In the last decades, assessment of trunk posture and motion has gained importance in clinical practice, and several instrumental non-invasive techniques have been developed to overcome limitations of manual and radiological methods. Despite the large effort spent in improving the underlying technologies, the actual role of these measures in the clinical setting remains still undefined due to a variety of issues. The main question concerns the provision of parameters providing a significant contribution to the clinical decision making. In this paper, we review the available spine surface measurement techniques from a technical viewpoint, and point out their current and potential applications according to a clinical perspective. Conclusions are drawn on the basis of both the technical features and accessibility in daily clinical practice, as well as of the validity, reliability and clinical value of the provided parameters. A well-defined clinical role is established for surface topography in the follow-up of spinal sagittal plane deformities, adulthood scoliosis and spine disorders involving the spino-pelvic alignment. Conversely, further studies are required to identify reliable key parameters for use in the clinical (adolescent scoliosis, back and neck pain), occupational (measurement of spine exposure to mechanical loads) and forensic (assessment of segmental functional impairments) fields.

**Key Words:** Spine - Posture - Biomedical technology - Scoliosis.

Apart from pure biomechanical research, in the last decades trunk functional assessment has progressively gained importance for clinical practice, due to both financial and clinical issues. The former are related to the growing pressure of both insurance companies and health institutions for an objective assessment of the impairments deriving from diseases involving the spine, which represent one of the largest source of health and social care cost. A wide range of clinical scales, either disease-specific or not, have been proposed as assessment tools, mostly based on self-report questionnaires. However, partly due to their intrinsic subjectivity and partly to the complex relationship between physical impairment and disability, such scales lack of reliability, disease-specificity and sensitiveness to changes, thus claiming for more quantitative and reproducible measurements of trunk function.

From a clinical point of view, interest in trunk functional assessment arises from the involvement of trunk malfunctioning in the pathogenesis of several musculoskeletal disturbances, whereas anatomical abnormalities are less frequent. For example, in more than 85% of patients referred to primary care...
for low back pain, symptoms cannot be attributed to a specific disease or spinal abnormality. Hence, clinical guidelines suggest to avoid imaging or other diagnostic tests in absence of any strong suspect of potentially serious conditions, and, conversely, to accurately assess functional deficits.\(^3\) A thorough trunk function assessment should include measurement of both kinesiological and neuromuscular parameters. Manual and instrumental measurements of maximal trunk range of motion and muscle strength are commonly used in the clinical practice. However, clinicians should be aware not only of the controversial reproducibility of these methods,\(^4\) but also of the poor relationship between these measurements and both pain and functional impairment, possibly because activities of daily living require only a relatively small percentage of trunk maximal strength and motion potentialities.\(^5\) Actually, such measurements merely represent a quantitative evaluation of parameters already assessed in a standard clinical examination, whereas the aim of a functional assessment should be to determine the actual biomechanical pattern of the spine in daily life activities.

These considerations explain the attempt to introduce the instrumentation, in terms of acceptable measurement error (possibly evaluated by comparative studies against radiography) and high reliability; 2) feasibility of use in the daily clinical practice, in terms of inexpensiveness, procedures' user-friendliness and time-consumption; 3) provision of parameters with a defined clinical significance. Indeed, we believe that, given a satisfying level of reliability, a parameter could be introduced in clinical practice only if it significantly contributes to establish diagnosis or prognosis, to facilitate screening programs and/or serial follow-up, to support the decision-making process in prevention and treatment programs, or to ameliorate the assessment of impairment.

During the 5th Evidence-Based Meeting "R&R - Rischi e Rehabilitation" organized by ISICO (Italian Scientific Spine Institute) and held in Milan in March 2010, a Consensus Session has discussed these issues, with the aim of reviewing the currently available automatic non-invasive instrumentations for the assessment of spinal function and proposing future directions for research from a clinical perspective.

The aim of this paper was to communicate to a wider audience the results of this Consensus Session. After a brief overview of the main issues common to all spine surface measurement techniques, we report about each instrumentation, describing the technical features and accessibility in daily clinical practice, and the validity, reliability and clinical value of the provided parameters. Finally, we draw conclusions concerning the current role of spine surface measurements in the clinical setting and the potential developments arising from research.

