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Use of Inertial Measurement Units in Handball: A Review

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ABSTRACT

In handball research, inertial measurement units (IMUs) have emerged as a popular tool for quantifying athlete movement. Despite their widespread use, there is a lack of consensus on data collection methods and data processing techniques in handball. This review aims to evaluate the current use of IMUs in handball research, focusing on the movement metrics considered and the attributes of IMU usage. A search was conducted across four online databases (EBSCO, PubMed, Scopus, and Web of Science) employing seven inclusive and six exclusive criteria. The gathered data was categorized into several areas: the purpose of using IMUs, the devices and sensors used, the number of devices utilized and their placement on the body, and the settings of the sensors. From this search, 28 studies were selected for review. These studies predominantly used IMUs to assess external loading (primarily employing the PlayerLoad™ metric), identify movement phenomena, and evaluate changes in movement following medical interventions. While complex diagnostic systems were typically used to assess loading, smaller IMUs were employed for investigating movement phenomena. The findings highlight inconsistencies in both the setup and the placement of the devices on the body. The results indicate that IMUs can serve as a valuable tool in handball research.

Keywords: Analysis; External Load; Movement; Performance; Sport Games

INTRODUCTION

Handball is a dynamic team sport requiring players to perform explosive movements, rapid direction changes, and high-intensity activities (Michalsik & Aagaard, 2015). These demands can lead to high internal loads and fatigue accumulation, significantly impacting performance and increasing the risk of injury (Meylan et al., 2017; Taylor et al., 2017). Coaches and researchers continually seek ways to improve players' physical fitness, agility, coordination (Font et al., 2021), and strategies for injury prevention (Luig et al., 2018). Acceleration is a critical aspect of a handball player's movement performance, offering a significant advantage over opponents. It enables players to quickly assume favorable positions, react to opponents, and disrupt their planned activities (Karcher & Buchheit, 2014; Michalsik & Aagaard, 2015; Póvoas et al., 2012; Wagner et al., 2014). Assessing a player's dynamic movement performance is crucial for game management and tailoring individual training needs, focusing on game performance nature during matches (Fleureau et al., 2023). During matches and training, current information on both internal and external loads is vital for coaches and players, as it allows for effective management of these processes to achieve maximum performance (Font et al., 2021; González-Haro et al., 2020), individualization of training load (Font et al., 2023), creation of intervention programs (Bassek et al., 2023; Taylor et al., 2017), or in mitigating injury risk associated with fatigue (Drole et al., 2023). Although such information is utilized in handball, the demand for more accurate, comprehensive, and real-time mediated information is growing alongside technological advancements (Font et al., 2021).

In recent years, inertial measurement units (IMUs) have become increasingly popular in team sports research for analyzing player movements in a variety of sports, including rugby, Australian football, football, basketball, volleyball, netball, and others (Camomilla et al., 2018; Damji et al., 2021; Quílez-Maimón et al., 2021; Smith & Bedford, 2020; Svilar et al., 2018). IMUs provide a range of outputs obtained from accelerometers (AC), gyroscopes (GY), and magnetometers (MA), such as acceleration, angular velocity, and orientation, respectively (Camomilla et al., 2018; Torres-Ronda et al., 2022). These outputs can assess player performance, offer feedback, and analyze the impact of training programs. The AC delivers information on the magnitude and direction of linear acceleration, useful for determining player load, identifying specific movements or movement patterns, and quantifying acceleration changes over time (Gómez-Carmona et al., 2020). The GY measures angular velocity, offering insights into the rate and direction of rotational movement, helpful for identifying specific movements like changes in direction, pivoting, and jumping (McGrath et al., 2021). The MA measures the IMU's orientation relative to the Earth's magnetic field, providing data on the device's heading, pitch, and roll, useful for tracking the player's position and movements in 3D space (Roell et al., 2018).

Given the potential benefits of using IMUs, incorporating them into handball monitoring would be advantageous for enhancing the accuracy and reliability of the monitoring process. To date, there is no comprehensive overview available of the use of IMUs in handball or methodological recommendations for their placement or configuration, considering the expected output of the application. Therefore, the aim of this study is to summarize and evaluate the current use of IMUs in handball research, mainly in terms of observed player movement attributes, the devices used and their settings, as well as the sensors contained therein. The obtained information should expand our understanding of IMU use in handball and determine the direction of future research, especially regarding methodological aspects and their practical application.

METHODS

This study adheres to the PRISMA statement guidelines for systematic reviews (Page et al., 2021); however, its protocol was not registered, as this study is not health-related. To determine relevant sources, both inclusive and exclusive criteria were utilized. The inclusive criteria focused on desired sources involving keywords related to the sport of handball, the use of IMUs, accelerometers, gyroscopes, and the monitoring of movement and external load. Based on these criteria, the following Boolean phrase was constructed:

- Inclusive Criteria: Terms associated with handball (handball or team handball) were searched within article titles (ti), while terms linked to IMUs, sensors (including accelerometers and gyroscopes), movement, skills or actions, and load were searched throughout the text of documents (tx).
- Exclusive Criteria: Sources containing information on other sport games, injuries, health, local or global positioning systems, and internal load were excluded from the search. This aimed to remove undesirable or irrelevant results.

