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MANUAL MATERIAL HANDLING

OCCUPATIONAL HEALTH

A SYSTEMATIC REVIEW OF THE METHODOLOGIES USED TO VALIDATE INERTIAL SENSORS FOR JOINT ANGLE ESTIMATION

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Resumen: anto los médicos como los investigadores utilizan ampliamente las mediciones del ángulo articular; dichas medidas se han empleado para cuantificar posturas neutrales y no neutrales, para evaluar el grado de deterioro, planificar estrategias de rehabilitación y evaluar el efecto de diversas intervenciones. Los sistemas convencionales de estimación de ángulos articulares (goniómetros) suelen ser sencillos de utilizar, pero es posible que no proporcionen toda la gama de datos necesarios. Además, los goniómetros proporcionan información en planos únicos y sólo para posiciones estáticas. Además, estos sistemas no son adecuados para su uso en entornos no controlados debido a su falta de portabilidad y la falta de experiencia técnica requerida. Esto puede limitar sus posibles aplicaciones de investigación. Como resultado, puede resultar complicado para los investigadores obtener datos sobre las posturas tridimensionales de los segmentos corporales.

Se ha demostrado que los acelerómetros son un método de medición válido y fiable. Sin embargo, se ha observado que los datos del ángulo de la articulación pueden no ser tan precisos como se desea, debido a la influencia de una mayor aceleración del segmento o la presencia de derivas. En respuesta a esto, la validación de los sensores garantiza que los datos que recopilan sean precisos y comparables con los métodos estándar. Esta revisión sistemática examina y sintetiza la literatura actual sobre los métodos y resultados utilizados para probar la validez y confiabilidad de los sensores inerciales cuando se usan para estimar los ángulos de las articulaciones. Este enfoque de revisión sistemática siguió la metodología PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) para realizar e informar revisiones sistemáticas en ciencias de la salud.

Para la revisión, se buscaron artículos publicados hasta junio de 2024 en cuatro bases de datos (ScienceDirect, PubMed, Web of science, MDPI), incluidas bases de datos específicas de ergonomía, biomecánica e ingeniería para garantizar una cobertura integral del tema. Los criterios de inclusión consideraron lo siguiente: estudios enfocados a la validación de IMU en evaluaciones ergonómicas; artículos de investigación publicados en revistas revisadas por pares o actas de congresos, estudios que comparan las IMU con los métodos estándar (por ejemplo, captura de movimiento óptico), artículos publicados en inglés, publicaciones de los últimos 10 a 15 años para garantizar su relevancia. Los criterios de exclusión consideraron estudios no directamente relacionados con validaciones de IMUS para la estimación de la articulación angular, artículos, editoriales o artículos de opinión no revisados por pares, así como estudios sin suficientes detalles metodológicos. Se seleccionaron diecinueve estudios para la revisión final. La revisión incluyó el tamaño y la composición de la muestra para cada muestra, el tamaño de la muestra, el sistema estándar de oro y los índices de validación calculados. Metodología para validar sensores inerciales al aplicarlos para estimar ángulos articulares. Los hallazgos destacan que la mayoría de los estudios (94,7%) utilizaron software comercial de captura de movimiento para analizar la postura y el movimiento, lo que subraya la dependencia de herramientas estandarizadas para la recopilación de datos precisos. La tendencia creciente en el uso de sensores inerciales durante la última década, con más de la mitad de los estudios (57,8%) publicados en los últimos cinco años, refleja el creciente reconocimiento del potencial de esta tecnología en las evaluaciones ergonómicas. El uso de métodos estadísticos avanzados, como coeficientes de correlación, RMSE y gráficos de Bland-Altman, confirma aún más el enfoque para evaluar la validez y confiabilidad de estos sensores.

Palabras clave: sensores, validación, confiabilidad, revisión.