**General issues**

The main concern in surface spinal evaluation is represented by the uncertainty about what is being actually measured: do surface measurements correspond, or strongly relate, to any skeletal measurement? In addition, are the measured postural and motor behaviors really representative of the individual subject? Consequently, controversial topics common to all techniques for trunk surface measurements include soft tissue artefacts, the relationship between back surface and spine shape (i.e., spine biomechanical models) and the biological variability of spine behavior in postural and motor tasks.
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Soft tissue artefacts

While a correct identification of anatomical landmarks, which is the prerequisite for any surface spinal analysis, represents a satisfactory warranty in static tasks, it is not adequate to avoid significant measurement errors in dynamic conditions, due to the relative motion occurring between skin and the underlying skeleton. This motion has a frequency content similar to the actual bone movement, its magnitude is task-dependent and not negligible, and it is only partially reproducible among subjects.6

Several experimental observations suggest that skin motion artefacts may be considered negligible: 1) relative movements between skin markers and vertebral landmarks are less than 2 mm in extreme trunk positions; 2) during trunk flexion, skin distraction represents movement of the spine segment immediately underlying the stretching skin; 3) external and internal rotation of lumbar vertebrae, calculated by surface markers and open MRI scanner, respectively, have been reported to be highly correlated in five different seating postures; 4) measurement of the sagittal vertical axis – a widely accepted radiographic measurement of global sagittal alignment of the spine – can be accurately performed by surface analysis, with the advantage of allowing the reproduction of the spinal functional standing posture without the limitation imposed by the lateral spinal radiograph.10

However, this point remains controversial. Even the relationship between coronal and sagittal vertical alignment calculated from radiographs and surface markers has been questioned.11 More thorough investigations, including estimates of the propagation of soft tissue artefacts on the calculation of intervertebral motion, demonstrated that skin stretching and muscle deformation determine a significant error in all spinal motions; in particular: 1) during flexion, an overestimation of the flexion angle; 2) during lateral bending, overestimation of the axial rotation component; 3) during back torsion, spurious lateral bending component and underestimation of the axial rotation component.12 Moreover, this error is not homogeneously distributed across the different spinal segments,13 and is strongly dependent on the marker set arrangement, with markers placed at the transverse processes suffering from the greatest inaccuracy and markers placed at the spinous processes sustaining less artefacts due to the low thickness of the soft tissues interposed between marker and bone.12

Conclusively, while there is evidence confirming a strong relationship between back surface and spine shape, differences between external, marker-defined intervertebral motion and actual internal vertebral translations and rotations cannot be excluded, suggesting a cautious use of surface motion analysis in diagnosing pathological conditions.14

Relationship between back surface and spine shape

Spine modelling still represents an unsolved biomechanical issue. Ideally, each functional spinal unit should be modelled as an independent mobile segment with six degrees of freedom.12 From a clinical point of view, calculation of intervertebral motion from surface data would allow to point out disordered intersegmental kinematics, which has been demonstrated to be involved in several spine diseases. Unfortunately, a full representation of the spine as a chain of almost 50 mobile segments would require an enormous computational effort and introduce a number of technical and procedural troubles, mostly irresolvable even with the most advanced measurement techniques.16

However, given the uneven, task-dependent distribution of the inter-segmental spine motion between spine levels, modelling the spine as a rigid body, like in the most used biomechanical models for upper and lower limbs motion, would introduce an unacceptable approximation of its actual behaviour and determine a loss of relevant kinematic information. Hence, a multi-segmental model is required for the understanding of movement-related spine pathologies and for accurate dynamic modelling.17 Consequently, researchers specifically interested in trunk motion have developed a series of biomechanical models which consider the spine as a kinematic chain of few segments, consisting of a series of adjacent vertebrae considered as a rigid body.18 However, even these models introduce a significant approximation, disregarding all intervertebral motions within each spinal segment: modelling the spine as a chain of semirigid segments or as an integral deformable body would be more appropriate.

Moreover, from a biomechanical perspective, spine functions in whole-body motor and postural tasks – absorbing or transmitting force and motion
between the lower and the upper limbs, preserving dynamic balance, allowing appropriate visual control — are achieved by a global rather than a local control of posture and motion, as suggested by the peculiar arrangement of trunk musculature, which, for the most part, links several non-adjacent vertebrae. In addition, in clinical practice, the need for an assessment of postural and motor abnormalities involving the whole spine is much more common than the need for an evaluation of single functional units, which usually requires a radiographic approach. Thus, a more global spine model would be desirable from both biomechanical and clinical viewpoints.

