

Review

Mobile Applications for Assessing Human Posture: A Systematic Literature Review

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Abstract: Smartphones are increasingly incorporated with features such as sensors and high resolution cameras that empower their capabilities, enabling their use for varied activities including human posture assessments. Previous reviews have discussed methods used in postural assessment but none of them focused exclusively on mobile applications. This paper systematically reviews mobile applications proposed for analyzing human posture based on alignment of the body in the sagittal and coronal plane. The main digital libraries were searched, 26 articles published between 2010 and 2020 were selected, and 13 mobile applications were identified, classified and discussed. Results showed that the use of mobile applications to assist with posture assessment have been demonstrated to be reliable, and this can contribute to clinical practice of health professionals, especially the assessment and reassessment phases of treatments, despite some variations when compared to traditional methods. Moreover, in the case of image-based applications, we highlight the advantage that measurements can be taken with the assessor at a certain distance with respect to the patient's position, which is an important function for assessments performed in pandemic times such as the outbreak of COVID-19.

Keywords: posture; human postural assessment; spine assessment; smartphone applications; mHealth

1. Introduction

Remote monitoring and management of health information for people outside the clinical and hospital environment has been favored with the use of mobile health (mHealth) [1]. The widespread use of portable electronic devices worldwide favors their formal application in health services, supporting the conduct and performance of health professionals [2]. The use of mHealth has been prioritized in healthcare models in countries whose life expectancy has increased and patients need continuous and

long-term monitoring [1]. mHealth received a new projection around the world, given the pandemic scenario caused by the new coronavirus (COVID-19). People are advised to avoid crowding, given the high rate of transmissibility of the virus and this social distance must also be maintained in health services worldwide. Healthcare service providers throughout the world have prioritized and upgraded themselves to care for patients with severe symptoms of respiratory failure caused by the coronavirus. Although the pandemic situation requires special attention, patients with chronic diseases and other health demands still need medical assistance. For this reason, professionals around the world have used consultations and remote monitoring of their patients. Although mobile devices are used primarily for monitoring patients with chronic diseases, their use also applies to new models of medical diagnostic procedures including human biomechanical functions such as gait and posture assessment.

Human posture is a physical variable of clinical and scientific interest since alterations in the axial alignment may be associated with numerous patient complaints, with pain being a common complaint among them. The ideal posture of human beings should produce greater biomechanical efficiency with lower energy expenditure [3,4]. For example, spine alignment is organized to ensure mobility and support load, contributing to a correct postural organization of the human being and functions performed by it. However, due to numerous structural overloads or congenital disorders which people are subjected to, as well as age-related modifications (e.g., muscle strength reduction and reduced range of motion), many individuals develop changes in the body alignment that can culminate in severe postural deviations. These alterations have a multifactorial etiology and can also be genetic, such as adolescent idiopathic scoliosis (AIS) [5] and Hyperkyphosis [6].

Human posture based on alignment of the body in the sagittal and coronal plane contributes to kinetic and functional changes not only locally but also throughout the osteomioarticular chain, compromising the functional health of the population [7]. By considering the relevance of postural alignment for the maintenance of body functional kinetic balance [8] and the increasing number of proposals for postural assessment based on the analysis of sagittal and coronal alignment, researchers have proposed methods that include other resources besides inspection and palpation [9]. For example, biophotogrammetry is explored in [10–12]. Researchers have also investigated reference values for postural alignment [7] and compared them by analyzing their applicability, similarities and differences [13]. Among the reviews involving postural assessment methods, we highlight the studies by Porto et al. [14] and Aroeira et al. [15], which conducted reviews on computational methods for postural assessment. However, research questions in those studies did not cover assessment methods based on mobile applications. Other reviews have also been performed but with a focus on anthropometric measures [16] or on applications available in application stores [17], which are not tested and validated experimentally with results presented in the research articles.

In recent years, smartphone applications have gained credibility as a method of social communication and, in the context of medicine, as instruments to support assessment and monitoring of patients. However, to the best of our knowledge, there is no Systematic Literature Review (SLR) that summarizes information about the types and characteristics of the smartphone applications used for human posture alignment assessment. The goal of this study is to identify and compare mobile applications for assessing human postural deviations proposed in the literature and to investigate their functionalities, metrics defined for validation, and obtain performance results. This SLR differs from the aforementioned cited ones by focusing on the postural analysis and assessment methods that are specifically implemented as smartphone applications, analyzing its technical features. We performed a review on relevant digital libraries, identified and compared studies by considering important features such as study design and functionalities provided by applications. Additionally, we summarized their limitations and identified trends which are useful for researchers to conduct further investigation.

The remaining of the paper is organized as follows. Section 2 introduces postural deviations and traditional methods used to evaluate human posture. Section 3 describes the methodology of this SLR. Section 4 presents the results, while Section 5 discusses them and highlights open issues and implications for future studies. Finally, Section 6 concludes the paper.

2. Background

2.1. Postural Deviations

The human spine is adapted to the upright position and is characterized by the presence of physiological curvatures called the thoracic kyphosis (from 20° to 40°) [18], cervical lordosis (from 10° to 30°) [19], and lumbar lordosis (from 34° to 42°) [20] that help maintain a stable posture [21,22]. When the human body is affected by internal and external overloads, changes in spine alignment occur [23]. Accentuation of anteroposterior and lateral curvatures such as hyperlordosis [24], hyperkyphosis [25] (both greater than 40°), and scoliosis (greater than 10°) [26,27], are illustrated in Figure 1.

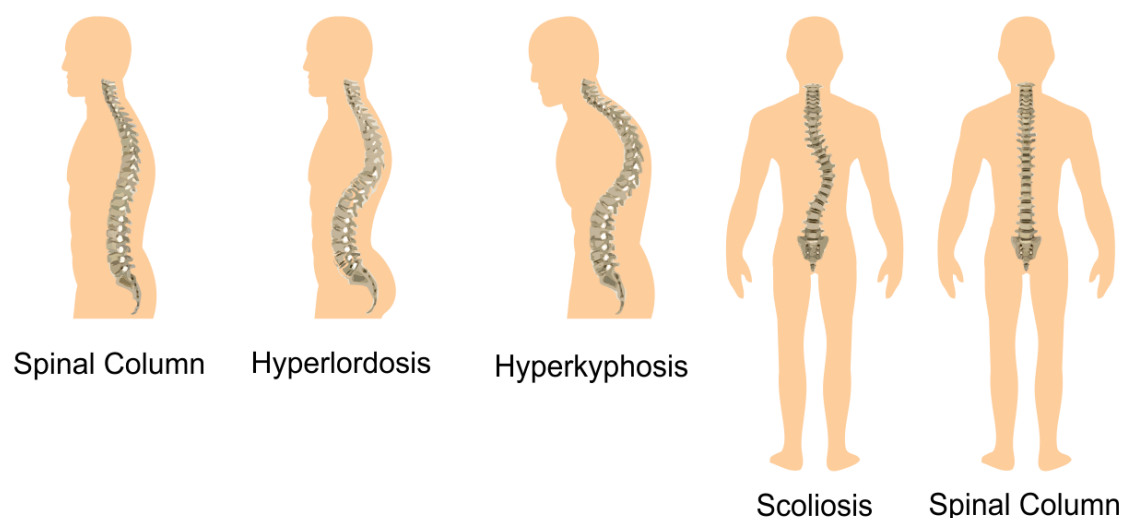


Figure 1. Postural deviations.