From these criteria, the following search phrase for databases was derived (minor corrections were made according to the specifics of the chosen database):

(ti handball* OR ti "team handball*") AND (tx inertial OR tx sensor OR tx accelerometer OR tx gyroscope OR tx imu OR tx microsensor) AND (tx movement* OR tx skill* OR tx action*) AND tx load* NOT (tx "other sport games" OR tx injury OR tx health OR tx "local positioning system" OR tx "global positioning system" OR tx "internal load")

Online databases EBSCO, PubMed, Scopus, and Web of Science were searched for sources. Only original articles or reviews published in peer-reviewed scientific journals in the English language were included in the search. The search for sources in the databases was conducted up to December 12, 2022 (the lower limit was not restricted). The search for sources in the databases was conducted from December 12, 2022, to December 15, 2022.

After extracting sources from online databases, all duplicates were removed. One author compiled a list of all studies found and marked those that did not align with the focus of this study based on the titles, abstracts, and, in cases of doubt, the full articles. Studies containing irrelevant data, such as those evaluating performance using sensors other than inertial or dealing with sports other than handball, were excluded. The second author independently verified the included and excluded studies. In cases of disagreement regarding the inclusion of a study, it was included only after a comprehensive review and consensus were reached.

The data items sought in the identified studies included the purpose of using the device, the target population (sex and performance level), the type and manufacturer of the used sensor, the number of used IMUs, the location of IMUs on the player's body, and the specification of IMU settings (sample rate and range). The extracted data was categorized into the following areas: the purpose of using IMUs, the devices and sensors used (including the number of devices and their location on the body), and sensor settings (AC and GY). Individual data items were not compared in terms of quality; instead, an overview was compiled in accordance with the objectives of this study.

RESULTS

In total, the authors retrieved 143 documents from four databases (EBSCO, PubMed, Scopus, and Web of Science). After removing duplicates, 90 articles remained for further review. Subsequently, the relevance of the articles was assessed by a person. Considering the inclusion and exclusion criteria, 62 records were removed based on the abstracts and full texts. The main reasons were the focus on other sports games (31), the use of global (6) or local (14) positioning systems, or the studies' focus on injury risks (11). Ultimately, 28 studies were included in the qualitative synthesis (see Figure 1), published between 2003 and 2022.