Several researchers have outlined the opportunity of modelling the spine as a curve rather than as a multi-segmental chain. For example, circular cervical model and elliptical thoracic and lumbar models have been demonstrated to fit closely with spine segmental shape and to allow discrimination between asymptomatic subjects and both neck pain and low-back pain patients. These methods share the concept of the spine as an arch, in which the control of posture, motion and mechanical load is global rather than local. However, only segmental models (mostly lumbar) applying this concept have been developed, whereas a model of the whole spine curvature has yet been developed.

Variability of spine behavior

Variability is a physiological, intrinsic feature of postural and motor behavior, pointed out by the "repetition without repetition" paradigm. Hence, researchers in the field of movement analysis routinely deal with the difficulty to consider the measured parameters as representative of any individual subject.

For example, despite range of motion measurements are recommended by the American Medical Association Guides to estimate the percentage of permanent impairment in patients with chronic low back pain, such methods have been demonstrated to be highly affected by within-day variability. This point represents a much more relevant concern in the measurement of free trunk posture and motion in everyday activities, and measurement of within-subject variability should be provided when attempting to introduce a parameter in clinical practice. Moreover, despite the increasing evidence that changes of motion variability may represent per se a peculiar alteration in spine pathological conditions, the large majority of studies concerning spinal motion has neglected this critical point.

Optoelectronic systems

In the last decades, optoelectronic motion analysis has become a common tool for researchers in the assessment of the neurophysiological and biomechanical basis of human posture and movement, thanks to the technical and procedural advances that allowed to reduce measurement errors and to the development of appropriate biomechanical models. In particular, technical assessment and analytical compensation procedures (camera calibration, filtering and smoothing of marker position data, procedures for marker imaged processing and missing marker recovery, techniques for minimization of error propagation) have been developed to cope with instrumental errors by reducing their propagation to kinematic variables. These advancements have markedly reduced measurement error, making soft tissue artefacts (i.e., skin deformation and displacement) the greatest source of error. Use of dwelling pins, though removing skin motion artefacts, is unfeasible in routinely clinical settings, due to invasive and laborious procedures and subject’s pain and discomfort. Hence, techniques for the assessment, minimization and compensation of the soft tissue artefacts have been developed, mostly including either a model of the skin surface and joint motion constraints, or using extended Kalman filters. A further variable source of error affecting kinematics accuracy is represented by the precision of rotation axes and anatomical landmark determinations; this error partly depends upon the features of the investigated motor tasks, partly upon procedural issues (e.g., correct identification of anatomical landmarks) and partly upon the validity of the biomechanical model. As far as concerns the former, it has been demonstrated that when motion mainly occurs along one axis, the measurement error is greater for calculation of minor rotations. With regard to the second factor, a technique using a digitizing probe to identify position of vertebral landmarks in relation to surface markers has been proposed to improve accuracy in constructing local coordinate axes; however, it seems unfeasible in the clinical setting.
latter issue represents the most controversial matter concerning spine movement analysis by optoelectronic systems. Indeed, a few methods have been strictly validated against invasive measurements. Protocols for measurement of sagittal spinal motion have been developed, based on transformation of skin marker coordinates into corresponding vertebral body coordinates, and validated by radiographic images; however, limiting spinal motion analysis to sagittal planar motion seems quite unsatisfactory for clinical purposes. A kinematical model based on evolutionary optimization has been developed for three-dimensional spinal motion analysis, characterized by determination of the actual location of the intervertebral rotation centres and minimization of soft tissue artefacts; however, despite providing reliable experimental data, only a qualitative comparison with radiographic images was performed. This point introduces the complex nature of spine modelling for motion analysis, which has already been discussed in the previous paragraph.

Several models for trunk kinematics have been developed, differing in terms of the included skeletal segments, marker-set, anatomical axis and frame definitions, and joint conventions. As a consequence, very different patterns and range of motion are provided, which limit their use in clinical setting. Here we provide a summary of the bi- and three-dimensional models used for both whole-body and spine motion analysis.

2-D spinal models

Models for measurement of 2-D spinal motion (flexion-extension and lateral bending movements) commonly require application of markers over the projection of spinous processes. Spine is modelled as a chain of segments linking pairs of adjacent markers, and the accuracy in spine motion reconstruction is given by the number of the segments, which is limited by the necessity of applying several markers in a small area. Furthermore, these models are not based on a calculation of the actual axes of rotation: motion is merely given by the projection of the angles between external segments on the planes of either the laboratory or the pelvis reference frame, and is responsible for misinterpretation of motion components (i.e., "projection effect" 19). Models including either two, three or more spinal segments have been developed to provide spinal postural and motion data during walking and basic trunk movements, but they did not undergo any radiographic validation. Lumbar sagittal spine motion was also calculated as the variation of the angle between a vector representing pelvis (determined by two markers applied over the projection of S2) and a vector representing spine alignment at the transition between thoracic and lumbar spine (determined by two markers applied over the projection of the spinous processes of T12 and L1 vertebrae); however, a validation of this method for calculation of lumbar spine motion has not been provided.