Increasing or decreasing these curvatures may change body biomechanics and consequently cause changes in the body posture and vice versa. In addition to the misalignments caused by anatomical changes in the spine, people adopt daily postures of tilting the head, trunk forward, backward or sideways. This in itself is not a problem, given that people are asymmetrical beings but in the long run, these situational inclinations can also cause biomechanical changes and therefore should also be considered during postural assessment.

2.2. Methods for Assessing Human Posture Deviations

One of the most widely used methods for assessing human posture deviations is visual inspection and palpation [28]. This method is highly subjective and assessor-dependent [29,30] and has low reliability and reproducibility, which makes its application in the scientific environment not recommendable [7]. To minimize biases produced by this analysis, new methods of postural assessment have been developed [31], which are based on tools to assist in manual assessment, digital tools, radiography methods [32,33] and computer-based solutions.

Barret et al. [34] listed 15 non-radiographic ones. We classified them into three categories: Manual Assessment Tools (MATs), Digital Assessment Tools (DATs), and Software-aided Assessment Tools (SATs). MAT devices require manual assistance to identify or to calculate the column deviations such as those listed in Table 1. Radiography methods involve the analysis of spine X-ray with manual demarcation of the upper and lower limit of the spine curvature, after calculating the degrees of this curve. As a result, it was also classified as a MAT. DAT instruments calculate body inclinations and deviations to present them on a digital display (Table 2). This category does not include software

solutions. SAT proposals have been classified as those methods or instruments which are supported by a computing system, which can be identified as given in Table 3.

Table 1. Summary of manual assessment tools for human postural deviations.

Study	Name	Description
[35]	Arcometer	Instrument with a main shaft and perpendicular rods and scales attached to the shaft of each rod.
[36]	Flexicurve Index	Flexible ruler positioned on the back, adopting thoracic and lumbar contours. The shape of the ruler is drawn on paper and the kyphosis index is calculated.
[36]	Flexicurve Angle	Similar to the flexicurve index but the kyphosis angle is calculated from the drawing using geometric formulas.
[37]	Debrunner Kyphometer	Two-arm protractor whose ends are positioned at specified bone markers.
[38]	Manual Inclinator	Instrument with a kind of pendulum that measures the angle of inclination and vertebral elevation when positioned over them.
[39]	Goniometer	An instrument with two rods connected by a 360° axis that is positioned at the center of the joint and enables the evaluation of the angle of movement of the body segment.
[40]	Spinal Wheel	It is a plastic wheel device 10 cm in diameter and with a reflective marker at the center that is guided along the midline from vertebra S1 to the occipital endpoint.
[41]	Pantograph	Instrument with articulated parallel rods at the end of which a low-frictioned wheel is mounted that contours the back.
[42,43]	Scoliometer	It is a fluid-filled inclinometer in which an enclosed ball shows the angle of trunk rotation.
[44]	Kypholordometer	Apparatus made up of an aluminum vertical rod and 39 horizontally shaped and deformable horizontal rods with cross section. These rods are pointed at the back and the contours of the vertebral curvatures are drawn on the paper attached to the back of the instrument.
[32,45]	Radiograph	It allows the quantification of the spine angles from calculations performed from the vertebrae visible through the X-ray using the Cobb method.

Table 2. Summary of digital assessment tools for human postural deviations.

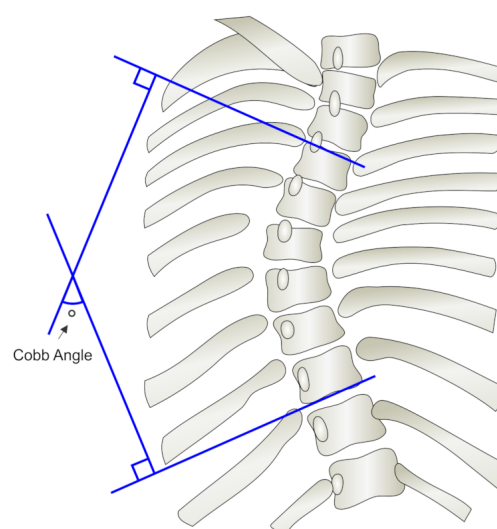
Study	Name	Description
[46]	Spinal Mouse	Manual and computer-assisted electromechanical device that is guided along midline of the spine starting at the spinous process of C7 and ending at top of the anal crease, approximately S3.
[47]	Digital Inclinator	Similar to manual inclinometer but it has sensors that capture body inclination.
[48]	Electrogoniometer	Instrument that allows continuous measurement of the angular displacement between 2 lightweight plastic end blocks at either end of a coil containing 2 strain gauges mounted at 90° to each other.

Table 3. Summary of software-aided assessment tools for human postural deviations.

Study	Name	Description
[49]	3D ultrasound	System that uses a point marker to identify column reference points. A directional microphone, a reference marker, and a computer with specific software that contains normative data on vertebrae distances, allowing it to calculate angles and distances of measured 3D data that is transformed into degrees of motion range.
[50]	Rasterstereography	Method for 3-dimensional back shape analysis. System that detects anatomical reference points, prominent vertebra and the two upper iliac spines, and coordinate the data of the back-surface points and the line of symmetry between them.
[51]	Stereovideography	Similar to rasterstereography, but it is based on system of stereo-video cameras.
[11]	Photogrammetry	Based on photographs added to the software, which processes them and calculates the distance between body segments and angles formed between them.

Some methods such as arcometer, goniometer and flexicurve enable to identify trunk inclination and spine curvatures based on protractor and rulers measures. Other methods use more current technologies that include, for instance, the assessment of the dorsal surface of human body and analysis of body images and their curvatures using DATs and SATs. Among SATs, the photogrammetry (based on photographs processed by software) [11] stands out as a method with various software solutions available [52–54]. Examples of photogrammetry software solutions are Posture Assessment Software (in Portuguese, *Software de Avaliação Postural-PAS*) [52], Digital Image-based Postural Assessment Software (DIPA) [53] and Posture Pro Software [54].

The standard method for identifying deviations in the coronal plane is the Cobb method [32], initially applied to traditional radiographs and later also to digital radiographs. A characteristic of this method is the demarcation of the vertebrae that limits the curve, as well as the values of the curve, as the values of the formed angles is determined manually with the aid of the ruler [55] (Figure 2). A Cobb angle of 10° is the minimum value for definition of scoliosis [56], showing that when variations of 5° in curve angulation in consecutive radiography exams are observed, it is understood that there is a progression of scoliosis [57,58].

**Figure 2.** Cobb angle.

3. Research Methodology

This SLR was conducted according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [59] and consists of planning, conducting, and reporting phases, in which each one has several activities.

3.1. Research Questions

To achieve the goal of this SLR, we considered the following Research Questions (RQs) presented in Table 4.

Table 4. Research questions.

