirical research. Methodology and results must be described in detail. Written in english. |
| Publication date | Between January 1, 1990, and May 1, 2024. |
| Participants' characteristics | Adolescents and adults. For HS, a significant level of skill in a sport defined by the authors. For LS, a lower level of skill than HS in the same study defined by the authors. |
| Motor variability outcomes | Kinematics (hip, ankle, elbow angle, etc.), kinetic (contact time, ground force reaction, etc.), or muscle activity (muscle synergy, lag time of activation, etc.). |
| Research design | Comparison between different levels of skill of athletes in a particular sport. No follow-up of an intervention was included. |
| Statistical information | Statistical findings on MV between groups must be presented by a specific statistical test. |

Sport was defined as: “an activity involving physical exertion and skill, one regulated by set rules or customs in which an individual or team competes against another or others” [22]. A minimum of two groups of different skills were needed: higher-skilled (HS) and lower-skilled (LS). Skills levels had to be specified in each study. Finally, to be included, MV must have been assessed during the task of the sport using quantitative instruments. MV could have been measured from direct tools used in sport (e.g., golf clubs position variability and ice tools angle variability).

Studies were excluded if they were not peer-reviewed, not in English, and if they were considered an expert opinion or editorial. Some studies grouped participants by age, but with similar levels of skill. These studies were excluded. Furthermore, if the research did not present a specific statistical analysis of MV, it was excluded.

Participants aged under 14 years old were also excluded from the review. Finally, studies assessing outcome variability (e.g., time to complete a distance or length of a throw) and strategic variability (e.g., hitting a forehand or backhand in tennis) were excluded.

### 2.3 | Charting the Data

All the data necessary for the analysis were extracted from the studies, sorted by key issues or themes, and tabulated in Microsoft Excel. The information was sorted as follows:

- Author(s), title, year of publication, location of first author.
- Sport and task assessed (e.g., dribbling in basketball or slap shot in ice hockey).
- Category of sport (strength, endurance, or precision and discrete or continuous).
- Performance measure.
- Metrics of variability (e.g., standard deviation and coefficient of variation).
- Intra- or inter-individual variability.
- Motor control parameters (e.g., angle coordination and muscle activity).
- Results of the variables (e.g., knee angle, RMS of tibialis, and center of mass mediolateral), and the direction of the variable (more or less variable).
- Study population (overall group size, by sex, by expertise, and by age).
- Expertise (criterion to be in the HS group or the LS group).
- Instruments and instruments validity.

According to the original grouping (e.g., 12 years of baseball experience vs. no experience [23]), the groups were classified as HS and LS. When studies presented three or more groups (e.g., 10 km race walking PB of 40 min 25 s vs. 43 min 27 s vs. 48 min 54 s [24]), every comparison, between two different groups, was reported. To facilitate comparison between studies, a ratio of variables was calculated. For each variable in a study, a score of −1, 0, or +1 was computed according to the direction of the variable. Minus one meant that the HS group was statistically less variable than the LS group, while +1 meant the opposite. Zero meant that there was no statistical difference between the groups. The ratio corresponded to the sum of scores obtained from a single study divided by the number of variables in a study (ratios are presented in the supplemental data file).

To compare studies that examine analogous variability, studies were classified into two groups. The first group encompassed research focusing on intra-individual variability, and the second group examined inter-individual variability. Intra-individual variability refers to the variation or differences observed within the performance of a single individual over multiple instances of the same task. It involves examining how a person's performance fluctuates or changes from one trial to another. In comparison, inter-individual variability pertains to the differences in performance or behavior observed between different individuals when performing the same task. Specifically, it focuses on comparing the performance of various individuals on a given task to understand the range of abilities, strategies, or characteristics that contribute to observed differences. Furthermore, a categorization was performed based on the type of task: discrete or continuous tasks. On the one hand, a discrete task refers to a motor activity with distinct and well-defined starting and end points. Examples of discrete tasks in sport include throwing a ball, kicking a soccer ball, or shooting a basketball. On the other hand, a continuous task involves actions that have no distinct or separate points of initiation and termination. These tasks typically involve repetitive and uninterrupted movements without clear breaks. Examples of continuous tasks in sports include cycling, swimming, and running. Finally, a classification was based on the main characteristic needed to perform the task, either strength, endurance, or precision. For instance, bench pressing would be included in the strength category, running in the endurance, and shooting arrows in the precision one.

## 3 | Results

The database search did not find any review on the effect of expertise on MV. Fifty-nine studies, all from peer-reviewed journals, were retained to extract data from the 24 788 studies found in the database (Figure 1). All data extracted from included studies were summarized and combined in the available supplemental data file. The included studies were published between 1990 and 2024 from 22 different countries. A timeline of the studies included in the review is presented in Figure 2.

### 3.1 | Study Population

Of the 59 included studies, the sample size ranged from 4 to 73 participants (mean = 21.92, SD = 12.50). In the studies included in the scoping review, a total of 1293 participants were evaluated. Male athletes ($n = 784$) dominated female athletes ($n = 276$) as only 21% of the participants were female athletes. No information about sex or gender was provided for 233 participants (Figure 3). The age of the participants ranged from approximately 14–32 years old, according to the available data. A total of 583 HS and 653 LS participants were included. No information about the number of participants in HS and LS groups was available for three studies [25–27], which included 57 participants (Figure 3). The grouping criteria were different for each study. For example, in 31 cases the expertise was identified by the time of deliberate practice [23, 26, 28–56]. In 22 other cases, expertise was classified by performance results, such as the best time on a particular distance [24, 25, 27, 35, 39, 42, 52, 56–70]. Plus, 18 studies grouped participants according to the level of performance in their sport [26, 28, 31, 37, 45, 48, 49, 52, 54, 71–79]. Eleven studies used more than one criterion to group their participant. More information about how the authors grouped their participants and the specific criteria used to define HS or LS are presented in the supplemental data file.