Relevancia para la ergonomía: Las unidades de sensores inerciales (IMU), que incluyen acelerómetros, giroscopios y magnetómetros, son utilizadas con mayor frecuencia en las evaluaciones ergonómicas para medir los movimientos y posturas corporales. Estos sensores proporcionan datos valiosos y objetivos, en tiempo real,

que pueden ser fundamentales para evaluar ergonómicamente una estación de trabajo, identificar factores de riesgo y mejorar el diseño de tareas y herramientas. Sin embargo, la precisión y fiabilidad de estas mediciones son cruciales para tomar decisiones informadas en ergonomía. La validación de las IMU garantiza que los datos que recopilan son precisos y comparables a los métodos de referencia, como los sistemas ópticos de captura del movimiento. Sin una validación adecuada, los datos de las IMU podrían dar lugar a evaluaciones incorrectas que podrían generar intervenciones ergonómicas ineficaces o incluso perjudiciales. El proceso de validación consiste en comparar los datos del sensor inercial con estándares conocidos o utilizarlos en experimentos controlados cuyos resultados se conocen bien. Este proceso permite descubrir problemas como la deriva del sensor, la sensibilidad a factores ambientales o imprecisiones en la medición de movimientos complejos. Una vez validadas, los sensores inerciales pueden utilizarse con confianza en diversos entornos, desde estudios de campo en lugares de trabajo reales hasta experimentos de laboratorio controlados, proporcionando datos fiables que mejoran la precisión y eficacia de las evaluaciones ergonómicas. La principal ventaja de las metodologías cuando se utilizan para validar sensores inerciales en cuestiones de ergonomía es que la calidad de las medidas parece ser superior a la obtenida mediante goniómetros y otros instrumentos. Esto permite realizar evaluaciones ergonómicas más objetivas y precisas. Por otra parte, en cuanto al proceso de revisión sistemática de literatura, es preciso señalar su potencial para identificar oportunidades para futuras investigaciones en el campo de la validación de instrumentos para propósitos de estudios ergonómicos.

Abstract: Joint angle measurements are used extensively by clinicians and researchers alike, such measures have been employed to quantify both neutral and no-neutral postures, to assess the degree of impairment, to plan rehabilitation strategies, and to assess the effect of various interventions. Conventional systems of joint angle estimation (goniometers) are often straightforward to use, but they may not provide the full range of data that is needed. Addionally, goniometers provide information in single planes and only for static positions. Besides, these systems are not suitable for use in uncontrolled environments due to their lack of portability and the technical expertise required. This may limit their potential research applications. As a result, it can be challenging for researchers to obtain data about three-dimensional body segment postures.

It has been demonstrated that accelerometers are a valid and reliable method of measurement. However, it has been observed that joint angle data may not be as precise as desired, due to the influence of increased segment acceleration or the presence of drifts. In response to this, the validation of the sensors ensures that the data they collect is accurate and comparable to gold-standard methods. This systematic review examines and synthesizes the current literature on the methods and outcomes used to test the validity and reliability of the inertial sensors when used to estimate joint angles. This systematic review approach followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology for conducting and reporting systematic reviews in health sciences.

For the review, articles published through June 2024 were looked up in four databases (ScienceDirect, PubMed, Web of science, MDPI), included databases specific to ergonomics, biomechanics, and engineering to ensure comprehensive coverage of the topic. Inclusion criteria considered the following: studies focused on the validation of IMUs in ergonomic assessments; research articles published in peer-reviewed journals or conference proceedings, studies that compare IMUs to gold-standard methods (e.g., optical motion capture), articles published in English, publications from the past 10–15 years to ensure relevance. The exclusion criteria considered studies not directly related to validations of IMUS for angle joint estimation, non-peer-reviewed articles, editorials, or opinion pieces, as well as studies without sufficient methodological details. Nineteen studies were selected for final review. The review included the sample size and composition for each sample, sample size, gold-standard system, and validation indexes calculated. methodology to validate inertial sensos when applying them to estimate joint angles. The findings highlight that most studies (94.7%) utilized commercial motion capture software to analyze posture and movement, underscoring the reliance on standardized tools for accurate data collection. The increasing trend in the use of inertial sensors over the past decade, with more than half of the studies (57.8%) published in the last five years, reflects the growing recognition of this technology's potential in ergonomic assessments. The use of advanced statistical methods, such as correlation coefficients, RMSE, and Bland-Altman plots, further confirms the approach to evaluating the validity and reliability of these sensors.