ID	Question
RQ1	What mobile applications have been used and proposed for analyzing the human posture based on spine alignment?
RQ2	What are the technical features implemented by those mobile applications for assessing the human spine alignment?
RQ3	What are the types of research presented in the literature regarding those mobile applications for assessing sagittal and coronal alignment of the human spine?
RQ4	What metrics are used to evaluate mobile applications?
RQ5	What are the performance results obtained by the mobile applications?

3.2. Search Strategy

Digital libraries searched were: PubMed, Scopus, Association for Computing Machinery (ACM) Digital Library, Web of Science, IEEEExplore and ScienceDirect. These databases were selected because they collect reliable studies related to both computer and medical sciences. The search was conducted in the following steps: (1) tests were performed using different terms according to the purpose of this review and with reference to PICO: Participants—individuals with or without postural alterations; Intervention—mobile application for postural assessment; Comparison—mobile applications and traditional methods for postural assessment; Outcomes—angular values of spine alignment; (2) definition of terms and their synonyms from the Medical Subject Headings (MeSH—<https://www.ncbi.nlm.nih.gov/mesh>); (3) terms used in the search (Table 5) were classified into primary (i.e., key terms used in initial search) and secondary (i.e., synonyms for the primary terms identified in the MeSH); (4) definition of search strings to the databases, which resulted from combining the primary and secondary terms.

Table 5. Terms used in the search string.

Primary Terms	Secondary Terms
“Mobile Application”	“Mobile System” OR “Mobile App” OR “Mobile devices” OR “Mobile phone” OR “smartphone application” OR iphone
Posture	“Static standing posture” OR “Posture Analysis” OR “Postural Assessment” OR scoliosis OR lordosis OR kyphosis

By considering characteristics of the databases, the syntax of each one was adapted. All of the search strings used in each database can be accessed in the electronic Supplementary Materials.

3.3. Selection Criteria

Studies were included in this review if they fulfilled the following criteria: (1) written in English; (2) published between 2010 and 2020; (3) publications that included development, test, validation, evaluation or comparison of mobile applications for assessing human posture based on coronal and sagittal alignment. Exclusion criteria were: (1) type of publication, by eliminating gray literature; (2) studies that involved the analysis of human posture deviations but considering only isolated body segment analysis such as arms and legs without spinal assessment (i.e., without evaluating spine misalignment); (3) papers that identified variations in body position regarding the balance; (4) papers with text unavailable in full; (5) papers that used mobile applications exclusively based on wearable devices.

3.4. Quality Assessment

Selected studies were assessed according to eleven questions that covered rigorousness, credibility and relevance. Questions evaluated were those adapted by Dybå and Dingsøyr [60,61]. The quality questions (QQs) are described in Table 6. Each question received dichotomous answers (yes or no) and each answer corresponded to one point in the analysis. At the end, a general quality score ranging from 0 to 11 was generated for each study.

Table 6. Quality questions used in this review [60,61].

ID	Description
QQ1	Is the paper based on research (or is it merely a “lessons learned” report based on expert opinion)?
QQ2	Is there a clear statement of the aims of the research?
QQ3	Is there an adequate description of the context in which the research was carried out?
QQ4	Was the research design appropriate to address the aims of the research?
QQ5	Was the recruitment strategy appropriate to the aims of the research?
QQ6	Was there a control group with which to compare treatments?
QQ7	Was the data collected in a way that addressed the research issue?
QQ8	Was the data analysis sufficiently rigorous?
QQ9	Has the relationship between researcher and participants been considered to an adequate degree?
QQ10	Is there a clear statement of findings?
QQ11	Is the study of value for research or practice?

3.5. Data Extraction

The data extraction process was conducted according to a predefined form that included the following data identified in each study: study identification (author and year), name of the proposed solution, study design (according to Wieringa et al. [62]), categorization based on the type of technical feature, availability in application stores, metrics used in the evaluation and validation of the mobile applications, main findings and quality assessment.

3.6. Review Conduction

Papers were selected by two independent researchers (a physiotherapist and a computer scientist) on 16 May 2020 from the application of the search string on digital libraries. Next, duplicate papers were removed and selection criteria were applied by the both researchers to the remaining papers based on the analysis of the titles and abstracts. Cohen’s kappa [63] was calculated and disagreements were resolved by consensus with the help of other researchers. After these steps, papers included in the review were read in full for assessing the quality and extracting data to be reported. Additionally, we performed a survey in application stores to find out their availability.

4. Results

4.1. Study Selection

The initial search on the databases resulted in 1127 articles (see Supplementary Materials) and after independent analysis by two reviewers, the Cohen's kappa index was ≈ 0.61 , which indicates moderate agreement between the two reviewers [64]. Next, disagreements were mediated and 26 studies were eligible for inclusion. Figure 3 shows the flow diagram of our review process.

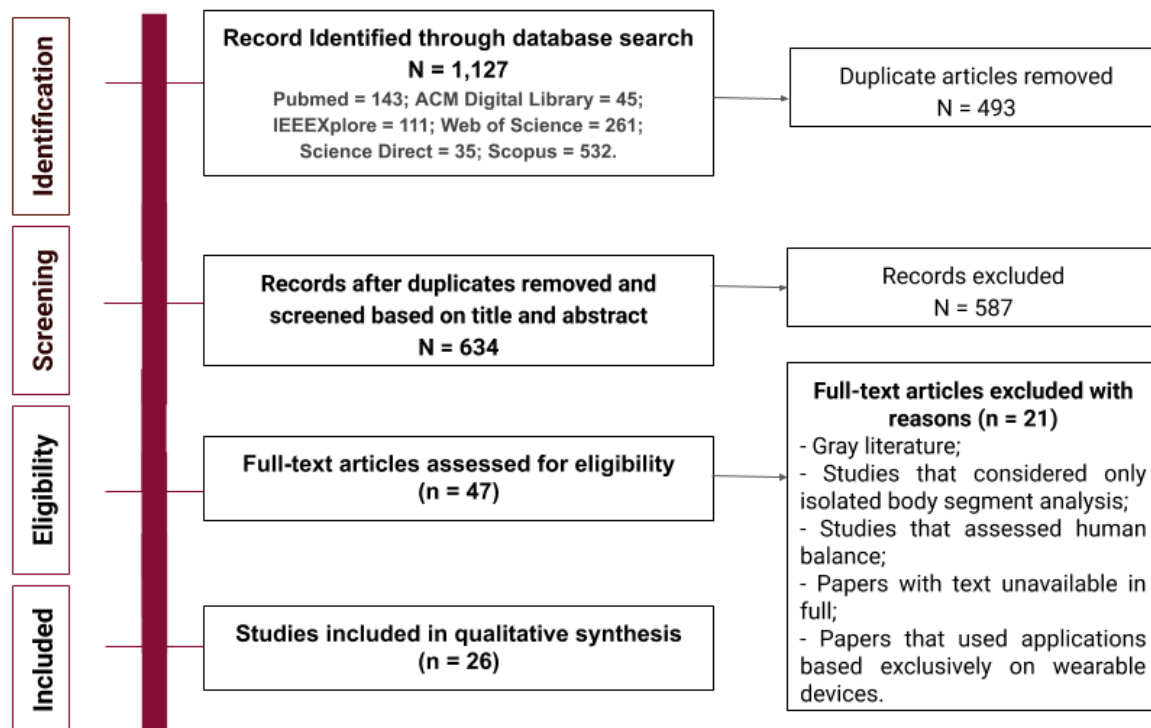


Figure 3. Flow diagram of the review process.