### 3.2 | Sports and Type of Tasks

This scoping review included many sports, from collective sports (e.g., soccer) to individual sports (e.g., running). In total, MV was

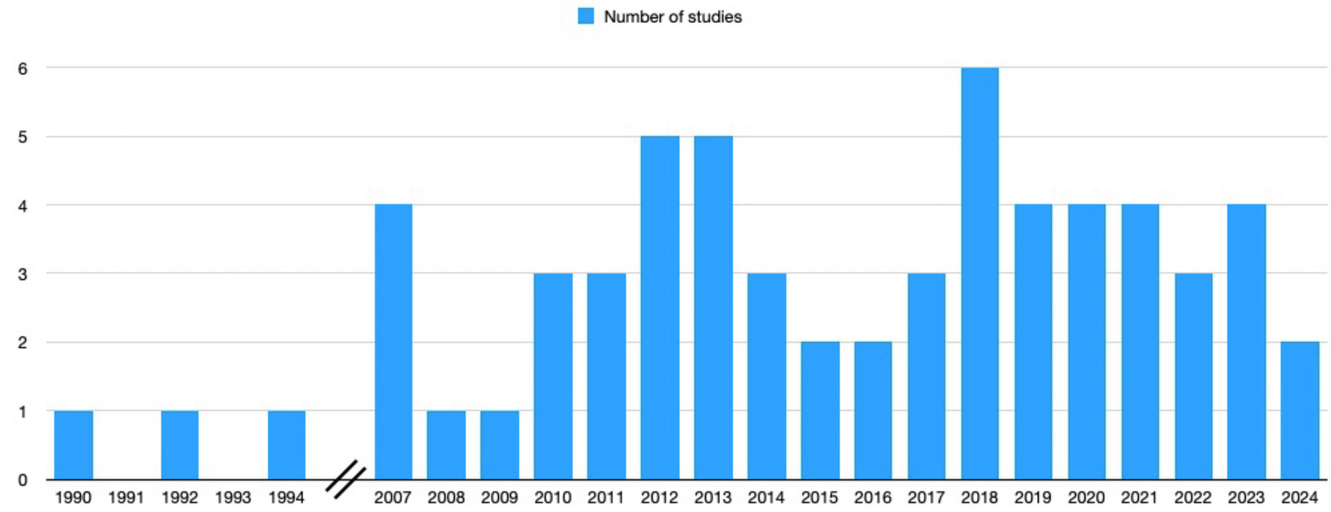


**FIGURE 2** | Publication year of studies on MV in sport from 1990 to 2024.

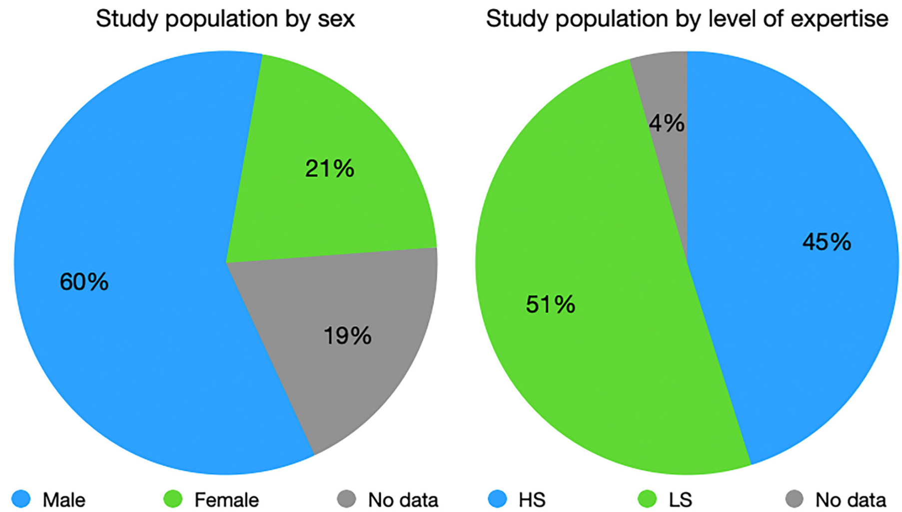


**FIGURE 3** | The participants' sex and level of experience. HS, higher-skilled athletes; LS, lower-skilled athletes.

assessed in 24 different sports (Table 2). First, studies that investigated sports tasks that mainly required endurance, precision, or strength were grouped accordingly (Figure 4A). Twenty-six studies were included in the endurance group [24, 27, 29, 31, 32, 35–37, 39–41, 43, 44, 46, 50–53, 56, 58, 59, 64, 68, 70, 73, 80] and in the precision group [25, 26, 28, 30, 33, 34, 38, 42, 45, 47–49, 54, 55, 57, 60–63, 66, 67, 69, 71, 75, 77, 81] group. Only seven studies explored strength-oriented sports [23, 65, 72, 74, 76, 78, 79]. Out of the 26 endurance tasks, 18 studies showed that HS athletes are less variable, seven showed the opposite and one did not show any differences. From the 26 precision tasks, 22 studies showed that HS athletes are less variable, two showed the opposite and two did not show any differences. From the seven studies evaluating strength-oriented tasks, four studies found that HS is less variable than LS [23, 76, 78, 79], one found the opposite [72] and two found no difference [65, 74]. Second, studies that investigated discrete and continuous tasks were grouped accordingly (Figure 4B). Twenty-nine studies evaluated discrete skills, such as baseball throwing, golf swing, bench pressing [23, 25, 27, 28, 33, 38, 45, 48, 54, 55, 57, 60–63, 65–69, 71, 72, 74, 76–79, 81]. The remaining 31 focused on continuous tasks, such as running, walking, and cycling [24, 26, 29–32, 34–37, 39–44, 46, 47, 49–53, 56, 58, 59, 64, 70, 73, 75, 80]. No distinct pattern of MV emerged between types of sports. Within the discrete task group, 20 studies indicated that HS athletes exhibit less variability than LS athletes, five presented opposite findings, and four observed no difference. In the continuous group, 25 studies concluded that HS athletes show less variability than LS athletes, 5 reported opposing results, and 1 did not detect differences.