Keywords: sensor, validity, reliability, review

Relevance to Ergonomics:

Inertial sensor units (IMUs), comprising accelerometers, gyroscopes, and sometimes magnetometers, are increasingly used in ergonomic assessments to measure body movements and postures. These sensors provide valuable, objective data in real-time, which can be critical in evaluating workplace ergonomics, identifying risk factors for musculoskeletal disorders, and improving the design of tasks and tools. However, the accuracy and reliability of these measurements are crucial for making informed decisions in ergonomics. Validating IMUs ensures that the data they collect is accurate and comparable to gold-standard methods, such as optical motion capture systems. Without proper validation, the data from IMUs could lead to incorrect assessments, potentially resulting in ineffective or even harmful ergonomic interventions. Validation typically involves comparing the IMU data against known standards or using them in controlled experiments where the outcomes are well understood. This process can uncover issues like sensor drift, sensitivity to environmental factors, or inaccuracies in measuring complex movements. Once validated, IMUs can be confidently used in various settings, from field studies in real workplaces to controlled laboratory experiments, providing reliable data that enhances the precision and effectiveness of ergonomic assessments. The primary benefit of methodologies when used to validate inertial sensors in ergonomics issues is that the quality of measures appears to be superior to that obtained through goniometers and other instruments. This allows for more objective and precise ergonomic evaluations. In addition, this systematic review can help identify potential avenues for further research in the field of ergonomics. Overall, the findings suggest that inertial sensor technology has become a critical tool in ergonomic research, with proven reliability and precision for estimating joint angles. As the technology continues to evolve, its application is likely to expand further, offering new insights and improving workplace safety and health outcomes.

4. INTRODUCTION

Joint angle measurements are used extensively by clinicians and researchers alike. Ceseracciu et al. (2014) indicates that such measures have been employed to quantify both neutral and no-neutral postures, to assess the degree of impairment, to plan rehabilitation strategies, and to assess the effect of various interventions. Conventional systems of joint angle estimation (goniometers) are often straightforward to use, but they may not provide the full range of data that is needed (Godfrey et al., 2008). Goniometers provide information in single planes and only for static positions. According to Fong and Chan (2008) electro goniometers and inclinometers may offer solutions for more than one plane, as well as provide dynamic data. However, the physical design of such sensors can restrict motion, which is something to consider. Besides, these systems are not suitable for use in uncontrolled environments due to their lack of portability and the technical expertise required (Walmsley et al., 2018). This may limit their potential research applications. As a result, it can be challenging for researchers to obtain data about three-dimensional body segment postures. It has been demonstrated that accelerometers are a valid and reliable method of measurement (Grimaldi et al.,2010). However, it has been observed that joint angle data may not be as precise as desired, due to the influence of increased segment acceleration or the presence of drifts. In response, several algorithms have been developed to address this issue. According to Abyarjoo et al. (2015) a possible solution to this problem is to combine a gyroscope and a magnetometer with an accelerometer in a sensor, which is called an inertial measurement unit (IMU; sensors combining accelerometer and gyroscope) and sensors combining accelerometer, gyroscope, and magnetometer (Magneto-inertial measurement units). It is proposed by Kok et al. (2016) that gyroscopes could be used to estimate sensor orientation by integration of signals (angular velocity relative to the sensor XYZ axis), accelerometers could be used to provide a static orientation measurement relative to gravity by analyzing the acceleration signal, and magnetometers could be used to provide heading using sensor orientation relative to Earth’s magnetic field (Sabatini, 2008).