4.2. Study Characterization

Table 7 presents a summary of the 26 studies sorted by year, including the names of the applications, a categorization according to the data extraction section (see Section 3.5) and study design. A total of 13 smartphone applications- RQ1 - for assessing human postural deviations were identified in this SLR and classified into applications based on the Use of Sensors (US) and Image-Based Solution (IBS) - RQ2. All mobile applications identified in the studies had an identification name, except that proposed by Estrada and Veia [65].

Table 7. Summary of reviewed studies.

Study	Name	Category	Study Design	Availability
[66]	Scoligauge	US	VR & ER	TopOrthoApps.com
[67]	Scoligauge	US	ER	TopOrthoApps.com
[68]	Cobbmeter	US	VR & ER	Apple Store
[69]	Cobbmeter	US	VR & ER	Apple Store
[70]	Tiltmeter Pro	US	VR & ER	Play Store * & Apple Store
[71]	iHandy Level	US	ER & VR	Play Store * & Apple Store *

Table 7. Cont.

Study	Name	Category	Study Design	Availability
[72]	Scoligauge	US	VR & ER	TopOrthoApps.com
[73]	Scoligauge	US	VR & ER	TopOrthoApps.com
[74]	iGonio	US	ER	148apps.com *
[75]	Cobbmeter	US	VR & ER	Apple Store
[76]	Cobbmeter + Tiltmeter	US	VR & ER	Apple Store
[77]	PostureScreen Mobile	IBS	ER	Play Store & Apple Store
[65]	Unnamed	US	PS & VR	No
[78]	iHandy Level	US	ER & VR	Play Store */ Apple Store *
[79]	Cobbmeter	US	VR & ER	Apple Store
[80]	Scoliometer 1.1	US	VR & ER	apkgoogle.org *
[81]	iPhone Clinometer app	US	ER & VR	Play Store * & Apple Store
[82]	Smartphone Protractor	US	VR	Play Store *
[83]	PostureScreen Mobile	IBS	ER	Play Store & Apple Store
[84]	PostureScreen Mobile	IBS	ER	Play Store & Apple Store
[85]	Scolioscreen	US	ER	spinologics.ca
[86]	PostureScreen Mobile	IBS	VR & ER	Play Store & Apple Store
[87]	PostureScreen Mobile	IBS	VR	Play Store & Apple Store
[88]	Sagittalmeter Pro	US	VR & ER	Play Store
[89]	iPhone's photo editing application	IBS	VR & ER	iPhone native application
[90]	Scoligauge	US	VR & ER	TopOrthoApps.com

Note: US = Use of Sensors; IBS = Image-Based Solution; ER = Evaluation Research; VR = Validation Research; PS = Proposal of Solution; * = Free of Charge

4.3. Technical Features

Mobile applications use available features in smartphones to assess body alignment and based on these features, they were classified into sensor-based (eleven applications) and image-based (two applications) solutions. Those based on the US have taken advantage of different types of sensors embedded in smartphones which include gyroscope and accelerometer. These sensors capture body displacement or part of it or are applied to analysis of radiographic images providing useful information about spine orientation, either of its isolated segments (e.g., the cervical spine) or the orientation of its entire length, including cervical, thoracic and lumbar segments (i.e., lordosis, kyphosis and scoliosis). Table 8 shows the summary of sensor types used in mobile systems identified in this review.

Table 8. Types of sensors used by the identified mobile applications.

Sensor	References
Accelerometer	[66–76,78–80,85,88,90,91]
Gyroscope	[65,81,91]

In IBSs, cameras embedded within the mobile devices are used by applications for analyzing spinal radiography images or photographs of subjects with anatomical points marked and used as a reference for postural assessment. Both of them aim to identify misalignments in spinal orientation such as lumbar lordosis orientation parameters, pelvic incidence, pelvic tilt, head tilt angle, shoulder tilt and hip tilt.

Table 9 shows the measured segments by all identified mobile applications.

Table 9. Measured segments by the identified mobile applications.

Study	Measures Taken
[66]	Scoliosis
[67]	Rib Hump Angle/Scoliosis
[68]	Kyphotic Angles
[69]	Cobb Angle/Thoracic Scoliosis
[70]	Cobb Angle/Thoracic Scoliosis
[71]	Lumbar Lordosis
[72]	Rib Hump Angle/Scoliosis Evaluation
[73]	Cobb Angle of Thoracolumbar Scoliosis
[74]	Cobb Angle
[75]	Cobb Angle
[76]	Cobb Angle
[77]	Head, Ribcage, Shoulder, Hip and Knee Tilt
[65]	Inclination of the Human Spinal Points
[78]	SS and Lumbar Curve
[79]	PI, PT and LL
[80]	Sagittal Curvaures
[81]	Thoracic Spine Rotation
[82]	LL, PI, and PT
[83]	Head, Ribcage, Shoulder, Hip Tilt
[84]	Head, Ribcage, Shoulder, Hip Inclination
[85]	Scoliosis Angle
[86]	Head, Shoulder and Ribcage Tilt
[87]	Head, Ribcage, Shoulder, Hip and Knee Tilt
[88]	LL, PI, SS and PT
[89]	LL, PT, and SS
[90]	Rib Hump/Scoliosis Evaluation

Note: LL = Lumbar Lordosis; PI = Pelvic Incidence; SS = Sacral Slope; PT = Pelvic Tilt.

The most cited IBS was PostureScreen Mobile (PSM), which takes pictures of the subjects from different angles: anterior and posterior (coronal plane), left and right (sagittal plane). Next, the application calculates posture variables using individual's anatomical points that are digitally marked depending on the number of variables of interest. This process of digitally marking points consists of demarcating the anatomical reference points (i.e., pelvic iliac spines, greater trochanter, femoral condyle and ear lobe), directly on the mobile device screen. Then, body angles are calculated. Furthermore, IBSs provide an output file with values of posture variables and images that illustrate the digitized points and their locations in relation to a neutral posture.

Different from PSM, the iPhone's photo editing application [89] was used to evaluate X-ray or three-dimensional computed tomography scans images and calculate lumbosacral spine–pelvic sagittal parameters. For this, Wang et al. [89] used the iPhone camera to take pictures of images in the frontal plane and the application was used to rotate them, allowing the angle rotation scale and the grid lines to appear clearly on the screen smartphone. The authors defined the spinopelvic parameters using what they called theory of end vertebra tilt angle. According to them, the images were rotated until the visually inspected connection lines of the upper end plate of the sacrum overlap or are parallel to the horizontal grid lines, and that rotated angle corresponds to the SS. The rotation angle is formed when the line connecting the L1 vertebrae runs parallel or overlaps the level grid lines. This rotation angle added to the SS angle is the angle of the lumbar lordosis. By continuing to rotate the image until the upper end plate of the sacrum and the midpoint of the femoral caput are parallel or completely overlapping the inter-vertical grid lines, it produces the pelvic tilt angle which is the absolute value of the rotated angle.