3-D spinal models

A model for measurement of spine three-dimensional motion requires application of three individual markers, or a triad of noncoplanar markers, over two or more spinal landmarks. The calculation of the segmental range of motion can be performed: 1) by projection of the angle between vectors linking two markers onto the planes of the global reference frame; 2) by calculation of the relative rotations between the coordinate systems associated with each segment (Euler-Cاردan angles); or 3) by decomposition of the motion in a rotation and an independent translation (helical screw axis computation). The first method can be affected by a significant error due to out-of-plane movements, which limits its application to well-defined, rigid motor tasks; the second method yields potential errors in calculation of minor rotations, depending upon the extent of angular motion and the conventional rotational sequence; both first and second methods neglect translations; the third, which yields the greatest mathematical robustness, is characterized by a measurement error depending on the marker configuration and the amount or rotation. An arrangement of both individual and triad markers for measurement of the lumbar range of motion during treadmill walking has been proposed, consisting of markers placed over the L1 spinous process, the lumbar vertebral junction and posterior superior iliac spines; measurement of angles of lumbar lateral flexion, lumbar axial rotation and lumbar flexion/extension is obtained by projection onto the planes of the global reference system; however, no validation of the method has been provided. Use of triad markers applied at the pelvis and upper thorax has also been proposed to assess 3-D spinal motion during walking and toe
touching test. Both the pelvic external fixator used to reduce skin motion artefacts and the placement of the spine triad yield distinguishing features with respect to most proposed methods. The former was validated by use of ultrasound imaging, and the latter was based on a previous work and aimed at reducing underestimation of spine motion by fixing the upper segment at a level higher than the most commonly used T₁₂ or L₁, thus avoiding to neglect motion occurring in the lower thoracic spine. Given the presence of a pad of subcutaneous fat in the immediate vicinity of the vertebral prominences, that removes the skin from immediate contact with the skeleton, they proposed that the ideal site for an upper thoracic skin surface marker is 5 cm caudal to the vertebral prominences. Spine modelization was significantly improved by the introduction of a kineastic spine model consisting of 3 linked, rigid body segments (cervical, thoracic, and lumbar regions). To quantify 3-D kineasticity, they applied non-collinear triad markers over the spinous processes of C₅, T₇, and L₃ vertebras, which were considered as the approximate centers of the anatomically distinct spinal regions. The angle between 2 adjacent segments was determined by calculating the orientation of the inferior with respect to the superior segments co-ordinate system, using the most suitable rotational sequence suitable for the gait task (transverse-coronal-sagittal). Joint centers positions in the transverse plane were estimated from data provided by 25 cervical, thoracic, and lumbar computed tomography scans. Validation of this kineastic model was accomplished through construction of a replica of the spine using a static mechanical model and comparison between optoelectronic and goniometric measurements. The difference between the angles measured with the goniometer on the static mechanical model and the angles computed by the kinematic spine model were less than 5° for all angular positions in all regions for both the uniaxial and coupled (with the aforementioned conventional sequence) motion validation. Main limitations of this study concern with 1) the partial representation of the spine as a three linked rigid body chain; 2) the approximation in the location of the instantaneous axis of rotation; 3) the absence of any correction for skin motion artefacts. A similar spine model has been recently proposed, consisting of sacral, lower lumbar, upper lumbar, and lower thoracic, mid-lower thoracic, mid-upper thoracic and upper thoracic segments, with the main difference concerning: 1) the location of the transverse instantaneous axis of rotation, that was not based on an anatomical criterium; 2) the rotation sequence (flexion, followed by the side-bending and then axial rotation), due to the different motor task investigated (target-directed trunk movement during sitting). Unfortunately, use of three individual markers for each segment increases the risk for unpredictable skin motion artefacts, and no validation of the model was performed. Finally, models based on similar cluster markers have been developed for the calculation of intervertebral motion, but in spite of their intraoperator, interoperator and circadian reliability, they lack of validation with respect to radiography and their use is far from a daily clinical application due to the large number of markers required.