The psychometric properties, such as validity and reliability of sensors for joint angle estimation have been extensively studied during the past few years. Two systematic reviews have been conducted to report on the psychometric evidence relating to IMU validity. The first systematic review, published in 2019 (Poitras, 2019), indicated that sensor technologies have been validated through several different methods, including coefficient of multiple correlation (CMC), intraclass correlation coefficient (ICC) and root mean square error (RMSE). The other systematic review, published in 2021, considered the use of ICC and Kappa Index, in addition to RMSE, as a means of evaluating the validity of the tests.

This systematic review examines and synthesize the current literature on the methods and outcomes used to test the validity and reliability of the inertial sensors when used to estimating joint angles. It is possible that some studies may have been missed because of the search keywords used. These may have been studies focusing on other applications.

5. OBJECTIVES

Several objectives have been considered in this systematic review, namely: To Identify and Synthesize Existing Research, which considers to gather and analyze existing studies and literature on the validation of inertial sensor units (IMUs) in the context of estimating joint angles, providing a comprehensive overview of current knowledge and methodologies; to assess validation methods and critically evaluate the different methods used to validate IMUs, including comparisons with gold-standard techniques, to determine their effectiveness, strengths, and limitations; to determine accuracy and reliability of IMU’s in measuring ergonomic variables such as posture, movement, and force, identifying factors that may influence these parameters; to identify gaps in the literature; highlighting areas where research is lacking or inconsistent, identifying gaps that need to be addressed in future studies to enhance the understanding and application of IMUs in ergonomics; to provide recommendations for best practices, developing evidence-based recommendations for the use and validation of IMUs in ergonomic assessments, guiding researchers and practitioners in selecting and applying these tools effectively; to evaluate the applicability in real-world settings, exploring the feasibility and practicality of using validated

IMUs in various workplace environments, assessing their potential to improve ergonomic interventions and reduce injury risks; to analyze the impact on ergonomic interventions, reviewing how the use of validated IMUs influences the outcomes of ergonomic interventions, determining their role in improving worker safety, comfort, and productivity; to establish a framework for future research, proposing a structured framework for future research efforts aimed at improving the validation and application of IMUs in ergonomic assessments, ensuring continued advancements in this field.

6. METHODOLOGY

3.3 Search strategy

This systematic review approach followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology for conducting and reporting systematic reviews in health sciences. For the review, articles published through June 2024 were looked up in four databases (ScienceDirect, PubMed, Web of science, MDPI), included databases specific to ergonomics, biomechanics, and engineering to ensure comprehensive coverage of the topic. Only studies in English were searched. A list of primary keywords and search terms related to the validation of inertial measurement units (IMUs) for joint angle estimation was developed. Primary key words included: "Inertial sensor units", "IMUs", "Ergonomics", "Validation", "Accuracy", "Reliability", "Posture assessment", "Movement analysis" and "Biomechanics". The search keywords used to identify studies on validation of inertial sensor technology for joint angle estimation included ["Inertial sensor units" OR "IMUs"] AND ["validation" OR "accuracy" OR "reliability"] AND ["ergonomics" OR "posture assessment" OR "movement analysis" OR "biomechanics"].

3.2 Inclusion criteria

Inclusion criteria considered the following: studies focused on the validation of IMUs in ergonomic assessments; research articles published in peer-reviewed journals or conference proceedings, studies that compare IMUs to gold-standard methods (e.g., optical motion capture), articles published in English, publications from the past 10–15 years to ensure relevance.

3.6 Exclusion criteria

The exclusion criteria considered studies not directly related to validations of IMUS for angle joint estimation, non-peer-reviewed articles, editorials, or opinion pieces, as well as studies without sufficient methodological details.