Regarding the US applications, although they have used sensors embedded in smartphones (i.e., accelerometer and gyroscope), they varied in relation to the measurement methods used by the

assessors. Some studies [68–70,74–76,79,82,92] used applications to analyze radiographs of the spine. For example, the method proposed by Allam et al. [76] positioned radiographs in the vertical plane on a backlit X-ray reader box. The smartphone with a tilt measurement application is positioned on the vertebra but inclined from the scoliotic curve, and then the inclination of a vertebra above and below the selected one is measured. With the application running, the smartphone is positioned at the level of the upper and lower final vertebral plates. To validate the position, the assessor clicks anywhere on the smartphone screen [68], then the angle is measured automatically and the information about the patient (i.e., name, assessment date, measured angle) is saved. Marchi et al. [79] also used CobbMeter for analysis of the sagittal spinal alignment (PI, PT and LL), based on the radiographys.

Another sensor-based mobile application applied to the assessment of column inclination parameters is SagittalMeter Pro [92]. Similar to Cobbmeter, the smartphone with SagittalMeter is positioned on sagittal radiographs following the protocol defined by the authors: the upper edge of the smartphone is positioned parallel to the plateau of the first sacral vertebra (S1). The lateral edge of the telephone is positioned at the center of S1 and the center of the femoral head. In the third stage, the upper edge of the smartphone is positioned parallel to the plate of the first lumbar vertebra (L1). After each step, the assessor clicks a button to confirm the position of the smartphone. At the end, the analysis of the sagittal balance is performed automatically.

Other US applications as Scoligauge [72,73,90] are applied directly to the back of patients who are instructed to do an anterior trunk flexion, that is, to tilt the trunk forward. In this position, the assessor positions the center of the smartphone in the spinal process of the vertebra at the level of the true rib hump, visually aligning the iPhone to measure the rotation angle of the trunk. However, although both used Scoligauge, Allan et al. [90] used it without the iPhone adapter, while Chen et al. [90] used a 3D printed frame with an opening adaptable to the thorny process to avoid direct contact from the iPhone. Izatt et al. [67] also used an adapter to position the smartphone, an acrylic sleeve designed to accommodate any device equipped with inclinometer, but to assess a set of plaster torsos which represent the range of torsional deformities seen in clinical practice.

In the study by Franko et al. [66], Scoligauge was used only in a biomechanical validation test protocol without the use of patients or medical information. In this context, the smartphone is aligned and held firmly against the flat top surface of the standard scoliometer. The device is rotated until it reached angular measurements varying between -30 and 30 degrees. When it reaches an immutable position, by remaining stopped for two seconds, two independent assessors record the measurements.

The Scoliometer 1.1 is another method that requires the smartphone to be positioned directly on the patient's back (free standing position and free sitting position) to determine the degrees of kyphosis and lordosis of the spine. In the study of Waś et al. [80], the smartphone with Scoliometer 1.1 application is positioned at the levels of the cervicothoracic junction (C7–T1), in the thoracic segment (T6–T7), at the thoracolumbar junction (T12–L1) and at the lumbosacral junction (L5–S1) to measure lumbar lordosis angle, upper and lower thoracic kyphosis angle. A similar process is performed by Koumantakis et al. [78] by marking the spinous processes of T12–L1 and S1–S2 to assess the lumbosacral parameters.

Except for the adapters used in the studies of Chen et al. [90] and Izatt et al. [67], only in the study of Estrada and Veia [65] was an auxiliary device (a kind of adjustable vest) used as a means of fitting the smartphones to the participant's body. The aim is to ensure that mobile devices are correctly in contact with the three points (thoracic, thoracolumbar and lumbar) of the spine. Additionally, they also developed a desktop application used to capture and record readings on smartphones.

As we can see, analysis methods of the mobile applications have varied. We classify the studies (and their mobile applications) based on these methods depending on whether the mobile device requires direct contact with the patient's body or not. We classify the applications with direct contact as those ones in which the practical use requires physical contact with the patient. Indirect contact with the body refers to analyzes based on radiographs. No contact with the patient's body means

that analysis is performed based on the patient's photos. Table 10 presents the studies organized in this classification.

Table 10. Analysis method.

Analysis Method	References
Direct contact with the body	[65–67,71–73,78,80–82,85,90]
Indirect contact with the body	[68–70,74–76,79,88,89]
No contact with the body	[77,83,84,86,87]

Among the studies identified, only one reported use of machine learning algorithms in the proposed mobile application. Estrada and Vea [65] developed a solution to detect proper/improper sitting postures based on the angles of the spinal curvatures. To identify the best algorithm to perform this task, the authors conducted performance evaluations with the machine learning classifiers: k-Nearest Neighbors (KNN), Support-vector Machines (SVM), Multilayer Perceptron (MLP), a class of artificial neural network, and Decision Tree. This last algorithm reached the best performance.

4.4. Study Design and Performance of the Mobile Applications

Papers included in this review were also categorized by study design according to Wieringa et al. [62] as shown in Table 7. Although the authors indicated six different types of classification, this review classifies them into three groups: ER, PS and VR-RQ3. We also sought to identify information related to metrics used to evaluate performance or validate proposed mobile solutions. Table 11 shows metrics for evaluation and valuation-RQ4, and the main findings of the studies-RQ5.

Table 11. Metrics and main findings of the reviewed studies.

Study	Metric	Main Findings
[66]	ICC and Pearson correlation coefficient for comparing Scoligauge with angle measures made with standard clinical scoliometer.	Scoligauge has validity and reliability when comparing it with the standard clinical scoliometer for assessing deformity in scoliosis.
[67]	ICC and Bland Altman analysis for rib hump angle.	The application proved to be valid for measurements of hump in the ribs. The inter- and intra-observer measurement variability using iPhone was similar to that of the Scoliotometer.
[68]	Mean, SD and ICC for measuring kyphotic angles.	The reliability analysis showed that measurements were highly correlated with those obtained using the standard method.
[69]	Mean, SD, ICC and paired t-test to measure Cobb Angle of thoracic scoliosis and compare the time consumed for the measurement between application and manual method.	Smartphone-aided measurement for the Cobb angle showed excellent reliability and efficiency. The average time spent for evaluating was shorter when using CoobMeter.
[70]	Mean, SD, and Bland Altman analysis for measuring Cobb Angle and comparing Tiltmeter with traditional protractor.	Tiltmeter is an equivalent Cobb measurement tool to the manual protractor, and measurement times are about 15% lower.
[71]	ICC, mean and SD for measuring body angles.	Both Bubble inclinometer and iHandy Level had good intra-rater and inter-rater reliability and concurrent validity for measuring lumbar lordosis.
[72]	ICC and Bland Altman analysis for measuring rib hump and comparing Scoligauge with traditional scoliometer.	Scoligauge showed excellent intra-rater and inter-rater reliability with valid measurements when compared to the scoliometer.
[73]	Mean and ICC to compare scoliometer and Scoligauge.	Scoligauge showed excellent reliability when compared to the scoliometer.

Table 11. Cont.