Figure 1. **Flow-chart of studies identification (Page et al., 2021)**

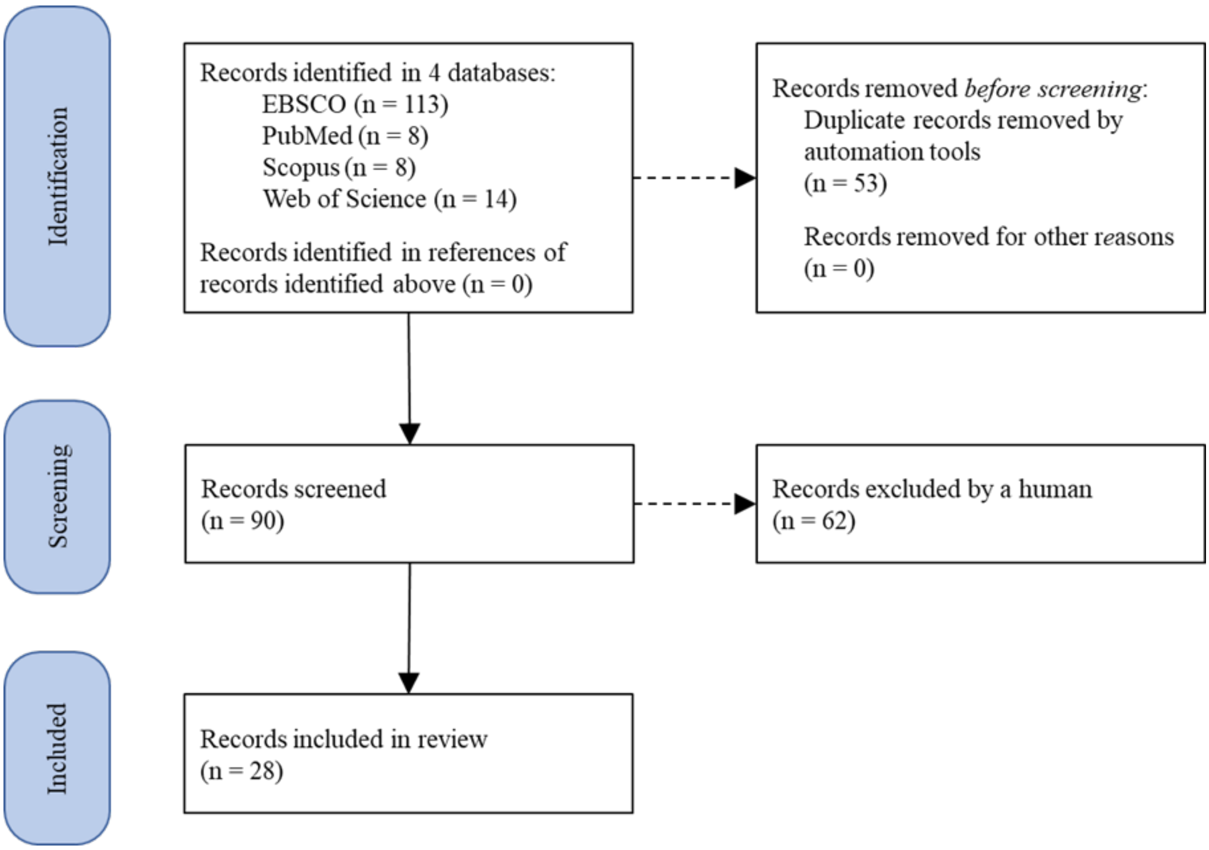

Table 1 aggregates data from 28 studies focusing on the application of IMUs in handball, with a wide range of study objectives indicating the technology's versatility in sports research. These objectives span from analyzing the effects of training on specific skills to evaluating player activities and physiological responses under various conditions, reflecting the depth and breadth of handball research utilizing IMU technology.

The participant demographics in these studies are diverse, encompassing both male and female players. Among these, 18 studies include male participants, while 19 studies specifically focus on female participants. This gender distribution shows the inclusive nature of handball research, addressing performance metrics across sexes.

Regarding player performance levels, the studies cover a spectrum from amateur to professional, signifying the broad applicability of IMU technology in capturing data relevant to different competitive standards. Specifically, the research encompasses semi-professional players in three studies, highlighting the technology's role in bridging amateur and professional analysis. Professional players are the focus in the majority of the studies, underscoring the importance of IMU data in high-performance sports analytics. A few studies also delve into the performance of amateur players, indicating the technology's utility in grassroots sports research. This detailed overview of the studies' objectives, participant demographics, and performance levels underscores the extensive application of IMU technology in handball research, covering various facets of the game and aspects of player performance.

Table 2 provides a succinct overview of IMU deployment in handball research, focusing on device configurations and methodological nuances. It compiles data from 28 studies, each employing IMUs to document the diverse dynamics of handball. This summary reflects the methodological considerations essential for capturing the intricacies of handball play, highlighting the customized approach researchers undertake to meet their specific research goals.

The majority of the studies (22 out of 28) utilized a single IMU unit, indicating a preference for simplified data collection setups. The choice of sensors varied, with 15 studies employing a combination of AC, GY, and MA to assess multidimensional movements. Conversely, 10 studies restricted their sensor use to ACs alone, suggesting a concentration on linear motion analysis. The placement of IMUs was customized according to the specific aims of each study, ranging from the upper thoracic back area to the wrist and lumbar spine. Such variability highlights the methodological diversity and the researchers' intention to precisely monitor player movements pertinent to handball.

The sampling frequencies for ACs in the reviewed studies were predominantly set at 100 Hz, aligning with common practice for monitoring handball movements. However, a select number of studies opted for significantly higher sampling rates, reaching up to 1000 Hz or 1125 Hz, to accommodate the precise measurement of rapid and brief actions, such as throws and strikes, indicating a focused effort to capture detailed data on specific in-game activities.

In contrast to the consistently set frequency data, only three studies specified the recording range for the devices, indicating variability in reporting. ACs had ranges from ±16 G to ±200 G, tailored to handball's dynamic movements. GYs were set to ±2000°/s for rotational motion, and MAs to ±4900 μT for orientation tracking. This specificity in AC, GY, and MA settings ensures data relevance across the physical demands of handball.

The selection of IMU manufacturers, from Catapult Sports to Xsens Technologies, demonstrates a strategic choice aimed at achieving precision, reliability, and sport-specific utility in handball research. This approach reflects a commitment to advancing performance analysis with technologically innovative tools.

It is crucial to approach these findings with caution, recognizing that the configurations and outcomes reported reflect the deliberate choices made to address the unique objectives of each study. For instance, in studies focusing on limb movements, placing IMUs on areas other than the limbs would be entirely irrelevant. Similarly, the choice of sensors, placement, and sampling frequencies are all decisions intricately linked to the study's aims. This understanding underscores the need for a nuanced interpretation of the data, appreciating the methodological diversity as a reflection of the specific research contexts within the field of handball performance analysis.

Table 1. **Overview of studies involved in the review with their characteristics**