3.7 Search and study selection

The selected databases were searched using the search terms developed. Filters were used to refine the results by publication date, language, and study type. Titles and abstracts were screened to identify potentially relevant studies. Study selection involved importing search results into a reference management tool (Zotero) to organize and manage references. An initial screening based on titles and abstracts was performed to exclude irrelevant studies. There was performed full-text screening of the remaining studies to confirm their eligibility based on inclusion and exclusion criteria. Finally, a PRISMA flowchart was used to document the study selection process, including the number of studies identified, screened, excluded, and included. The initial search identified a total of 275 studies based on title, abstract, and keywords, and after discarding duplicate articles. Review articles were excluded according to exclusion criteria. The chosen studies (n = 58) were examined in their entirety based on the study's title, abstract, and full text (Step 1 in Fig 1), and they were disqualified from further analysis if they: did not use human subjects; used inertial sensing for purposes other than measuring a particular aspect of body posture (Step 2 in Fig 1), studies that used accelerometers to measure the vibration or movement of inanimate objects or machinery, for instance, were not included. After full review were selected 19 articles.

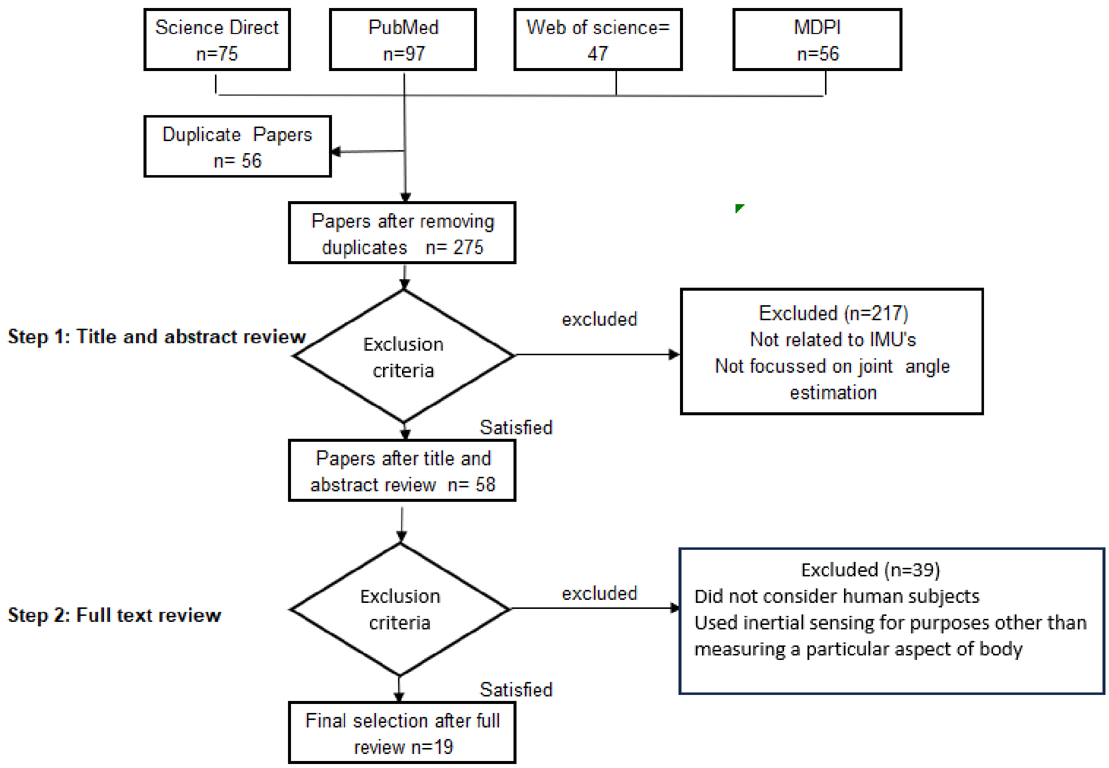


Fig 1. PRISMA flowchart of the document and selection process.

3.8 Data extraction and analyses

The data extraction and analysis phase included the following: author (s), year of publication, title, journal, study objective, study sample, study location, location of sensor in body, type of tasks performed, exposure characteristics, type of statistical technique used for validation, gold-standard system, and validation indexes calculated.