Study	Metric	Main Findings
[74]	Mean and SD to compare measurements made by using standard protractor and iGonio.	iGonio proved to be reliable and efficient for measuring Cobb angle.
[75]	Mean, SD, paired t-test and Kappa to compare measurements of scoliosis made by using the manual method and CobbMeter.	Authors reported that CobbMeter is reliable, although there was a significant difference between values found with the two methods.
[76]	Mean, SD and Bland Altman analysis to compare measurements of scoliosis performed with Oxford Cobbmeter and digital Cobbmeter+Tiltmeter.	Integrated Tiltmeter and Cobbmeter consist of a Cobb measurement tool equivalent to the Oxford Cobbmeter.
[77]	ICC to assess the reliability of the measurements of body displacement angles.	Posture assessment with PostureScreen showed substantial reliability.
[65]	Accuracy and kappa for assess cervical, thoracic and lumbar angles.	The proposed mobile solution was able to detect proper and improper sitting postures.
[78]	Mean, SD, Repeated measures ANOVAs, ICC, Bland Altman to measure sagittal lumbosacral posture.	iHandy Level is a reliable and valid tool for measuring lumbosacral standing spinal posture in the sagittal plane.
[79]	ICC and Kappa to compare measurements made by the Cobbmeter and goniometer along with a dermatograph pencil in the analysis of sagittal alignment of the spine.	CobbMeter is a valid and reliable instrument for measuring the angle involved in the sagittal balance of the spine.
[80]	Mean, SD, ICC, Mann Whitney and Student's t-distribution to assess and compare measurements of spine curvatures in the sagittal plane performed with digital inclinometer and Scoliometer 1.1.	Measures of spinal curvatures with both instruments showed reliable values.
[81]	Pearson correlation coefficient, ICC, mean and SD for measuring thoracic spine rotation in the heel-sit position.	Digital Inclinometer and iPhone Clinometer application proved to be reliable for assessing thoracic spine rotation.
[82]	ICC and mean for measuring lumbar lordosis, pelvic incidence, and pelvic tilt angles and determining the validity of Smartphone Protractor.	The application proved to be reliable for assessing adult spinal deformity of radiographic parameters.
[83]	Mean and SD for body angles.	PostureScreen detected posture variables in the sagittal and coronal planes.
[84]	Mean, SD and ICC for body angles.	PostureScreen proved to be a useful tool for dentists in the early diagnosis of dental occlusion pathology.
[85]	Mean, SD, Student's t-distribution, ANOVA and Fisher's exact test for detecting scoliosis in school children.	Scolioscreen showed high sensitivity and specificity, demonstrating to be useful for the early diagnosis of scoliosis.
[86]	ICC, mean and SD for body angles.	PostureScreen showed strong reliability for assessing human posture.
[90]	Cohen's kappa and Pearson correlation coefficients for comparing measures performed with Scoligauge and scoliometer.	The sensitivity of the smartphone screening was not acceptable for recognizing scoliosis.
[87]	ICC, mean and SD to assess the reliability for measuring body angles in the sagittal and frontal planes.	PostureScreen was able to detect postural measurements, but its use showed significant bias in postural measurements of the frontal and sagittal planes.
[88]	Mean, SD and ICC for comparing PACS and SagittalMeter Pro for measuring spinopelvic sagittal parameters.	Measurements performed with both methods were equivalent and the time required to obtain measurements was shorter when using SagittalMeter Pro.
[89]	ICC, Mann-Whitney test, One-way ANOVA for measuring lumbosacral spine-pelvic sagittal parameters performed by PACS and iPhone.	iPhone showed similar accuracy when compared with PACS.

Note: ICC = Intraclass Correlation Coefficient; SD = Standard Deviation; MSE = Mean Squared Error; NMSE = Normalized Mean Squared Error; ANOVA = Analysis of Variance; PACS = Picture Archiving and Communication System.

Not all studies included in this review made comparisons between the studied/proposed mobile applications and other postural assessment methods. Some of them [65,77,83–86] evaluated the ability of mobile applications to measure postural deviations, but without comparisons with other tools or traditional methods used for postural assessment. Analyses, comparative or not with other methods, were based on a varied number of statistical analysis, as indicated in Table 11.

In general, mobile applications proved to be reliable and valid for assessing human posture when compared to other postural assessment methods such as Standard Protractor [82] and Digital Inclinator [81], but two applications showed inconsistencies in performance. iHandy Level [71] was compared with the Bubble Inclinator and they had slightly different performance results. However, according to the authors [71], this result does not indicate a real clinical difference since it may occur due to differences in device handling by assessors. When PostureScreen was compared with Vicon by Hopkins et al. [87], their performance results were not similar either. Only 6 of 10 postural measurements were similar to the Motion Capture system (the Vicon system-<https://www.vicon.com/what-is-motion-capture>), which is based on multi-view triangulation using markers.

Regarding the performance of the mobile applications, it is not possible to state that these solutions improve the performance of human postural assessment, but they proved to be valid for detecting angular changes in the body segments and they have similar performance to manual methods. However, regarding the time required to perform the assessment, some smartphone applications were significantly faster [66,69,70,74,76,82,88,89] when compared to traditional methods. For example, Smartphone Protractor [82] was significantly faster on average of 107 seconds, when compared with Standard Protractor. Another example is the CobbMeter used by Qiao et al. [69] whose the mean time consumed was 13.7 seconds for the smartphone application, whereas it was 37.9 seconds for the Cobb standard measurement method. The time spent for evaluation using CobbMeter was also shorter compared to Oxford Cobbmeter, but in this case, Allam et al. [76] pointed that the advantages of Cobbmeter combined with Tiltmeter are the accuracy in determining the most inclined vertebrae and the Cobb angle measurement.

4.5. Quality Scoring

Regarding the quality assessment, none of the included articles reached the maximum score based on the application of the questions described in Table 6. As we can see in Table 12, the lowest quality assessment score attributed to studies was 6 (one paper), and the highest one was 10 (three papers). In all studies with score 10, only question 6 (see Supplementary Materials) was not answered satisfactorily.

Table 12. Quality Scores.

Score	References
6	[66]
7	[75]
8	[65,67,69,74,77,84]
9	[68,70,71,73,76,79,81–83,85–90]
10	[72,78,80]

5. Discussion

5.1. Analysis of Results

Smartphone devices available on the market today are increasingly robust, integrating high computational power (i.e., processing, memory and storage), high resolution cameras, and connectivity with different wireless interfaces. The functional features of these devices have made them popular in several areas, including medicine, which make health assessment and monitoring methods more

agile, easier and cheaper [93]. These advances have also been used in the field of human postural assessment based on alignment in the sagittal and coronal planes. These applications use techniques that take advantage of the usage of embedded sensors and image analysis. Scoliguage and Cobbmeter were the US applications most studied (5 times for each) and PostureScreen was the most cited IBS application (5 times). All applications demonstrated to be valid for assessing human posture based on the identification of inclination degrees of body segments and spinal curvatures. However, Hopkins et al. [87] suggested caution when using PSM because they found differences in postural measurements in sagittal and frontal plane when compared with Vicon system [94] in evaluations. This comparison should be prudently evaluated to avoid hasty analysis, since the Vicon system is a software for kinematics and kinetics analyses of subjects made by a set of cameras positioned at different angles, while PSM uses only the smartphone camera. In other words, Vicon may have advantages over the ability to frame and process images when compared to PSM. Despite these technical advantages of Vicon, PSM presented positive results in identifying postural deviations, which shows the potential of IBSs.