Study	Intention of the study	N (sex)	Player performance level
Abuajwa et al. (2022)	To assess how a customized, five-week training program focused on speed can affect the strength and speed of throwing in handball.	22 (M)	Semi-professional
Akyüz et al. (2019)	To evaluate the impact of muscle fatigue on shooting accuracy and ball velocity in goal shooting.	16 (M)	Professional
Carneiro et al. (2022)	To describe physical and physiological activity in a team of handball players over 60 years old in different game formats.	17 (M)	Amateur
Ermidis et al. (2021)	To quantify the intensity and technical involvement of U9 boys and girls in team handball during various game formats.	57 (20 F)	Performance
Fleureau et al. (2022)	To describe peak locomotion intensity during handball matches by player positions and compare them with small-sided games programmed during training in elite handball players.	11 (M)	Professional
Font et al. (2021)	To characterize the physical demands of an elite handball team throughout the entire sports season.	16 (M)	Professional
Gençoğlu and Gümüş (2020)	To predict the release speed when shooting on goal using wearable IMUs placed on the wrist.	4 (both)	Semi-professional
Gümüş and Gençoğlu (2020)	To evaluate PlayerLoadTM and heart response to stress in small-sided handball games specifically designed with an additional rule for outfield players.	13 (F)	Professional
Kniubaite et al. (2019)	To assess simultaneously external and internal game loads in elite female team handball players and verify differences in game loads between matches with different durations.	8 (F)	Professional
Luteberget and Spencer (2017)	To describe high-intensity events in international women's handball matches concerning playing positions.	20 (F)	Professional
Luteberget, Holme, et al. (2018)	To assess inter-device reliability of commercially available IMUs for measuring physical demands in handball.	22 (both)	Professional
Luteberget, Trollerud	To compare PlayerLoadTM and high-intensity events in two game-like training sessions with an official handball match.	31 (F)	Professional
et al. (2018)	To describe and compare the characteristics of game activities, internal load, technical involvement, perceived enjoyment, and effort in 13-year-old boys and girls in five different handball game formats.	48 (24 F)	Performance
Madsen et al. (2019)	To explore internal and external training loads during young handball players' matches.	12 (M)	Performance
Maric et al. (2021)	To compare the effects of different small-sided games and simulated handball training on physical performance and game activity profiles of handball players.	24 (F)	Semi-professional

Mikalonytė et al. (2022)	To conduct in-depth analyses evaluating external loads in beach handball players.	69 (N/A)	Professional
Müller et al. (2022)	The objective of the study is quite complex. In terms of the intent of the review on the use of IMU, the relevant sub-objective is to evaluate heart rate and physical intensity using IMU during the participation of the national handball team in the Tokyo Olympics during the third wave of the COVID-19 pandemic.	29 (F)	Professional
Ogasawara et al. (2021)	The objective of the study is quite complex. In terms of the intent of the review on the use of IMU, the relevant sub-objective is to evaluate heart rate and physical intensity using IMU during the participation of the national handball team in the Tokyo Olympics during the third wave of the COVID-19 pandemic.	29 (F)	Performance
Ortega-Becerra et al. (2020)	To describe the physical and physiological demands of adolescent handball players and to compare the analysis of movement and exercise intensity between the first and second half and between playing periods.	14 (M)	Performance
Pedersen et al. (2021)	(1) To determine the convergent validity of session rating of perceived exertion load (perceived exertion rating) through the correlation between session rating of perceived exertion and objectively obtained measures of training load (heart rate and PlayerLoadTM). (2) To determine the ability of the session rating of perceived exertion load to discriminate between categories of low and high training loads created independently based on objective measures.	47 (both)	Professional
Pueo et al. (2017)	To analyze the physical demands of elite beach handball players using temporal motion analysis with GPS technology and physiological response using heart rate.	24 (12 F)	Professional
Setuain et al. (2015)	To determine if there are biomechanical differences in jump performance in a group of elite female beach handball players with previous anterior cruciate ligament reconstruction several years after returning to elite competition.	21 (F)	Professional
Setuain et al. (2019)	To analyze the biomechanics of horizontal jumps in elite female beach handball players with or without previous anterior cruciate ligament reconstruction.	21 (F)	Amateur & Professional
Skejø et al. (2020)	To develop a new model for estimating throwing velocity in handball using an inexpensive AC-based device.	19 (8 F)	Performance
Skejø et al. (2021)	To determine and validate acceleration and angular velocity thresholds for identifying overhead throws in female handball players based on measurements from a wearable IMU placed on the forearm.	10 (5 F)	Professional
Soler-López et al. (2022)	To investigate the concurrent validity and reliability of multiple devices for measuring jump height in female handball players.	16 (M)	Performance
van den Tillaar et al. (2021)	(1) To determine the accuracy of machine learning models for detecting throw type and ball velocity from IMU data. (2) to determine if accuracy increases with the use of 200 g IMUs compared to 16 g IMUs.	17 (7 F)	Professional
Wik et al. (2017)	To describe and assess activity profiles for individuals and the team using IMU.	18 (F)	Professional
Zapardiel and Asín-Izquierdo (2020)	To evaluate the performance of beach volleyball players in specific game positions during competition without changing specific game structures.	57 (32 F)	Professional

Note. N = the number of players. M = male. F = female. IMU = inertial measurement unit. # = for both men and women in the research population, the value represents the number of women. N/A = not available.