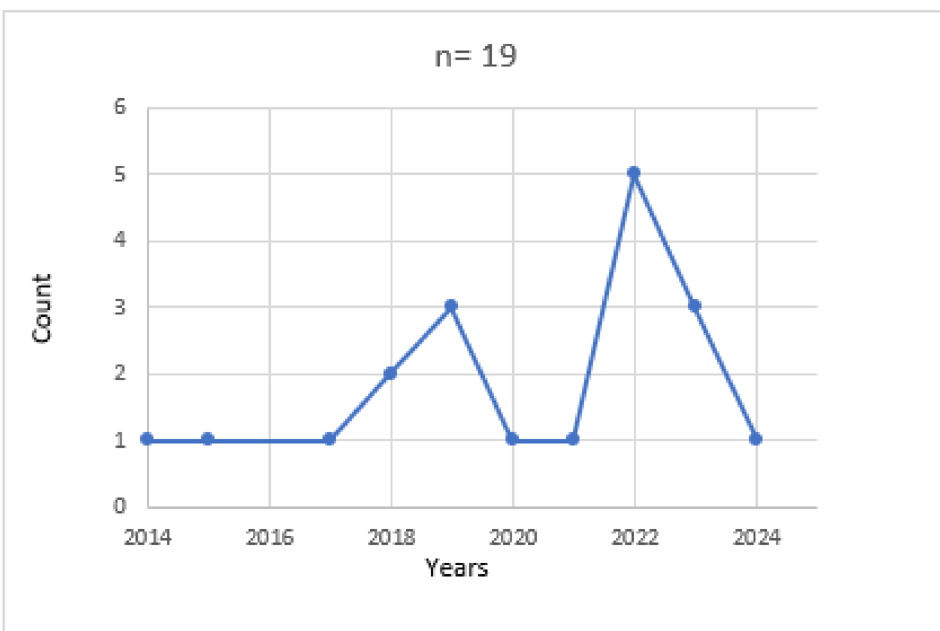
7 RESULTS

The growing adoption of inertial sensor technology in ergonomics research reflects a shift towards more precise and accessible methods for assessing their validity and reliability. In recent years, these sensors have become increasingly valuable in both laboratory and field settings, offering detailed measurements of body kinematics that are crucial for understanding and mitigating occupational hazards. This review examines 19 studies that present methodologies to validate and examine reliability of inertial sensors to estimate joint angles, providing insights into their effectiveness and reliability across various applications. The analysis focuses on the validation of inertial sensors against gold-standard systems, the statistical methods employed to assess their accuracy, and the contexts in which these studies were conducted. The review also highlights the trends in research over the past decade, revealing a significant increase in the use of these sensors, particularly in scientific and healthcare environments. Table 2 gives a general overview of the 19 studies that were examined, including the sample size and composition for each sample, sample size, gold-standard system, and validation indexes calculated.

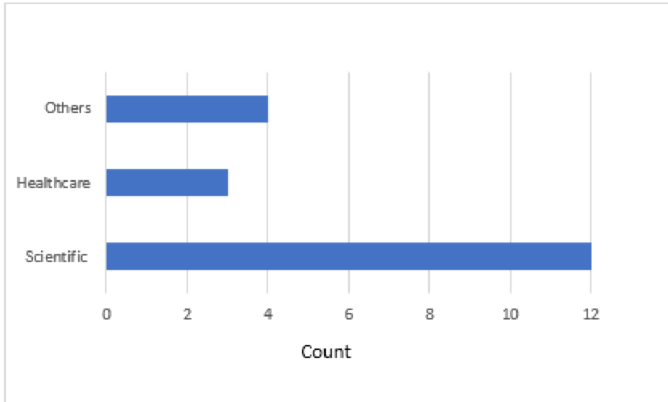
Table 2 Publications selected after final review.