Eligible studies for this review were classified in Table 7 according to their study design [62]. Results indicate that the mobile applications for postural assessment have been presented as experimental researches and proposals of solutions, but few papers described information regarding implementation aspects. Despite this, studies included in this review used statistical tests to compare smartphone applications and traditional methods. Results indicated that proposed solutions presented reliability for measuring body angles, including the spine. This means that the intra- and inter-rater angular measurements, as well as the obtained measurements, compared to other methods were homogeneous and reproducible. Another point to be highlighted is the shorter evaluation time when using mobile applications. When the assessment time is reduced, patients are exposed to a shorter period and this reduces the possibility of exposure with less clothing and fatigue due to repetition of measurements. This factor is important, mainly because patients usually need to wear short clothes and wait until the professional demarcates all anatomical reference points of the process used in the traditional posture assessment software solutions such as Posture Assessment Software (PAS) [52] and DIPPA [53]. Despite this encouraging advantage, results found in this review do not allow us to state that mobile applications are better instruments for postural assessment than traditional methods. However, as the measurements made by applications are valid, they can be used as a method of tracking deviations in the spine and body angles inclinations and, therefore, they can assist professionals in evaluative procedures.

Regarding the year of publication of the articles, it is noticed that most papers (16) were published in the last five years (Figure 4), of which 20 presented US applications and only 6 presented IBSs applications. This data reveals a current trend of health professionals and researchers to seek faster, more practical and more reliable ways of assessing postural deviations. There seems to be a preference for the development and use of sensor-based applications, given the high number of studies involving such mobile applications. However, when analyzing the scientific production found between 2012 and 2020, a recent trend identified is the investigation of IBSs, specially the PSM. Although most previous studies have investigated the use of sensors to develop mobile applications and this is still being investigated in current studies such as that one by Chen et al. [90].

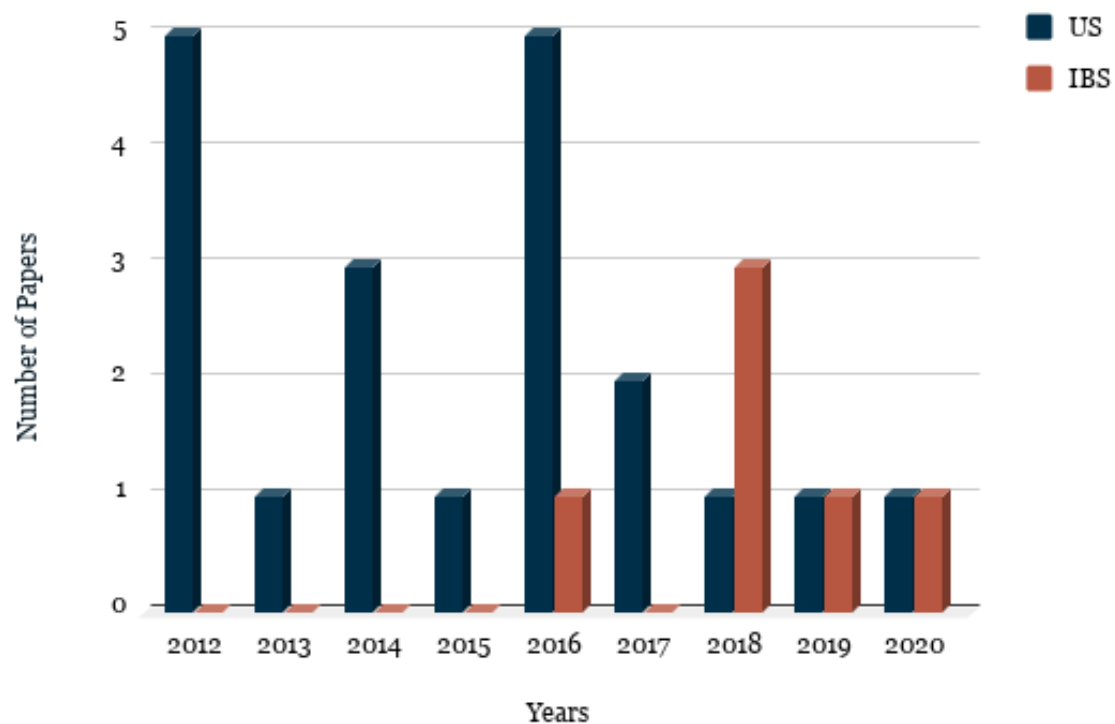


Figure 4. Number of papers by year of publication.

Motion sensors such as an accelerometer and gyroscope are small but highly sensitive devices that integrate smartphones available on the market today. Due to this sensitivity to monitor movement, sensors are widely used in rehabilitation and health monitoring systems, both in clinical and home environments. In this context, they are also widely used to assess and monitor angular displacements of the human body, as identified in this SLR. Despite this advantage, sensor-based applications identified in the studies usually require the placement of the smartphone close to the patient's body or to radiographic images of the spine. The exception was the study by Estrada and Veia [65], in which three smartphones were attached to a vest worn by the study participant. In routine situations, direct contact with patients is not a problem, on the contrary it allows the professional to associate manual assessment with mobile applications. However, it is worth noting that in situations such as the outbreak of COVID-19 coronavirus, which requires social distance, methods like these proposed ones do not seem to be the best option. In this sense, applications based on images are more advantageous, given that images can be taken at a certain distance between the patient and the professional. In addition, applications based on photographic images (i.e., not requiring X-rays) minimize the patient's exposure to radiation.

It is worth noting that most of the studies that used US applications were applied to radiographic analysis. Although these applications speed up the assessment process, we understand that they offer advantages to the professionals who use them, but it is not possible to identify a direct advantage to the patients since they still need to undergo X-ray diagnosis. That is, they continue to be exposed to the radiation emitted during that examination. In this sense, the use of mobile applications in which smartphones are positioned directly on patients' back seems to be advantageous in eliminating or reducing the need for exposure to X-rays.

As we can see in Table 10, applications are used on mobile devices directly, indirectly or without contact with the patient's body. In this context, it is necessary to clarify that in cases of direct contact, the handling and interpretation of results by health professionals are clearly required. On the other hand, even in applications used with indirect contact or without contact with the patient's body, it is

still necessary for the data to be analyzed by health professionals. We understand that results from IBSs should also be analyzed by a qualified professional. Therefore, we believe that photos can be taken at home by a member of the patient's family using a IBS but the analysis and interpretation of the results require technical knowledge that only professionals such as doctors and physiotherapists have. Experiments of the studies reviewed did not include tests of this nature and, therefore, we cannot confirm that mobile applications are valid for remote assessments.

The reviewed articles have obtained between 6 to 10 points in the quality scoring and, despite the fact that these studies showed a few pieces of technical information about mobile applications, they maintained a methodological organization rigorous enough to achieve scores greater than or equal to 6 points Table 12. Therefore, results show that none of the papers had a quality lower than 50% and most of them had a score equal or superior to 8 points, which reveals that the studies included in this review were able to meet the quality criteria adapted by Dybå and Dingsøyr [60,61].