### 3.3 | Instruments

Many instruments were used in the different studies (Table 2 and Figure 5). For instance, kinematic variability was assessed using motion capture systems (e.g., Vicon MX, Oxford Metrics), video cameras (e.g., Panasonic NV-MS1 HQ S-VHS), and inertial measurement units (IMU; e.g., Xsens, MTx). Kinetic variability was assessed using pressure plates (e.g., h/p/cosmos Quasar, h/p/cosmos Sports, Medical gmbh) and force plates (e.g., Bertec 4060-15, Bertec). Variability of neuromuscular activity was assessed using electromyography (e.g., Delsys DE

**TABLE 2** | Details on sports, tasks, and instruments used in each included study.

| Sport | Tasks | Instruments | Articles |
|---|---|---|---|
| Alpine ski | Ski simulator | Motion-capture system | [53] |
| Archery | Shots at 30 m | Pressure plate | [57] |
| | Shots at 15 m | Motion-capture system | [69] |
| | Shots at 20 m | Motion-capture system | [28] |
| Baseball | Batting | Video camera | [23] |
| | Throwing fastball | Motion-capture system | [74, 78] |
| Basketball | Free throwing | Motion-capture system | [61] |
| | Dribbles | Motion-capture system | [49] |
| | Dribbles | Force plate | [26] |
| Cricket | Throwing as hard as possible | Motion-capture system + force plate | [76] |
| Cycling | Cycling at 60, 90, 120 RPM at 120, 210, 300 W | Motion-capture system | [40] |
| | Cycling at preferred cadence, 60, 80, 95 RPM at RPE of 15 | EMG | [80] |
| Dancing | Arabesque | Motion-capture system | [33] |
| | Greek and Ireland dancing Sautés | Magnetic tracking system | [34] |
| | Basic street dance move | Motion-capture system | [47] |
| | Sautés | Motion-capture system + force plate | [81] |
| | Sautés | Motion-capture system | [54] |
| | Dance-like movement | Motion-capture system | [30] |
| Dart | Throwing at 2.44 m | Motion-capture system + video camera | [55] |
| Golf | Putting | Motion-capture system | [62] |
| | Swing mid-iron | Motion-capture system | [63] |
| | Shots with 5-iron club on target | Video camera | [60] |
| | Shots with pitch wedge | Motion-capture system | [25] |
| | Putting at 3 m and 5 m | EMG + Motion-capture system | [67] |
| Gymnastic | Giant circle | Motion-capture system | [42] |
| | Long swing | Motion-capture system | [75] |
| Handball | Throwing | Motion-capture system | [80] |
| Ice climbing | Climb the ice wall | Video camera | [27, 68] |
| Ice Hockey | Slap shot | Motion-capture system | [72] |
| Nordic ski | $VO_2$ max test | Motion-capture system | [37] |
| Powerlifting | Bench press at 60 of 3RM | EMG + accelerometer | [65] |
| Race walking | Incremental speeds | Motion-capture system | [24] |
| | 103% of race pace | Force plate | [73] |
| Rowing | Mean power until exhaustion | EMG + Strain gauge | [46] |
| Running | Submaximal running | Pressure plate | [58] |
| | Anaerobic threshold speed | Motion-capture system | [32] |
| | 3 m/s, 5 m/s, sprinting | Motion-capture system | [35] |
| | Comfortable speed | Motion-capture system | [36] |
| | 4 m/s | EMG | [41] |
| | 5 k speed | IMU | [43] |
| | Preferred pace | IMU | [50] |
| | Anaerobic speed | Motion-capture system | [51] |
| | Preferred speed | Force plate | [44] |
| | 80%, 100%, and 120% of preferred race speed | Insole force sensors | [70] |
| | 10 and 15 km/h | Motion-capture system | [56] |
| Shot put | Shot put | Video camera | [79] |

(Continues)

**TABLE 2** | (Continued)

| Sport | Tasks | Instruments | Articles |
|---|---|---|---|
| Soccer | Kicking ball on target | Motion-capture system + video camera | [48] |
| | Walking | IMU | [31] |
| Squash | Hunt squash accuracy test | Motion-capture system | [66] |
| Swimming | Crawl sprint | Video camera + Force plate | [59] |
| | Breaststroke at 80% | Video camera | [64] |
| | Breaststroke at 80% + max speed | Video camera | [39] |
| | Incremental front crawl speed to exhaustion | Video camera | [29] |
| | Front crawl 100 m | Video camera | [52] |
| Table tennis | Return a ball to the target | Motion-capture system | [38] |
| | Hit topspin forehands | Motion-capture system + video camera | [77] |
| Tennis | Serves | Motion-capture system | [71] |

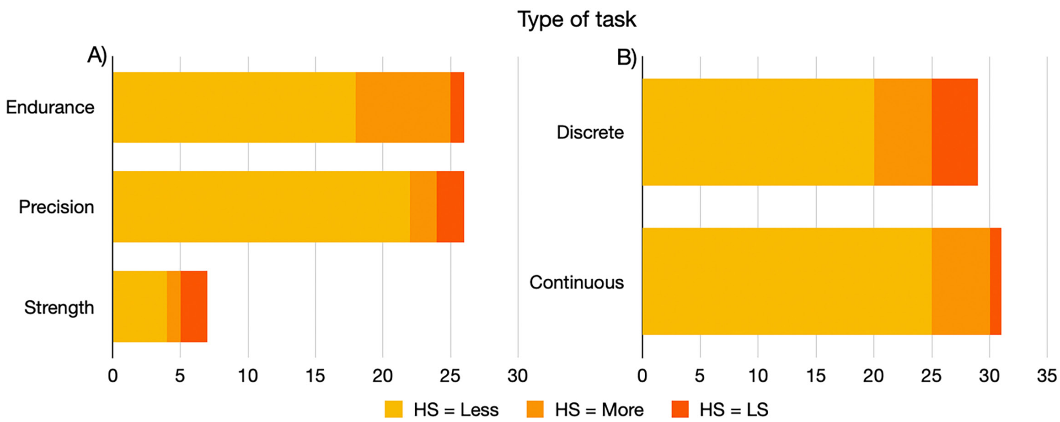


**FIGURE 4** | (A) The number of studies evaluating endurance, precision, or strength sport and their overall conclusion. (B) The number of studies evaluating discrete or continuous tasks in sport and their overall conclusion. HS = less, higher-skilled athletes are less variable than lower-skilled athletes; HS = more, higher-skilled athletes are more variable than lower-skilled athletes; HS = LS, higher-skilled athletes are as variable as lower-skilled athletes.