Table 2. **Purpose of using IMU, utilized sensors and their settings**

Study	Purpose of IMU Use	IMU Brand [included sensors]	Number of Used IMUs	IMU Location	Sampling Frequency (Hz)	Range
Abuajwa et al. (2022)	To establish an individualized model of training load in terms of weightlifting speed.	BT [AC, GY, MA]	1	Outside the individual (on the load)	50	N/A
Akyüz et al. (2019)	To determine the level of acceleration when kicking the ball toward the goal at different levels of fatigue.	SS27L [AC]	2	Dorsal wrist	1000	± 50 G
Carneiro et al. (2022)	To express the degree of match load as the overall sum of load and the percentage of time spent in load zones.	Catapult-M Catapult-O [AC, GY, MA]	2	The upper thoracic back area	100	N/A
Ermidis et al. (2021)	To evaluate the intensity of load - here use the parameter of the so-called ACell'Rate (formula in the study) as a total measure of mechanical load.	Polar [AC, GY]	1	Sternum	200	N/A
Fleureau et al. (2022)	To assess the intensity of load - here use the parameter of the so-called ACell'Rate (formula in the study) as a total measure of mechanical load.	Kinexon [AC]	1	The upper thoracic back area	100	N/A
Font et al. (2021)	To determine the overall PlayerLoad™, the total number of accelerations and decelerations, high-intensity acceleration (HIA), high-intensity deceleration (HID), and HIA/HID per minute. HIA and HID were defined as events >2 G.	WIMU PRO [AC, GY, MA]	1	The upper thoracic back area	100	N/A
Gençoğlu & Gümüş (2020)	IMU is used to measure wrist acceleration during ball release.	Notch-Sys [AC]	2	The wrist of the dominant hand	500	N/A
Gümüş & Gençoğlu (2020)	To express external load.	Catapult-S [AC, GY, MA]	1	The upper thoracic back area	100	N/A
Kniubaite et al. (2019)	To express external load.	Catapult-S [AC, GY, MA]	1	The upper thoracic back area	100	N/A
Luteberget & Spencer (2017)	To determine PlayerLoad™, acceleration, deceleration, and directional changes.	Catapult-O [AC, GY, MA]	1	The upper thoracic back area	100	N/A

Luteberget, Holme, et al. (2018)	To determine PlayerLoad™ and perform inertial motion analysis (parameters for evaluating reliability).	Catapult-O [AC, GY, MA]	1	The upper thoracic back area	100	N/A
Luteberget, Trollerud et al. (2018)	To express external load.	Catapult-S [AC, GY, MA]	1	The upper thoracic back area	100	N/A
Madsen et al. (2019)	To compare acceleration activities and patterns in individual games.	Polar [AC]	1	Sternum	200	N/A
Maric et al. (2021)	To determine the number of steps, estimate the total energy expenditure, and time spent in activity zones.	Actical [AC]	1	Right-sided ankle	N.A.	N/A
Mikalonytė et al. (2022)	To determine the overall PlayerLoad™ and relative load (per minute).	Catapult-O [AC, GY, MA]	1	The upper thoracic back area	100	N/A
Müller et al. (2022)	To determine the overall PlayerLoad™ and relative load (per minute), acceleration and deceleration, explosive efforts, changes of direction, and the number of jumps.	Catapult-O [AC, GY, MA]	1	The upper thoracic back area	100	AC: ±16 G GY: ±2000 °/s MA: ±4900 μT
Ogasawara et al. (2021)	3D data from the AC was used to determine effective playing time during the match based on the threshold acceleration intensity (0.3 G).	SS-ECG [AC]	2	On the torso	200	N/A
Ortega-Becerra et al. (2020)	To describe exercise intensity during the match for comparison of games and their different phases.	SPI Pro X [AC]	1	Between the shoulder blades	100	N/A
Pedersen et al. (2021)	IMU was used to express the degree of training load (PlayerLoad™) as a comparative method to determine convergent validity with session rating of perceived exertion.	Catapult-O [AC, GY, MA]	1	The upper thoracic back area	N.A.	N/A
Pueo et al. (2017)	For individual assessment of the magnitude of acceleration changes during exercise.	SPI Pro X [AC]	1	On the back	100	N/A
Setuain et al. (2015)	For 3D-acceleration analysis of vertical jump motion.	Xsens [AC]	1	L3 lumbar vertebra area	100	N/A
Setuain et al. (2019)	To determine acceleration values in the Cartesian coordinate system (x, y, and z axes).	Xsens [AC]	1	L3-L4 lumbar vertebra area	100	N/A
Skejø et al. (2020)	To determine throwing speed in handball.	ADXL377 [AC]	1	The distal part of the forearm	500	±200 G

Skejø et al. (2021)	To determine the threshold values of acceleration and angular velocity during overhead ball throwing to identify the type of throw.	ADXL377 ICM-20600 [AC, GY]	1	The wrist of the throwing arm	200	AC: ± 200 G GY: ± 2000 °/s
Soler-López et al. (2022)	To verify the reliability and concurrent validity of two IMUs.	a) WIMU PRO b) VERT [AC, GY, MA]	2	a) Between the shoulder blades b) Slightly below and laterally to the navel	100	AC: ± 16 G ± 32 G ± 400 G GY: ± 2000 °/s MA: N/A
van den Tillaar et al. (2021)	To predict the type of throw (circular and whip) and approach (standing, running, jumping).	IMeasureU [AC, GY, MA]	1	Distal dorsal side of the throwing arm	AC: 1125 1600 GY: 1125 MA: 100	AC: ± 16 G ± 200 G GY: ± 2000 °/s MA: ± 4900 µT
Wik et al. (2017)	To express the level of match load for individual positions and periods using 5 and 10-minute intervals."	Catapult-S [AC, GY, MA]	1	The upper thoracic back area	100	N/A
Zapardiel & Asín-Izquierdo (2020)	To determine the number of accelerations greater than 2.5 m/s^2 and jumps higher than 0.4 m.	Catapult-O [AC, GY, MA]	3	The upper thoracic back area	100	N/A