Study	Authors (Year)	Participants	n	Gold-sample system	Validation index
1	Thompson et al. (2024)	Cyclists	17	Marker-based three-	Intra-class Correlation Coefficients (ICC)
2	Zahn et al. (2023)	Hospital patients	39	A marker based system	Correlation coefficient
3	Riek et al. (2023)	Healty adults	12	Motion capture	Bland–Altman and intraclass correlation (ICC) analysis
4	Ortigas et al. (2023)	arthroplasty patients	N/E	ground truth simulator values	RMSE
5	Lewin et al. (2022)	adults	20	Qualisys motion capture, AMTI	Intra-class Correlation Coefficients (ICC)
6	Evans et al. (2022)	cyclists	4	MoCap System	Pearson's correlation coefficient ® and Root Mean Square Error (RMSE)
7	Blandeau et al. (2022)	Healty adults	15	Optoelectronic reference system	Bland–Altman plots and Lin's concordance correlation coefficient
8	Piche et al. (2022)	Young adults	22	optoelectronic motion capture	Root Mean Square Deviation (RMSD) and Lin's Concordance Correlation (LCC)
9	Cudejko et al. (2022)	Young adults	21	Xsens motion tracking system	R-squared values
10	Park and Yoon (2021)	Healty adults	10	statsitical parametric	Hypothesis testing for diffences in mean values
11	Aqueveque et al. (2020)	Healty adults	20	Motion capture system	Correlation coefficient
12	Teufl et al. (2019)	College students	28	A marker based OMC System	Root mean squared error (RMSE), range of motion error (ROME), Bland-Altman (BA) analysis, and the coefficient of multiple
13	Bessone et al. (2019)	College students	14	Optoelectronic system	Coefficient of repeatability and RMSE
14	Abhayasinghe et al. (2019)	Not specified	N/E	Vicon Optical Motion Capture	Root Mean Square Error (RMSE)
15	Cho et al. (2018)	Hospital patients	3	Camera based system	Root mean squared error (RMSE) and intraclass correlation coefficient (ICC)
16	Parrington et al. (2018)	Young adults	10	Motion capture	Intra-class Correlation Coefficients (ICC), root mean square error (RMSE), and percent error
17	Lanovaz et al. (2017)	Children	10	3D motion capture system	Overal partial R squared, RMS, Bland-Altman plots
18	Winter et al. (2015)	Runners	10	Motion analysis system	Correlation coefficient
19	Leardini et al. (2014)	Healty adults	17	stereophotogrammetry	Root mean square deviation

Ten of the 19 studies collected data in field settings, with 9 (47.3%) of the studies taking place in laboratory settings. Scientific in laboratory ambiance and health services, were the most frequently studied (18 of the 19 studies). Three of the studies (15.8%) used measurements of angular displacement, as well as acceleration. Joint angle kinematics for upper arms, neck and trunk was calculated using various pairs of sensors. All the studies performed in lab settings validated inertial sensor measurements for accuracy and precision in ergonomics applications. By statistically comparing kinematic measurements obtained using inertial sensing to equivalent measurements obtained from a reference gold-sample system, Root mean square error (RMSE) was assessed by Ortigas et al. (2023), Evans et al. (2022), Blandeau et al. (2022), Teufl et al. (2019), Abhayasinghe et al. (2019), Cho et al. (2018), and Parrington et al. (2018). Correlation coefficients paired and independent sample t-tests, summary statistics on root mean squared errors (RMSE), and limits of agreement were among the statistical techniques were used to evaluate the accuracy of inertial sensor-derived measures in comparison to reference instrumentation measures (Park and Yoon, 2021. By measuring inter-rater reliability and intra-rater repeatability, the precision of sensor measurements was evaluated (Thompson et al., (2024); Lewin et al. (2022), and Parrington et al. (2018). Correlation coefficient was evaluated by Zahn et al. (2023), Evans et al. (2022), Piche et al. (2022), and Aqueveque et al. (2020). Bland-Altman plots were used by Riek et al. (2023), Blandeau et al. (2022), and Teufl et al. (2019). To compare the measurements obtained after multiple attachments of sensors to the same participant by the same examiner, intra-rater repeatability was typically investigated Thompson et al. (2024) and Lewin et al. (2022). A 94.7% of the studies used commercial software, such as MoCap system, Vicon Optical motion capture, Xsens motion MTS) to categorize various postures from inertial sensor data over time. According to the review's findings, over the past ten years, an increasing number of studies have used inertial sensors to evaluate the risk of MD. Over 57.8% of the studies examined (n=11 of 19) were published in the five years prior to the current year (2024); Fig 2 a). Most studies were developed in scientific context (63.15%), a 15.7% took place in healthcare service, and 21.1% covered other areas (cycling children, runners); fig 2 b).