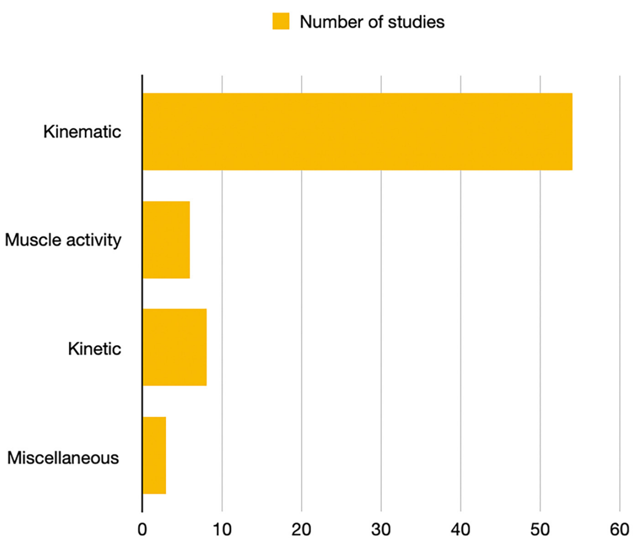


**FIGURE 5** | Measuring instrument types across all studies. Kinematic instruments included motion-capture system, camera, and IMU; muscle activity instruments included EMG; kinetic instruments included force plate, force sensor, and pressure plate.

2.1, Delsys Inc). More details on the instruments are in the supplemental data file.

### 3.4 | Validity of the Instruments

We evaluated the validity of each instrument included in this scoping review with the information available. Thirty-nine instruments were considered as the gold standard in their field. For instance, motion-capture systems, such as Vicon system, are among the most valid instruments for measuring kinematic variables. For the remaining 18 instruments, seven showed good validity, one showed poor validity, and 10 had no information on validity. More information about the validity is presented in the supplemental data file.

### 3.5 | Metrics of Variability

A total of 21 different metrics of MV were used in the studies included. The most common was the standard deviation, which was present in 31 different studies [23, 25, 26, 28, 30, 32, 34, 35, 38–40, 42, 44, 45, 47, 50, 52–55, 57, 64, 66–69, 74, 75, 77, 78, 81]. The second most common was the coefficient of variation, which is a variation of the standard deviation (CoV = SD/mean), with nine occurrences in the review [33, 43, 51, 58, 60, 62, 70, 76, 80]. All metrics are presented in the supplemental data file. Additionally, a brief interpretation of these metrics and their behavior in relation to variability are also included. Three studies performed multiple variability assessments [24, 49, 59].

## 3.6 | Intra-Individual Variability

In the following sections, only studies comparing intra-individual variability are presented. As a reminder, intra-individual variability refers to the differences in performance within the same individual across multiple instances of the same task, highlighting how a person's motor control changes from trial to trial. Fifty-five of the 59 included studies compared intra-individual variability.

### 3.6.1 | HS Athletes Are Less Variable Than LS

Forty-two out of 55 studies concluded that the HS athletes had less MV than LS athletes [23–26, 28–34, 38, 40–45, 47, 49, 51, 52, 54–62, 66, 67, 70, 73, 75–81] (Figure 6A). The previously explained ratio was used to categorize the studies. All studies in this section that exhibit a ratio below 0. In this group multiple sports are represented: archery [28, 57], swimming [29, 52, 59], golf [25, 60, 62, 67], running [32, 41, 43, 44, 51, 56, 58, 70], race walking [24, 73], dancing [30, 33, 34, 54, 81], baseball [23, 78], basketball [26, 49, 61], table tennis [38, 77], soccer [31], golfing [25, 62], cycling [40], gymnastics [42, 75], handball [45], cricket [76], squash [66], darts throwing [55], and shot put [79].

### 3.6.2 | HS Athletes Are More Variable Than LS

MV was greater in HS athletes in nine studies [35, 37, 39, 50, 64, 68, 69, 71, 72] (Figure 6A). These studies evaluated different sports: tennis [71], running [35, 50], swimming [39, 64], archery [69], ice climbing [27, 68], Nordic skiing [37], and ice hockey [72]. Whiteside et al. found that HS tennis players had more angle variability with a motion-capture system while serving on a target compared to LS. Wang et al. studied runners with IMU at different speeds (3, 5 m/s, and sprinting). At sprinting speed, they found that three different angle coordination variables had more variability in athletes versus non-athletes [35]. However, they found that stride length was more consistent in the athlete (HS). Hafer et al. studied running as well, but