Feasibility of use in clinical practice

Despite the widespread distribution of optoelectronic systems, due to their uncontrovertible accuracy, their use in the clinical setting is limited for a series of practical issues: the requirement for a large space for set-up, the confinement of data capture within the laboratory, the limitation of recording time to short-term measurements, and the procedures for markets arrangement, which are quite time-consuming. In particular, with the aim of reducing the burden of time spent for marker placement, preliminary and encouraging experiences have been reported for marker-free optical techniques.

A clinical role for the biomechanical assessment of lumbar spinal motion has been proposed, based on the hypothesis that low back patients may differ from healthy subjects in terms of range of motion during simple trunk movements, higher order kinematics (displacement, velocity, and acceleration) during complex movement tasks and spinal proprioception. The flexion-extension lumbar trajectory during forward bending and return to an upright position was compared between asymptomatic subjects with and without a history of low back pain, demonstrating that the former yielded greater lumbar motion and velocity during the initial phase of both flexion and extension with respect to the latter: unfortunately, the experimental design was inadequate to judge the observed differences a consequence or a predisposing factor of the recurrent low back pain. Similarly, the differences observed in
trunk control during treadmill walking — a less variable kinematic coordination in the transverse plane, and a less tight and more variable coordination in the frontal plane in aspecific low-back pain patients compared to asymptomatic subjects — cannot be attributed to the presence of low back pain per se, as stated by some researchers.46

Data concerning spinal motion in scoliotic subjects are far from finding practical applications either as functional and biomechanical assessment tools or as treatment outcome measures.28,49,50 Recently, a method for automatic classification of scoliosis based on the projection of spine shape on a spinal reference system has been proposed and validated; the main source of error seems to be related to the postural adjustments occurring during recording; however, further follow-up studies are required to establish the clinical significance and potential usefulness of this method.51

Concerning cervical spine, a good reliability has been reported for measurements of active range of motion, showing that primary movements are always associated with out-of-plane components.52 However, these methods did not undergo radiographic validation and they all provide data concerning head movements with respect to the thoracic spine, without discriminating between upper and lower cervical motion. This last point represents a limiting factor for practical applications, since measurement of the relative contribution of segmental cervical vertebral motion to the whole cervical range of motion has been shown to potentially discriminate between malingering and actually restricted neck motion, which is a point of relevant interest for forensic purposes.53

Surface topography

Surface topography techniques yield maybe the greatest chance to achieve increasing importance in clinical practice, if technical and procedural advances as well as clinical trials will allow these systems to ignore changes due to varying posture, establish disease-specific gold standard parameters and reliably detect differences that are clinically significant.54, 55 Three-dimensional reconstruction of human trunk surface can be performed via rasterstereography and laser scan. In video rasterstereography, three-dimensional shape is produced by analysing the distortion of parallel horizontal white light lines projected on the patient’s back, followed by image processing and mathematical modelling.56 In laser optical scanning, a series of laser cameras move along a vertical axis, and a topographical mapping of the entire torso is provided by mathematical processing.57 While both techniques share an acceptable spatial definition, rasterstereography yields the advantage of performing the simultaneous capture of the entire back surface, which reduces the error due to postural sway. However, despite allowing a precise and accurate reconstruction of back shape, with provision of reliable surface parameters, both techniques deliver only indirect information about the three-dimensional shape of the spine, making indispensable a validation with X-ray methods if the aim is to surrogate radiography. Commonly, a curvilinear model of the spine shape is calculated by mathematical algorithms in order to derive spine parameters, as outlined below, while being a distinctive feature of these techniques, this characteristic hinders in most cases a direct comparison between surface and radiographic parameters.

**Video rasterstereography**

The major differences among the most widespread rasterstereographic instruments are: 1) discrepancies in image processing, including the use of either interpolation algorithms (Quantec and Formetric systems) or Fourier transform profilometry (ISIS2 system), and the use of either body (Formetric and ISIS2 system) or laboratory (Quantec system) axes; 2) the requirement of an operator intervention for image processing for some equipments (Quantec system), whereas measurements are completely automatic for others (Formetric and ISIS2 systems), and the need for applying stickers to mark bony landmarks on the patient’s back for some equipments (ISIS2 and Quantec systems) and not for others (Formetric system); 3) the method used to take into account fluctuations due to the breathing excursion and postural sway, i.e. either digitizing a single image obtained in a short capture time (ISIS2 and Quantec systems) or averaging measurements performed over few seconds (Formetric system). Concerning the former point, error measurements appears satisfactory for all processing techniques. For the second point, the automatic determination of a small set of landmarks (commonly, the verte-
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The prominen, the dimples of the posterior superior iliac spines and the sacrum point) is based on the identification of their distinctive surface curvatures in a specific region of interest. Variations in these landmarks have been demonstrated to slightly affect localization of most landmarks, and also automatic detection of the dimples of the posterior superior iliac spines has been improved to a satisfactory degree by use of a point distribution model. About the latter point, averaging seems to represent a better solution to avoid back surface reconstruction from being susceptible to postural sway.