Note. AC = accelerometer. Actical = Actical Respironcis, Philips. ADXL377 = ADXL377, Adafruit Industries, United States. BT = Beast Technologies. Catapult-M = Catapult MinimaxX S4, Catapult Sports, Australia. Catapult-O = OptimEye S5, Catapult Sports, Australia. Catapult-S = Catapult Sprint, Catapult Sports, Australia. GY = gyroscope. ICM-20600 = ICM-20600, InvenSense, Inc. IMeasureU = IMeasureU, New Zealand. Kinexon = Kinexon, Kinexon GMBH, Germany. MA = magnetometer. Notch-Sys = Notch system, Notch Interfaces Inc. Polar = Polar Team Pro, Finland. SPI Pro X = SPI Pro X, GPSports Systems, Australia. SS27L = SS27L, Biopac. SS-ECG = SS-ECG, Teijin Frontier Sensing Co. VERT = VERT® Fort Lauderdale, USA. WIMU PRO = WIMU PRO system, RealTrack Systems S.L., Spain. Xsens = Xsens Technologies B.V. Enschede, The Netherlands. N/A = not available.

DISCUSSION

In recent years, IMUs have gained popularity as portable and user-friendly tools for capturing high-quality data in sports (Rana & Mittal, 2021). Similarly, in handball, IMUs have been utilized both in practice and research to assess various aspects of game performance and sub-attributes of player movement (Maric et al., 2021; Mikalonytė et al., 2022; Müller et al., 2022; Ogasawara et al., 2021; Wik et al., 2017). This study aimed to provide insights into the attributes related to the use of IMUs in handball research, with a focus on assessing player movement.

To achieve this objective, we conducted a comprehensive review of existing studies that utilized IMUs for data collection in handball. Our review presents the latest insights into the application of IMUs in handball research, emphasizing the objectives of such studies and the methods employed to analyze player movements. The synthesis of our study, which encompasses 28 selected handball research papers extracted from an original set of 143 documents across four databases, demonstrates the extensive use of IMU technology in the sport. Our analysis, including studies up to 2022, underscores the role of IMUs in exploring a wide array of handball aspects, from the effects of training to players' actions under different conditions. The inclusion of both genders across amateur and professional levels indicates the broad applicability of IMUs in sport sciences. From a methodological standpoint, our study illustrates a variety of strategies for IMU placement, sensor selection, and data collection methods tailored to the specific requirements of handball research. This diversity underscores the crucial contribution of this technology in enhancing the analysis of handball performance.

Diversity of Research Studies' Objectives

The diversity of objectives identified in our analysis underscores the expansive scope of IMU technology application in handball research. As evidenced in Table 1, the studies included in our review span a broad spectrum of aims, from assessing the impact of training programs on specific skills such as throwing speed and accuracy (Abuajwa et al., 2022; Gençoğlu & Gümüş, 2020) to exploring physiological responses and player activities under varying conditions (Carneiro et al., 2022; Ermidis et al., 2021). This range highlights the adaptability of IMU technology in addressing both the physical and technical dimensions of handball performance.

The application of IMUs to investigate player movements and game performance reflects an ongoing effort to enhance the understanding of the sport's demands. Studies focused on evaluating the effects of muscle fatigue on shooting accuracy (Akyüz et al., 2019) and characterizing physical demands across different player positions (Fleureau et al., 2022) point to a thoughtful approach to performance analysis. Such diversity in objectives demonstrates the versatility of IMUs in capturing a wide array of data and indicates the technology's potential to inform training and development strategies that are closely aligned with the specific needs of handball players and teams.

IMUs have proven effective in identifying a variety of game events across several studies. Researchers have identified game-related phenomena in terms of acceleration intensity (Font et al., 2021), analyzed effective game time through player movement acceleration (Ogasawara et al., 2021), observed ball release above head height (Skejø et al., 2021), and examined different throwing techniques (van den Tillaar et al., 2021). Furthermore, specific aspects of game activities have been investigated, including wrist acceleration during ball release (Akyüz et al., 2019; Gençoğlu & Gümüş, 2020), changes in acceleration during jumps (Setuain et al., 2015, 2019), and the estimation of throwing speed (Skejø et al., 2020; van den Tillaar et al., 2021). It is anticipated that future research will also focus on other movements that occur during the game, akin to other sports. For example, locomotion was identified in netball as a much more effective method than traditional video coding methods (Smith & Bedford, 2020). The combination of information on external and internal loads and relevant movement patterns occurring during these loads is useful for better specifying athlete load. This can be used for match management, individualizing training, and preventing injuries, particularly those related to the lower extremities, shoulder, and arm (Luig et al., 2018; Moller et al., 2012).