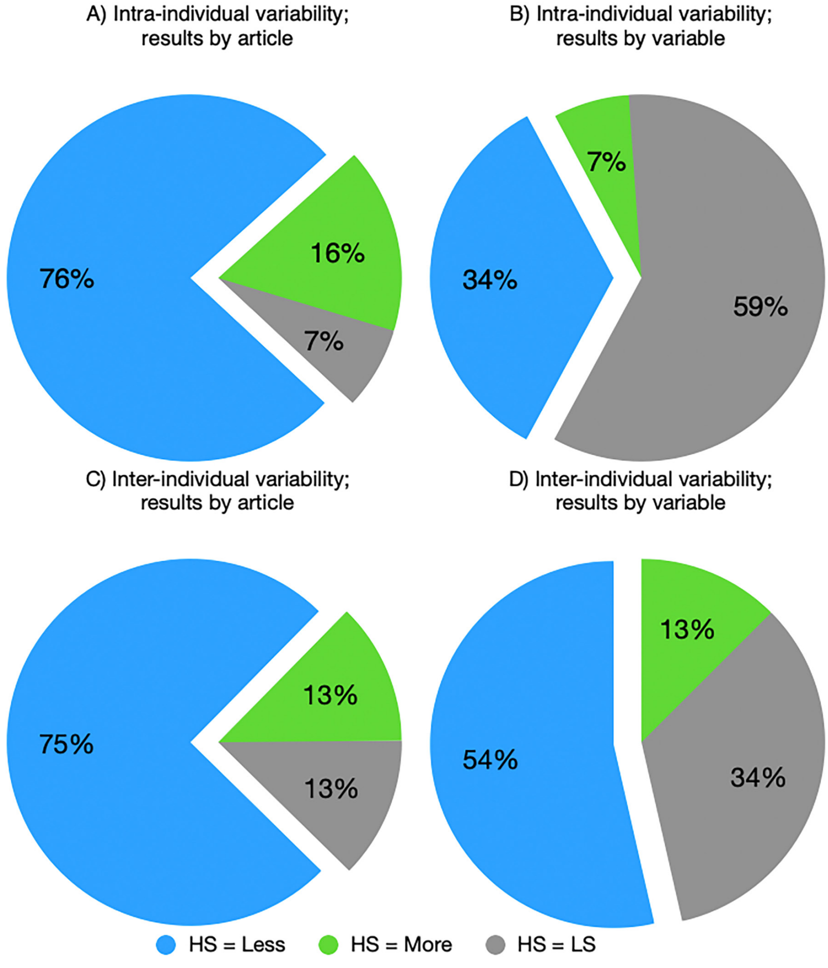


**FIGURE 6** | Percentage of study (A, C) and of variables (B, D) that concluded that the HS are less, more or as variable as LS participants. HS = less, higher-skilled athletes are less variable than lower-skilled athletes; HS = more, higher-skilled athletes are more variable than lower-skilled athletes; HS = LS, higher-skilled athletes are as variable as lower-skilled athletes.

at preferred speed using a motion-capture system, and found greater variability in angle coordination in the lower extremities in HS runners versus less experienced runners [50]. Seifert et al. showed with a video camera that competitive breaststroke swimmers had more angle coordination variability in the continuous relative phase of the elbow-knee than recreative swimmers [39, 64]. Stuart and Atha found, with a motion-capture system, that lower handicap archers (HS) have more variability in the stretch length of their bow compared to higher handicap archers (LS) [69]. Seifert et al. evaluated with a video camera ice climbing MV in two studies and found greater angle variability in climbers than in non-climbers [27]. Frayne et al. found that national-level Nordic skiers' centre of mass is more variable in position and velocity compared to non-skiers [37]. Finally, Robbins et al. found that competitive hockey players have more angle coordination variability than recreational players during slap shots [72].

#### 3.6.3 | Similar Variability Across Different Skill Levels

Four studies showed that there is no difference in MV between HS and LS athletes [36, 48, 63, 74] (Figure 6A). These studies looked at four sports: running [36], golfing [63], soccer [48], and baseball [74]. Floría et al. explored MV in runners and asked participants to run at a comfortable speed [36]. They used a motion-capture system and sought knee-ankle and knee-hip angle coordination as variables. Langdown, Bridge, and Li compared the pelvis and shoulders angles and the position of the body relative to the ball of two groups of golfers with different handicaps [63]. They performed 10 to 15 normal mid-iron swings. Ford et al. did not identify differences in the movement variability of the hip-knee and knee-ankle angle coordination from kicking a soccer ball [48]. Scarborough et al. explored MV in baseball at different skill levels [74]. The players had to throw a fast ball and the time to maximal velocity variability of their hands, forearm, arm, trunk, and pelvis was assessed.

#### 3.6.4 | HS Versus LS Athletes

Of the 55 studies that assessed intra-individual variability, 37 compared HS athletes with LS athletes [24, 25, 29–33, 36, 39, 41–43, 45, 48, 50–52, 56–61, 63, 64, 66, 67, 69, 72–80]. For example, archers [57] were grouped according to their FITA score (more than 1250 vs. less than 1150) while race walkers [24] were divided by their PB time on 10 km (PB = around 40 min vs. PB = around 43 min). From those studies, 27 found that HS athletes are less variable [24, 25, 29, 30, 32, 33, 41–43, 45, 51, 52, 56–61, 66, 67, 73, 75–80], 6 found the opposite, [31, 39, 50, 64, 69, 72] and 4 found no difference [36, 48, 63, 74] (Figure 7).

#### 3.6.5 | HS Versus No Skill

Of the 55 studies that assessed intra-individual variability, 18 studies compared HS athletes in a sport with participants who did not have skill in the same sport [23, 26, 28, 31, 34, 35, 37, 38, 40, 44, 47, 54, 55, 62, 70, 81]. For example, in a study on basketball dribbling [26], the authors compared Korean national amateur competition players with inexperienced participants. Shih et al. [81] compared cyclists who trained at least 5 h a week with participants who did not cycle at any point. From those studies, 15 found that HS athletes are less variable [23, 26, 28, 31, 34, 38, 40, 44, 47, 54, 55, 62, 70, 81] and 3 found the opposite [35, 37, 68] (Figure 7). Three studies compared HS athletes with athletes from a different sport [23, 37, 44].