As for the Formetric system, given its initial field of clinical application, both validation processes and technical advances have been mainly concerned with the upgrading of the scoliotic shape reconstruction from the three-dimensional measurement of the spine profile. Given the curvilinear representation of spine shape, rater stereographic reconstructions have been compared to digitized radiographic or MR tomography curves by best fit superimposition and calculation of the root-mean-square difference. At the moment, an active shape model, based on an approximation of the X-ray curve, appears the best proposal to improve the original frequency modulated sine model. Several studies have searched for the best Formetric parameters to be used for both follow-up and outcome purposes. In particular, lateral vertebral deviation and vertebral rotation have been proposed in the evaluation of the outcome of surgical procedures. Moreover, in a retrospective longitudinal long-term follow-up study good correlations have been demonstrated between the progression of the radiographic Cobb angle and both parameters, with lateral vertebral deviation which slightly over-estimating and vertebral rotation slightly under-estimating, respectively, Cobb angle progression. Other parameters, including measures of spine sagittal and coronal balance, as well as of pelvis three-dimensional posture, are provided for the assessment of global spine alignment. A potential application to scoliosis screening has also been proposed in an attempt to improve the current gold standard, i.e., scoliometer measurement of the angle of trunk rotation. However, it has been reported that the correlation of back surface rotation amplitude in standing with that in forward bending posture is poor; compared to the standing posture, forward bending unpredictably changes trunk rotation. Hence, even if a future application of Formetric system in screening programs cannot be excluded, studies on large cohorts are required to establish surface parameters' thresholds for referrals to X-ray. Conversely, a current role of Formetric can be already defined in the assessment of the sagittal plane deformity (both in scoliosis and Scheuermann's disease), on the basis of the reliability of sagittal plane measurements and their technical error comparable to the X-ray measurement. There are at least three points supporting the use of rater stereography instead of X-ray: 1) sagittal plane deformity in scoliosis is commonly represented by a non-harmonious distribution of kyphosis in the thoracic spine, with adjacent local hyperkyphotic and hypokyphotic zones, making the global thoracic kyphosis angle a misleading parameter; moreover, the actual sagittal plane of the scoliotic curve does not correspond to the standard anatomical one due to lateral deviation and axial rotation of the vertebrae; hence, a measurement of the local curvature taking into account the three-dimensionality of the deformity, as provided by Formetric system, would be advisable. 2) radiographic methods for calculation of spinal sagittal angles are still a point of debate: e.g., vertebral centroid or posterior tangents methods for the measurement of lumbar lordosis, which eliminates error due to local abnormalities, yield a greater reliability compared with the Cobb technique. This point supports the use of a geometrical rather than a pure anatomical approach, and explains the difficulty in comparing video rater stereographic and radiographic measurements of the sagittal angles, depending on the different intervals used for calculation. Indeed, a sagittal angle is measured in the lateral radiography according to an anatomical criterion (e.g., for the kyphotic angle, from T4 to the lower end vertebra), whereas in video rater stereography a "maximal" sagittal angle is calculated, based on a geometrical criterion (e.g., for the kyphotic angle, from the cranial transition between lordosis and kyphosis to the caudal transition between kyphosis and lordosis). Consequently, the two measurements commonly yield a highly significant correlation but also a systematic, significant difference. 3) the anatomical position imposed by X-ray techniques affect both the global and segmental sagittal spine alignment, whereas rater stereography allows to maintain the natural standing posture. This last two points also support use of rater stereography in the follow-up of sagittal plane deformity, such as Scheuermann disease.
ease, whereas its use to discriminate between "normal" and pathologic kyphosis would require specific reference values. As a more recent field of application, Formetric system has also been used to search for potential relationships between the sagittal jaw position and the body posture; while correlations have been demonstrated between several craniofacial and trunk and pelvis postural parameters, these preliminary observation need further confirmation prior to establish a potential clinical use.69