a)



b)

Fig 2 Summary of the review results in terms of the number of studies by publication year between 2014 and 2024 (a), by field study site where the data collection was performed (b)

When using body-worn inertial sensors for ergonomics applications, the location of the sensors on the body must be carefully considered. Most studies used were focused on the sensor placement on upper body segments (Table 3) (65.8%). The placement decision was related to the study main research question. However, the locations varied according to postural models considered. Most studies reported segment or joint angular displacement in terms of flexion/extension, abduction/adduction, rotation using the sensor frame reference, but they were not standardized making the comparisons undetermined.

Table 3 Sensor placement

Body segment	Quantity	Upper body	Lower body	Study number from table
Head	3	x		1,5,17,19
Forehead	1	x		6,9
Cervical	1	x		16
Chest/Sternum	6	x		15,18
Scapular	3	x		1
Thoracic	4	x		7,8,9,11,15,18
Upper Arm	7	x		1,2,3,4,5,8,9,13,14
Lumbar	1	x		5,9,11,12,17,18
Sacral	1	x		8,11
Lower Arm	8		x	4,5,8,9,10,11,12
Pelvis	1		x	13,14
Hand	2	x		1

Thigh	3		x	12,13,15

It was identified the need to demonstrate the validation process for the sensor attachment placements.

8. CONCLUSIONS

This literature review underscores the role that inertial sensor technology plays in modern ergonomics research. This systematic review of 19 studies assessed the available evidence on the psychometric properties of the use of inertial sensors to estimate joint angles. The widespread use of these sensors across various settings—both laboratory and field—demonstrates their versatility and growing importance in capturing detailed kinematic data. The studies consistently validated the accuracy and precision of inertial sensors against gold-standard systems, employing robust statistical methods such as RMSE, correlation coefficients, and Bland-Altman plots. The focus on joint angle kinematics for key body regions, such as the upper arms, neck, and trunk, further highlights the applicability of these sensors in evaluating complex postural and movement dynamics. Regarding validity, inertial sensors appear to provide a suitable alternative measure angles for flexion/extension postures at the upper limb joints. The review provides a comprehensive overview of the recent advancements and applications of inertial sensor technology in ergonomics research, particularly in assessing the methodology to validate inertial sensos when applying them to estimate joint angles. The findings highlight that most studies (94.7%) utilized commercial motion capture software to analyze posture and movement, underscoring the reliance on standardized tools for accurate data collection. The increasing trend in the use of inertial sensors over the past decade, with more than half of the studies (57.8%) published in the last five years, reflects the growing recognition of this technology's potential in ergonomic assessments. The research predominantly focuses on laboratory settings (47.3%), with scientific and healthcare contexts being the most frequently studied environments. This suggests a strong interest in validating inertial sensor measurements for their accuracy and precision in controlled conditions before wider application in more complex, real-world environments. The use of advanced statistical methods, such as correlation coefficients, RMSE, and Bland-Altman plots, further confirms the approach to evaluating the validity and reliability of these sensors. Moreover, the review identifies key areas of focus, such as joint angle kinematics and the assessment of inter-rater reliability and intra-rater repeatability, indicating a comprehensive effort to ensure the robustness of inertial sensor data in ergonomic applications. The involvement of diverse fields, including scientific research, healthcare, and sports, demonstrates the versatility of inertial sensors in monitoring posture and movement across various contexts. Overall, the findings suggest that inertial sensor technology has become a critical tool in ergonomic research, with proven reliability and precision for estimating joint angles. As the technology continues to evolve, its application is likely to expand further, offering new insights and improving workplace safety and health outcomes.

Declaration of competing interest

The authors declare that there were no commercial or financial relationships that could be interpreted as a conflict of interest during the conduct of the study.

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