#### 3.6.6 | Results By Variable

A total of 478 MV variables were identified from the 55 studies that evaluated intra-individual variability (an average of 8.7 variables by study). Of this number, 164 showed that HS athletes are significantly less variable than LS, 282 did not show a

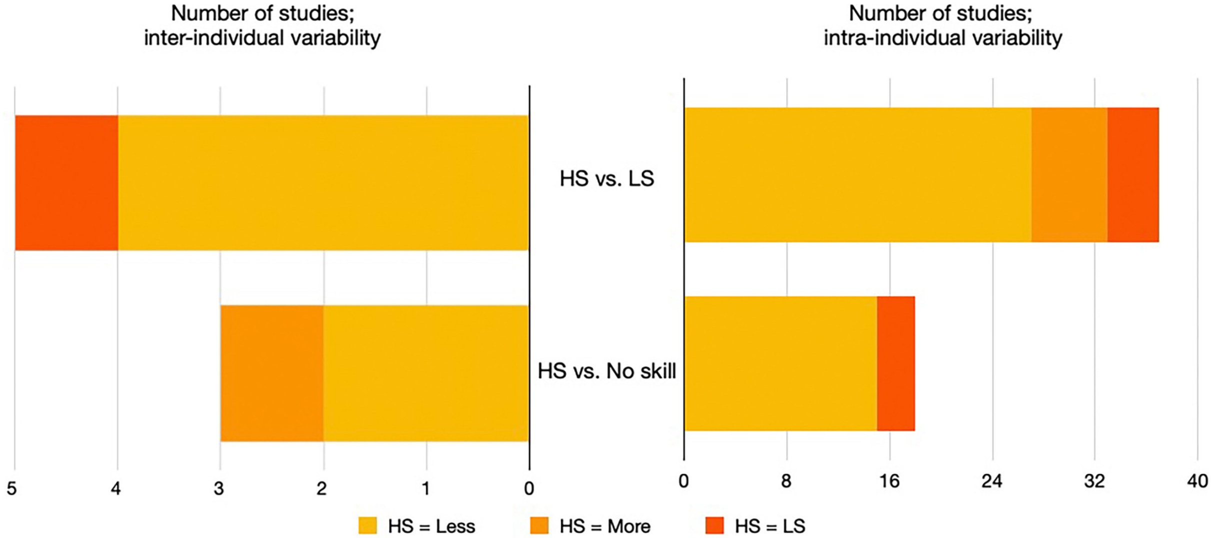


**FIGURE 7** | Number of studies that compared HS athletes to LS athletes and those that compared HS athletes to no skill participants and their overall conclusion. The different color represents the direction of the results. HS = less, higher-skilled athletes are less variable than lower-skilled athletes; HS = more, higher-skilled athletes are more variable than lower-skilled athletes; HS = LS, higher-skilled athletes are as variable as lower-skilled athletes.

significant difference and 32 showed that HS athletes are significantly more variable than LS (Figure 6B). From the 478 variables, many motor control parameters were assessed. The most studied motor control parameter was the angular parameters which included the angle, the angle coordination and angular velocity with 245 occurrences. The second most studied motor control parameter was the position of the body, including the length and displacement with 90 occurrences. The third most studied motor control parameter was muscle activity, which included muscle coactivation with 37 occurrences (Figure 8). More data on motor control parameters are presented in the supplemental data file.

#### 3.6.7 | Performance

To assess the impact of expertise on sports performance, data on performance outcomes were extracted from the 55 studies. Not all studies provided performance-related data. Indeed, 33 studies did present performance data. Within this subset, 27 studies demonstrated that HS athletes outperformed their LS counterparts [32, 35–39, 43–45, 48, 51, 52, 55, 57–61, 64, 66–68, 70, 73, 74, 78, 79]. Six studies did not find any difference in performance between the HS and the LS [24, 31, 47, 50, 54, 72]. In two studies, participants had to run or race walking at a uniform pace, regardless of their skill levels, thus avoiding observable differences in performance outcomes [24, 50]. Yaserifar et al. asked their soccer players to walk at preferred speed [31]. Even though the experienced soccer player walked faster, the difference did not reach significance. Robbins et al. found no difference in puck velocity between competitive and recreational hockey players [72]. Finally, two studies asked both groups (HS and LS) to perform the same dance move without performance criteria [47, 54].

### 3.7 | Inter-Individual Variability

In the following sections, only studies comparing inter-individual variability are presented. As a reminder, inter-individual variability focuses on the differences in motor control between individuals when performing the same task. Eight of the 59 included studies compared inter-individual variability.

#### 3.7.1 | HS Versus LS Athletes and No Skill

From the eight studies assessing inter-individual variability, six found that HS athletes are less variable than LS [29, 41, 46, 53, 64, 80], one found the opposite [27], and one found no difference [65]. Out of the six that found HS less variable than LS, four compared HS athletes with less experience athletes [29, 41, 64, 80], and two compared HS athletes with no experience participants [46, 53] (Figure 6C).

Seifert et al. evaluated front crawl and breaststroke swimming between different levels of swimmers [29, 64]. The first study found that HS swimmers angle coordination variability was lesser than LS swimmers. The second study found that HS swimmers' kinematic pattern variability was lesser than LS swimmers. Chapman et al. found that muscle synergy variability was lesser in the specific runner group compared to the triathlete group [41]. They found similar results between novice cyclists and highly trained cyclists [80]. Dutt-Mazumder and Newell found that angle variability was lesser in the experienced alpine skier group compared to inexperienced skiers on a ski simulator [53]. Turpin et al. assessed force production and muscle activity of Olympic-level rowers and compared them to no experience rowers [46]. They found that the HS athletes are less variable than their LS counterparts.