Despite the extensive application of IMUs in these areas, to date, only three studies have explored or partially evaluated the methodological foundations of using IMUs in handball, which is crucial for advancing research in this field. These studies have focused on assessing the validity of IMUs in measuring vertical jump height (Soler-López et al., 2022) and the reliability of specific devices (Luteberget, Holme, et al., 2018; Soler-López et al., 2022). Specifically, the reliability of the Catapult-S device in determining the PlayerLoad™ parameter has been scrutinized (Luteberget, Holme, et al., 2018). Van den Tillaar et al. (2021) provided essential insights into the optimal sampling frequency and measurement range for sensors in detecting motion events, emphasizing the importance of a high sampling frequency (1600 Hz) and a broad measurement range (± 200 G AC value) for accurate motion event identification in handball. This underscores the significant demands handball's dynamic nature places on IMU devices, affecting memory capacity, battery life, and the computational power required for data processing. Notably, while studies on external load evaluation typically employ a sampling frequency of 100 or 200 Hz, the adequacy of these settings remains underexplored. This is consistent with a review by Gómez-Carmona et al. (2020), which reported a sampling rate setting of 100 Hz in 86.4% of studies focusing on team sports (handball not included). The findings from van den Tillaar et al. (2021) suggest these settings might be insufficient, underlining the need for future research to meticulously consider the methodological aspects of IMUs in handball, particularly regarding appropriate sampling frequencies and ranges. These insights highlight the fact that the dynamic nature of players' movements necessitates recording at frequencies significantly higher than the default setting of 100 Hz provided by many devices. The findings of this study further reveal (see Table 2) that this frequency was the most frequently employed.

Differences in IMUs Usage Across Sex and Performance Level

The results showed (see Table 1) that IMU use was independent of gender and performance level. This inclusiveness highlights the application of the technology across different gender groups..

It was observed that IMU technology is applied across all performance levels in handball, from amateur to professional athletes. This range demonstrates the technology's versatility in addressing issues relevant to players at various stages of their sporting careers. Predominantly, studies focus on professional players, aligning with the objective of understanding the dynamics of play and training at higher competition levels. This focus may also reflect the better financial and logistical support available to professional teams, facilitating more comprehensive research in these settings.

Despite the widespread application of IMU technology across diverse demographic and performance levels, there is a notable gap in research regarding how these specific factors influence the reliability and validity of IMU measurements. This oversight suggests an area for future research, aiming to ensure that IMU technology can be effectively and accurately applied across the full spectrum of handball participation, from grassroots amateurs to elite professionals.

Methodological Diversity and Its Implication for Handball Research

The deployment of IMU technology in handball research, as depicted through the summarized insights from Table 2, demonstrates both consistency and variance in the methodological approaches employed across studies with analogous objectives. The range of IMU brands indicates a wide array of technologies used based on specific research needs, although the Catapult brand is the most dominant. These devices predominantly include AC, GY, and MA, with some supplemented by additional sensors such as global or local positioning systems, heart rate sensors, and thermometers. Diversity in sensor settings is also evident, with sampling frequencies primarily aligning at 100 Hz, and deviations up to 1000 Hz and 1600 Hz for detailed motion analysis, reflecting tailored approaches to study design. The sensor range varies, especially for ACs, from ±16 G to ±200 G, indicating the varied requirements of the studies. Placement of IMUs across different body locations, such as the upper thoracic back area or the wrist, underscores the methodological flexibility in capturing relevant motion data, revealing a nuanced application of IMU technology based on each study's unique objectives. This diversity raises legitimate questions about whether it results from well-thought-out and justified study designs or stems from arbitrary decisions related to "device availability" and "default device settings."

A vein of consistency is observable in studies aimed at assessing external loads and PlayerLoad™ metrics. For instance, investigations conducted by Carneiro et al. (2022), Gümüş & Gençoğlu (2020), Kniubaite et al. (2019), Luteberget & Spencer (2017), Luteberget, Holme, et al. (2018), Luteberget, Trollerud et al. (2018), Mikalonytė et al. (2022), Müller et al. (2022), and Wik et al. (2017) predominantly employ the Catapult device, situating the IMU on the upper thoracic back area. This uniform methodological selection suggests a move towards a standardized approach in capturing external load dynamics in handball, indicating a convergence in research methodology that facilitates comparability across studies. Kinexon and Catapult, known for similar default sensor settings and placement, dominate as analytical tools in handball. For example, in the German Bundesliga, Kinexon is now part of almost every sports hall where Bundesliga matches are played.

In contrast, the diversity in methodological execution becomes pronounced in studies focused on specific movement analyses. Akyüz et al. (2019) and Gençoğlu & Gümüş (2020), despite their distinct research objectives, both pivot towards movement analysis but opt for divergent IMU settings – emphasizing the methodological variability present even within similar research themes. The criteria for selecting IMU brands, the number of sensors deployed, their bodily placements, and the sampling frequencies employed reveal a tailored approach that resonates with each study's unique objectives, reflecting detailed and customized use of IMU technology driven by specific research needs, availability of technological resources, and potentially researcher preferences.

This intentional application is further illustrated when examining the deployment strategies of IMUs across studies with similar purposes yet varying configurations – highlighted by differences in the number of IMUs used, their placement on the athlete's body, and the utilized sampling frequencies (Abuajwa et al., 2022; Carneiro et al., 2022; Ermidis et al., 2021; Fleureau et al., 2022). Such methodological diversity, while showcasing the flexible utility of IMU technology, also underscores the bespoke nature of research design in the domain of handball performance analysis.