The Quanteq system produces a three-dimensional surface representation of a single image which is captured in 0.92 seconds; given the influence of postural sway on instantaneous back surface shape, a satisfactory reproducibility is guaranteed by performance of 3 scans.70 Parameters are calculated referring to a spinal curve reconstruction, and a tentative to provide normative data has been performed for a population of 40 children without clinical evidence of pathology.71 A simulated Cobb angle (Quanteq Q-angle), calculated between the lines perpendicular to the spinal curve reconstruction in the inflection points, has been reported to correlate well with the radiographic Cobb angle, with the closest correlation yielded for small curves with minimal rotation.72 Nevertheless, only a small percentage of its variability can be attributed to the spine deformity, suggesting to limit its use to patient monitoring 54,73 and to measure outcome of surgical correction.71,74

ISIS2 system represents an evolution of a previous apparatus, with improvements in calculation of transversal and sagittal plane parameters, whereas the coronal plane reconstruction, based on a fifth order polynomial curve fitted through the spinoous process markers, is almost identical to the original one.75 Parameters proposed for the assessment of scoliosis patients includes: 1) in the sagittal plane, the maximum kyphosis and lordosis angles, calculated between the lines perpendicular to the spinal curve reconstruction in the inflection points; 2) in the transversal plane, the skin angle between the coronal plane and the line joining symmetric paramedian points at each definite level, and the height of the rib hump; 3) in the coronal plane, the lateral asymmetry, i.e., a simulated Cobb angle calculated between the lines perpendicular to the spinal curve reconstruction in the inflection points.76 Additionally, for global spine alignment, two relevant parameters are provided: coronal imbalance is defined as the linear distance between the vertical line dropped from the vertebra prominens and the sacrum; sagittal imbalance as the angle between the vertical and the line joining the vertebra prominens and the sacrum.77 As far as concerns clinical applications, evidence has been provided that the inherent variability in calculation of the kyphosis angle caused by natural change in the patient's stance, breathing and muscle is lower than the clinically significant change reported in the literature, suggesting that kyphosis angle in ISIS2 is suitable for monitoring progress in kyphotic deformities.78 Conversely, use of transversal plane parameters in the follow-up of scoliosis patients in not yet defined.

Inspek system is a particular rasterstereographic apparatus, consisting of four 3-D digitizers, each providing a partial surface from a distinct angle, which is merged with the others to reproduce the overall shape of the trunk.79 Although this technique has been proposed to document the external asymmetry associated with different types of spinal curves, as well as the cosmetic improvement obtained after surgical interventions, there is still a lack of evidence concerning its accuracy - primarily, relative to the non-instantaneous recording of the partial surfaces - and its correlation with radiographic parameters.

Laser scan

In the laser scan technique, data acquired with a high accuracy by a series of laser topographic scanners are used to calculate a 360° torso surface model by mathematical algorithms.80 A series of indices of torso asymmetry are then computed, such as back surface rotation or spinous process line location, at each vertical level, and the range and maximal values over the entire torso are calculated for each asymmetry parameter; additionally, the angles of curvature are calculated for all definable curves between points of inflection. Hence, a mass of numerical information is provided, most of which is not meaningful for the clinician. This critical point explains the attempt to provide a correlation with the Cobb angle, aiming at surrogating X-ray measures in the assessment of scoliosis.80 While several torso asymmetry indices correlated well to the Cobb angle, such as rib hump, lateral deviation, left-right area asymmetry and torso rotation, the closeness of the relationship was variable, depending on the extent of the scoliosis deformity and the bracing
treatment. This suggested to search for a model to detect scoliosis magnitude and progression based on a series of surface parameters. Hence, aiming at detecting the optimal set of input torso indices, estimation of the Cobb angle from indices of torso surface asymmetry was attempted by artificial neural network using a genetic algorithm. Despite results are encouraging, further longitudinal studies are necessary to establish a role in the assessment of scoliosis progression.70