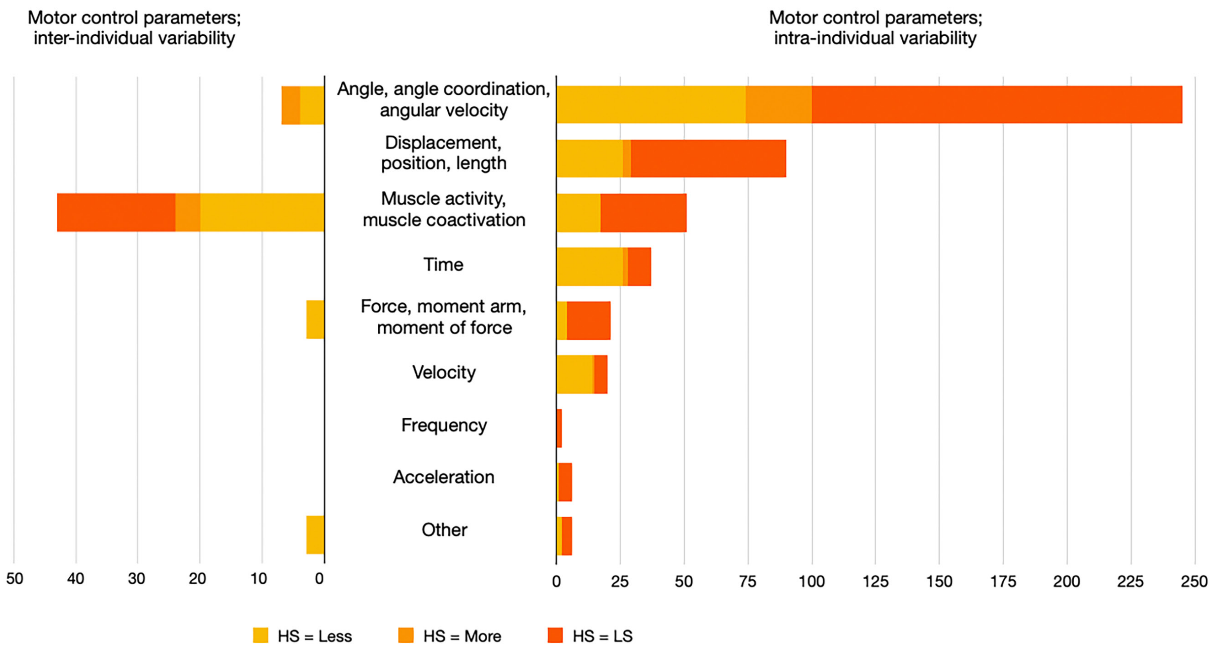


**FIGURE 8** | The number of motor control parameters used to assess MV in the different studies evaluating inter-individual and intra-individual variability. HS = less, higher-skilled athletes are less variable than lower-skilled athletes; HS = more, higher-skilled athletes are more variable than lower-skilled athletes; HS = LS, higher-skilled athletes are as variable as lower-skilled athletes.

The only study that found that the HS group was more variable evaluated the angle coordination variability of intermediate and novice rock climbers [27]. The study that found no inter-individual variability difference assessed muscle synergy variability in powerlifters during bench pressing compared to unexperienced participants [65].

#### 3.7.2 | Results By Variable

A total of 56 different variables were assessed (an average of 7 variables by study). The results of 30 of them indicated that the HS groups are less variable, 7 the opposite and 19 found no difference (Figure 6D). From the 56 variables assessed, multiple motor control parameters are presented. Forty-one variables assessed muscle activity, while six assessed angle or angle coordination, three assessed forces, and three assessed other motor controls specific to the study (Figure 8).

#### 3.7.3 | Performance

To assess the impact of expertise on sports performance, data on performance outcomes were extracted from eight studies. Only five studies did present performance outcomes. All of them demonstrated that HS athletes outperformed their LS counterparts [27, 46, 53, 64, 65]. The three studies remaining did not present performance outcomes [29, 41, 80].

## 4 | Discussion

The objective of this scoping review was to present an overview of the most recent evidence and the body of knowledge concerning the influence of expertise on execution MV during sports tasks. More precisely, this review (1) assessed the effect of expertise on MV in sports, (2) identified how researchers qualified expertise, (3) what instrument they used to assess MV, and (4) how MV was calculated in sports. Twenty-four different sports and a total of 59 studies were included. Most studies have been published in the last 10 years, which confirmed the growing interest in this field. In general, most studies concluded that HS athletes had a lower MV than LS athletes. Many criteria were used to determine the level of expertise of the participants. MV was mostly evaluated by movement angular parameters collected with motion-capture systems. Finally, the most common MV metric was the standard deviation.

### 4.1 | High Skilled Athletes Are Less Variable Than LS

Most of the studies included in this scoping review concluded that HS athletes exhibit less MV compared to LS athletes. This MV pattern was observed both within individuals (intra-individual variability) and between individuals (inter-individual variability). Our findings represent a substantial and innovative addition to the ongoing debate on the degree to which training can affect motor control. Despite the absence of longitudinal follow-ups in the selected studies, it could be hypothesized that training, by motor learning, has an impact on MV. This hypothesis is in line with motor control theories describing a decrease in MV through practice [9, 82]. For instance, Schmidt's Schema Theory (1975) proposes that we develop generalized motor programs which are fine-tuned by "schemas" through practice [83]. During motor execution, the sensory outcomes of the movement are anticipated using the schema. Each sensory outcome is then compared with the corresponding incoming sensory information during or after the movement. Errors arising from the mismatch between anticipated and actual sensory consequences, believed to be responsible for MV, can be used to update the schema. During motor learning, one of the primary goals is to reduce these movement errors and error variability [84, 85]. In addition, Sternad [82] argues that while mastering a new skill involves reducing variability or noise in motor performance, variability is crucial for exploring successful actions during the initial stages of learning. In sum, novices (LS) use variability to explore and learn motor strategies and experts (HS) tend to reduce variability to reduce functional cost.

Furthermore, most of the HS athletes outperformed the LS athletes. With motor learning, athletes experience trial-and-error processes. This exploration could, according to the reinforcement learning theory [86], guide the sensorimotor system toward the development of novel motor control strategies that improve performance and reduce functional costs [6, 7]. This improvement in performance associated with decreasing in MV is the conclusion of most of the studies included in this scoping review.

### 4.2 | High Skilled Athletes Are More Variable Than LS

Inconsistency was found across studies as 10 studies reached the conclusion that HS athletes exhibit greater variability compared to LS athletes [27, 35, 37, 39, 50, 64, 68, 69, 71, 72]. No discernible pattern emerged from the extracted variables. Neither the criteria used to evaluate the level of expertise, the instrumentation used, the selection of metrics, nor the nature of the sporting task could explain why HS athletes were more variables in these studies. However, a few hypotheses could explain why HS athletes were more variable in these studies. The important number of comparisons, sometimes higher than 50 [35], can increase the risk of type I statistical error. Another explanation might be the small sample size, sometimes <10 athletes [69], which limits the possible generalization and may present a sampling error.