As evidenced by the studies presented in Table 2, the concurrent use of multiple IMUs in handball is not widespread. Out of the total number of studies, only five employed two IMUs, and one study used three IMUs, with the devices typically located in a single body area (either the trunk or arm). This likely reflects that most studies relying on data from a single IMU use complex systems operating with a single IMU primarily attached to the player's body via a vest provided by the manufacturer. Moreover, unless they were examining specific movements of individual body segments, authors typically considered the player's movement as that of the whole body. However, the movements of individual body parts are crucial in handball, both in terms of the structure of gameplay activities and the external load. Despite this, such movements are often overlooked. Therefore, it is worth considering the potential benefits of employing multiple IMUs to enhance the accuracy and reliability of movement identification and other analytical outputs. Furthermore, incorporating multiple IMUs would likely provide a more comprehensive understanding of the kinematics of handball gameplay.

Building on the detailed examination of IMU technology application in handball research, several critical implications emerge from the observed methodological diversity and uniformity. These implications not only underscore the need for further methodological refinement but also highlight potential pathways for future research in sports science.

Firstly, the trend towards methodological standardization, particularly evident in studies focused on external load and PlayerLoad™ metrics, suggests a growing consensus on best practices for employing IMU technology in handball research. This move towards uniformity could greatly enhance the comparability of results across different studies, facilitating a more cohesive body of research that can cumulatively advance the field. Standardization might also streamline the process for future studies, allowing researchers to build on established methodologies without the need for extensive preliminary validation work.

However, the diversity in IMU application underscores the technology's adaptability and the innovative potential of varied research designs. This methodological flexibility attests to the IMU technology's capability to address a wide range of research questions, from specific movement analyses to broad performance metrics assessments. It encourages researchers to explore novel applications and methodologies, potentially leading to new insights into player performance and sport sciences at large.

Given this methodological diversity, further studies focusing on methodological aspects are essential to enhance the accuracy and reliability of IMU-based measurements in handball. First, there is a need for studies that propose valid metrics for dynamic load, as the most commonly used metric, PlayerLoad™, has several limitations. Refining its definition or proposing a new metric would be beneficial. Second, the influence of instrument settings, such as sampling rate and measurement range, as well as individual sensors, should be investigated more comprehensively in the context of handball's specific movement patterns. Third, the impact of the location and number of IMUs on the final outputs should be assessed to ensure comparability of results across different studies. In this context, it's crucial to consider the rules of handball and the risks of injury associated with device placement (especially in the event of a fall), both to the player and in relation to physical contact with other players. The simultaneous use of multiple devices placed in various locations on the player's body is directly related to the research purpose. However, given the nature of the player's movement, the optimal combination seems to be placing devices on the player's torso and dominant (throwing) hand. Additionally, it remains unclear whether using data from all three spatial axes is more advantageous than using only some of them. Addressing these methodological considerations will help establish a strong theoretical foundation for future IMU research in handball.

Recommendations for Practical Use of IMUs

- Evaluation and Adjustment of Appropriate Sampling Frequencies: Considering the observation that the dynamics of movement in handball may necessitate a higher sampling frequency than the standard 100 Hz, explore the capabilities of your IMU device for setting a frequency that more effectively captures rapid and complex movements. Engage in experimentation with higher frequencies to ensure the data collected are as precise and relevant as possible for your specific training objectives.
- Optimization of Sensor Placement: Reflect upon the variability in the placement of IMU sensors noted across various studies. Tailor the positioning of sensors to the movement specifics of handball, the rules of handball, and the requirements of individual players, aiming to achieve the optimal data collection for analyzing movement and load. However, bear in mind that varying device placement might demand a different approach to data processing and interpretation.
- Exploration of New Possibilities and Metrics: In light of discoveries regarding the diversity in the use of various sensors and metrics, assess which devices, sensors, and metrics derived from the data best suit your needs. They could offer additional valuable insights for enhancing performance or for the prevention of player injuries.

CONCLUSION

The results of the reviewed studies have demonstrated that IMUs play a significant role in analyzing various aspects of handball, predominantly in evaluating external loads. Additionally, IMUs have proven to be effective in identifying movement phenomena and assessing changes in movement patterns following medical interventions. It was found that IMU technology is utilized across both male and female genders and at all performance levels, from amateur to professional.

In handball research, PlayerLoad™ is the most frequently applied metric, which has been shown to facilitate the comparability of results across different studies, teams, and sports. The review highlights the predominant use of complex systems for data collection and analysis, with AC being the primary data source, supplemented by GY and/or MA depending on the research objectives. Such complex systems are typically applied when assessing external load. In the case of analyzing specific movements or movement patterns, smaller IMUs are utilized.

Inconsistency in IMU setup was observed across the studies, specifically in terms of the sampling frequency for data recording and the variability in device placement on the body, although the most common placement was from the upper chest to back. These findings underscore the necessity for future studies to rigorously validate specific IMU configurations in association with used metrics and sensor placement. These efforts should aim to develop a standardized approach that aligns with both research objectives and practical needs, enabling its adoption with confidence in the broader handball research community.

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