5.2. Open Issues and Implications for Further Investigation

A variety of mobile applications for human postural assessment are available from application stores but few of them have been studied in the scientific literature. Therefore, those applications require to be scientifically validated and evaluated which could show their effectiveness. Even those mobile solutions found in this review did not provide detailed technical information about the used development techniques and implementation aspects. This prevents us from exhaustively detailing the technical characteristics of the mobile applications. Therefore, this is an open field for further investigation. Future studies involving proposals of solutions require to provide more technical information of the development process of mobile solutions to broaden knowledge about them. This would be interesting to awaken new ideas and minimize limitations regarding the effectiveness and usability of systems, which could expand the use to professionals from various areas.

When comparing US solutions with IBS applications, we can highlight the advantage that the first ones have, since they not only evaluate but also enable the monitoring of human posture and send feedback in real-time by alerting users to modify their posture, although this has not been emphasized, not even in the study of Estrada and Veia [65]. In this context, it seems to be feasible that the development of new solutions include electronic wearable devices that enable mobile applications to be used not only as an assessment tool, but also as a biofeedback system for the user. This can make it possible to constantly monitor and correct the postures adopted daily, thereby reducing the risk of injuries. Furthermore, a monitoring system can provide the health professional with additional information about the biomechanical and functional behavior of the patient's body, which may influence the patient's response to treatment.

Although new features may be added to mobile applications, US applications already enable the evaluation of spinal inclination angles regardless of whether they are structural anatomical variations, while IBSs provide data related to angles of spinal curves caused by anatomical misalignment of the spine such as hyperlordosis, hyperkyphosis and scoliosis, or body inclinations not associated with these pathological curvatures. Another important advantage of US applications is that they allow for the assessment of the Cobb angle, a method considered gold standard for the assessment and quantification of scoliosis. However, it is worth mentioning that this assessment is based on the radiography analysis, that is, exposure to radiation during the imaging exam is required.

According to the analysis of results, US solutions provide useful information for assessing human posture, but IBSs supply additional information such as the calculation of sizes of the body segments (e.g., leg, arm, forearm) based on the distance between anatomical reference points (e.g., iliac crest, patella, malleoli, elbow, shoulder, ear lobe). Despite this advantage, identification of anatomical points, which are the basis for correct postural evaluations, does not occur automatically. Such automation would make the evaluation process less susceptible to bias and human errors. It would also reduce the time spent for defining anatomical points in pictures compared to doing this activity manually as it occurs in software solutions such as PAS [52] and DIPA [53], in which manual identification of

anatomical reference points is performed with the use of reflexive markers, providing agility during the evaluation process [66,69,70,74,76,82,88,89]. This automation would reduce the need to perform palpation frequently and hence, reduce the chance of the patient complaining of discomfort related to the manual touch performed repeatedly. In this sense, a first initiative is the PhysioCode Posture (<https://play.google.com/store/apps/details?id=com.smolve.posture&hl=en>), a market solution that offers the feature for automatically detecting anatomical points.

In addition, the picture capture process of identified IBSs is also performed manually. So, a helpful feature would be the automatic picture taking when both the patient and smartphone are positioned correctly. Another desirable feature would be to combine sensor technologies with image analysis techniques, making it possible to simultaneously identify both angles, inclination and rotation based on the angular displacement of the body as well as the calculation of angles of the spine curves.

None of the articles included in this review presented applications used in association with smart bands or smartwatches, although these wearable devices are used frequently and popularly to monitor health status. Future solutions could take advantage of popular devices that already have embedded sensors such as gyroscope and accelerometer to identify postural deviations.

Although US applications allow us to assess the Cobb angle, which is considered the gold standard for measuring and classifying spine deviations, it is still necessary to do so by analyzing spine X-rays. This indicates that although the mobile applications identified in this review are reliable for assessing human posture, other advances can still be implemented. New applications may follow the development trend based on the use of sensors and image analysis and processing, but being enriched with machine/deep learning models to improve the accuracy of the measurements [95]. This may help optimizing the time of the assessor in capturing important information, as well as it can facilitate the monitoring of the treatment progress more quickly and easily by both professionals and patients. Moreover, to make the procedure of human postural assessment even more realistic, as well as easier and more accurate to see the anatomical points, vertebral curves and their angles, future solutions could be developed to use augmented reality technologies to draw the patient's body skeleton by interconnecting elements from the real to the virtual world. This would help patients to understand their postural misalignment.

5.3. Limitations

There are some limitations inherent in this study. The first limitation of this review includes the English language restriction. Scientific studies developed and published in different languages from English have not been screened and included in this review. Second, the search for articles was conducted only on six well-known digital libraries. An additional search for articles can be performed to include other databases. Finally, we analyzed only published articles and the methods proposed in them. Therefore, our findings are constrained by what is being reported in the published literature.

6. Conclusions

Researches on the technological development field for postural assessment are not so recent but image-based applications have advanced in the last few years. Identified studies have revealed that mobile systems applied for postural evaluation especially based on column alignment can provide valid information that helps identifying the main postural deviations. Furthermore, it was possible to identify current trends for the development of new mobile applications with growing popularity of smartphones. However, we cannot ignore that despite the fact that mobile solutions provide resources of interest for postural assessment, there are limitations to overcome, such as the manual marking of anatomical reference points and calculating the Cobb angle for scoliosis classification, which is still performed based on the analysis of radiographic images. In this case, although sensor-based solutions provide faster analysis than manual analysis, the patient is still subjected to radiation and this limits the repeatability of the test in clinical practice during reassessments. When overcoming this limitation, the professionals will be able to easily use the Cobb angle (i.e., the gold standard) in patient monitoring.

In addition, IBSs are useful in pandemic times such as the outbreak of COVID-19 coronavirus, since the assessment can be performed at a distance (about 3 meters) from the patient, ensuring physical distance to minimize the chance of contamination by the virus. On one hand, we cannot state that mobile applications may be used remotely, since a health professional is required to assess the patient and interpret results. On the other hand, even if the health professional and the patient are located at the same physical environment, they will be separated by a safe distance without the need for direct physical contact and, therefore, some IBSs are able to perform posture assessments with validated methods and possible reduced contamination risks. Further studies are required to demonstrate this.

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Abbreviations

The following abbreviations are used in this manuscript:

AIS	Adolescent Idiopathic Scoliosis
DATs	Digital Assessment Tools
DIPA	Digital Image-Based Postural Assessment Software
ER	Evaluation Research
IBS	Image-Based Solution
ICC	Intra-Class Correlation Coefficient
kNN	k-Nearest Neighbors
LL	Lumbar Lordosis
L1	First lumbar vertebra
MATs	Manual Assessment Tools
MeSH	Medical Subject Headings
mHealth	Mobile Health
MLP	Multilayer Perceptron
MSE	Mean Squared Error
NMSE	Normalized Mean Squared Error
PACS	Picture Archiving and Communication System
PI	Pelvic Incidence
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSM	PostureScreen Mobile
PS	Proposal of Solution
PT	Pelvic Tilt
QQs	Quality Questions
RQ	Research Questions
SD	Standard Deviation
PAS	Posture Assessment Software
SATs	Software-Aided Assessment Tools

SLRs	Systematic Literature Reviews
SLR	Systematic Literature Review
SS	Sacral Slope
SVM	Support-Vector Machines
S1	First sacral vertebra
US	Use of Sensors
VR	Validation Research

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