### 4.3 | Similar Variability Across Different Skills

Six studies did not find any difference in MV between HS and LS athletes [36, 48, 63, 65, 74]. Again, no discernible pattern emerged from the extracted variables. Floría et al. did not reach statistical differences for any of the variables studied but showed a trend suggesting that HS runners have less MV than LS runners [36] which is consistent with most studies. Langdown, Bridge, and Li [63] suggested that the similarity between HS and LS athletes may be attributed to the experimental conditions. In their study, golfers were required to execute their typical swing to achieve a consistent ball trajectory, accuracy, and distance toward a predefined target on a golf net. The absence of a realistic environment restricted extrinsic knowledge of results, consequently reducing the athletes' capacity to adjust their swings in anticipation of subsequent shots. This could explain the absence of a difference between HS and LS golfers. Also, it is possible that these studies mainly assess task irrelevant variability which is known not to change through motor learning [10].

### 4.4 | Expertise In Sports

Qualification of expertise can be quite challenging in the field of sports. According to Anders Ericsson, expertise is reached after 10000h of practice of a particular activity (music, sport, or leisure) [1]. This definition of expertise is strict, and no author used it in this review. According to Macnamara, Hambrick, and Oswald, only 18% of the variance in performance can be explained by deliberate practice [87]. Therefore, the 10000-h rule is increasingly contested. As seen in this review, it is possible to categorize athletes as experts according to different criteria. Expertise may be related to previous results (nation record holder, PB, etc.), the level at which the athlete performed (MLB vs. minor leagues, national vs. regional, etc.), or the amount of deliberate practice. Also, experts in sport may be defined simply as better than average. In conclusion, the way athletes are classified according to their expertise does not appear to influence MV results, as previously indicated. However, for future investigations, it could be advantageous to adopt a structured approach to delineate expertise groups. For example, the participant classification framework presented by McKay et al. has potential value for implementation [88]. This framework, divided into six tiers, establishes guidelines for classifying athletes in a wide range of sports. It also suggests that it maximizes the probability of a meaningful change in the findings if comparisons are made between tiers [88].

### 4.5 | Instrument To Assess MV In Sports

In this review, the instruments used were categorized into four groups: kinematic, muscle activity, kinetic, and miscellaneous. Kinematic instruments were the most explored component of MV. Due to its substantial quantity, kinematic studies yield more robust conclusions regarding the impact of expertise on MV, while only a few studies have investigated MV using muscle activity and kinetic measurements. However, EMG studies consistently indicated that HS athletes exhibited lesser variability than LS athletes [41, 46, 65, 67, 80]. Furthermore, this trend was also corroborated by all studies using force plate measurements. Consequently, more research is needed using these two types of instruments to be able to generalize their results to a broader athlete population. Only eight studies used more than one instrument type [46, 47, 54, 59, 65, 67, 76, 81]. They all concluded that HS athletes are less variable than LS athletes. The use of multiple distinct instruments could contribute to a better understanding of alterations within the sensorimotor system. For example, if EMG data are recorded alone, variations in EMG signals between trials can indicate execution variability. However, if there is a change in strategic variability, EMG alone would not discern the difference between execution and strategic variability [13]. Therefore, combining kinematics and EMG provides a more comprehensive assessment of changes in motor strategy between trials. Researchers should consider the incorporation of multiple types of instruments to offer a more comprehensive understanding of alterations in MV in sports performance.

### 4.6 | Metrics To Assess MV In Sports

To assess the difference in MV between HS and LS athletes, the authors used multiple metrics. Twenty-one different cycle-to-cycle metrics were identified in this scoping review. Standard deviation was the most popular metric. Robalo et al. were the only one to use non-linear analysis in their study [49]. The extensive range of metric types posed challenges in terms of inter-study comparisons. In this scoping review, the studies were compared using a ratio between variables that exhibited statistically significant differences and those that did not. In addition, the research protocols encompassed a spectrum of one to 54 distinct variables within a single study, and such heterogeneity in variables could potentially introduce errors attributable to the selection of inappropriate variables or chance [89]. Future investigations related to MV in sports should include the most appropriate measure of variability (task-relevant and task-irrelevant variability [90]) and the most important variable based on the specific task.

### 4.7 | Perspectives

It is important to note that the studies included in the review had a relatively small sample size (Mean = 22). Future studies should aim to recruit larger cohorts of athletes to enhance the statistical robustness and significance of their findings. Implementing this recommendation would also improve the potential for a wider generalization and reduce the risk of sampling bias. There was a gender bias in the samples, with male athletes significantly outnumbering female athletes. Future studies should strive for gender balance to ensure that research findings are not biased toward one gender. Additionally, it is necessary to perform subgroup analyses to explore possible gender-specific differences. Also, it would be interesting to have data on participants aged under 14 and over 30. With a wider range of ages, we could learn how younger athletes develop motor strategies and whether there is a plateau at which there is no more change with practice.

## 5 | Conclusion

Most studies indicate a consistent tendency of reduced MV among HS athletes in various sports compared to LS athletes. These results seem independent of how expertise is qualified, the type of instrument, and the metrics used to quantify MV. However, if the motor control parameters are evaluated this tendency is not that clear. Indeed, most motor control parameters indicate no difference in MV between HS and LS athletes. Both tendencies are mainly observed in intra-individual variability, but some studies also note them in inter-individual variability. Despite substantial research on MV regarding expertise, further research is warranted to explore broader cohorts, more female athletes and participants of varying ages. In addition, the use of multiple instruments should be encouraged in the future to better understand different types of variability. Finally, the mechanisms and implications of the motor control parameters that affect or do not affect MV or performance should be investigated.

## Conflicts of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

The data that supports the findings of this study are available in the supplementary material of this article.

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## Supporting Information

Additional supporting information can be found online in the Supporting Information section.