Feasibility of use in clinical practice

Research leading to the development of surface topography was initially motivated by the aim of reducing X-rays exposure for patients with a scoliosis by substituting the X-ray Cobb angle with a surface measure. Hence, strong efforts have been directed to search for the best surface parameter approximating radiological Cobb angle. The unsatisfactory results are maybe the main reason that introduced the surface topography in a blind alley.55 However, recently, there is increasing consensus among researchers about the potential clinical usage of surface topography in scoliosis evaluation, with surface measures considered as independent parameters, based on a series of assumption: 1) current technical capabilities offer reliable and precise surface measurements;60 2) the surface and the X-rays are not measuring the same aspect of the scoliotic deformity;56 despite the presence of a relationship between skeletal and surface measures in most cases, concordance between back topography and radiography relative to the present, level, and side of a scoliosis curvature is variable;53 3) surgical treatment produce not only correction of spine but also of back surface asymmetries.62 According to these assumptions, several surface measures have been proposed to complete assessment of scoliosis subjects with a reliable information concerning trunk deformity.60 The Posterior Trunk Symmetry Index (POTS1) is a comprehensive indicator of the coronal plane asymmetries of the back, including calculation of six symmetry indices relative to the shoulders, waist, and C7 position.62 The values of POTS1 below 27.5 were reported to be within normal limits; the intra-observer error of 5.5 and the inter-observer error of 6.4 were reported. The Hump Sum is a comprehensive indicator of the transverse plane asymmetry of the back, calculated as the sum of three hump indices determined at the proximal thoracic, the main thoracic and the lumbosacral or lumbar spine levels.83 Similarly, the Deformity in the Axial Plane Index (DAPI) is calculated by addition of the difference of the depths of symmetrical points, at the level of the scapulae and waist.82 Alternative measures have been proposed, obtained by different instrumentations and sharing similar significance.78

As far as concerns clinical application, DAPI and Hump Sum have been reported to be highly sensitive to scoliosis progression,85 Hump Sum to correlate with quality of life,87 and both POTS1 and Hump Sum to represent relevant outcome measures in surgical treatments.87 Moreover, in a preliminary study, the use of a combined diagnostic criterion, consisting of considering as positive subjects with either high POTS1 of high DAPI, and as negative subjects with both normal DAPI (≤3.9%) and normal POTS1 (≤27.5%), yielded a sensitivity of 79.6%, a specificity of 91%, and a positive predictive value of 82% were reported.82 Finally, as improvement of cosmetic appearance represent a major outcome of both brace and surgical treatment,85, 86 surface topography may be used to provide an objective quantification and documentation of the postoperative cosmetic changes of the back shape in standing posture.62, 87 However, there is still a lack of consensus concerning which indices should be introduced in clinical practice. Nevertheless, recently an agreement has been found about the basic requirements that should be common to any clinical index of trunk deformity: 1) indices should be measured with simple measuring protocols, high accuracy and in a direct manner; 2) should be independent from the method of measuring, the coordinate system and the patient’s size; 3) should be based on automatically detectable anatomical landmarks, robust procedures and automatic measurements, eliminating as far as possible the human intervention; 4) should distinguish between different types of surface deformities (e.g., coronal, sagittal or transversal plane, spine level); 5) should provide a clear and safe difference in magnitude between normality and pathology.89 Taken together, these indications support the search for standardized parameters provided by surface topography, focusing on the direct measurement of the back surface and decreasing interest in spine shape reconstruction.

The high reliability of both global and segmental spinal sagittal parameters provided by surface to-
pography and their strong correlation with radiography support their use for the assessment of spine sagittal balance, an increasing point of interest in clinical practice. Indeed, a series of biomechanical observations from radiographic assessment suggests the need to investigate the whole trunk sagittal profile during standing: 1) thoracic and lumbar spine sagittal parameters have been proved to generate the amount of shear compressive stresses on spinal tissues; 2) postural adaptations aimed at preserving trunk function (e.g., maintaining a forward visual gaze) may occur at any level of the spinopelvic chain; 3) the length of each spinal segment, either lordotic or kyphotic, is characterized by a significant between- and within-subjects variability. Furthermore, these points have been confirmed in several clinical contexts. Indeed, peculiar alterations (e.g., anterior translation of the C7 plumb line, loss of lumbar lordosis and decrease of sacral slope after matching according to pelvic incidence) have been demonstrated in several spinal disease. Hence, assessment of the sagittal spinopelvic balance may contribute to establish appropriate treatment and prevention objectives and measure outcomes at follow-up. Finally, sagittal spinal alignment has been used to identify postural adaptations to aging, possibly predisposing to degenerative disease: longitudinal studies of the sagittal alignment in the elderly have indicated that lumbar-pelvic congruity (i.e., a ratio of lumbar lordosis to sacral inclination between 0.7 and 0.9) is a protective factor against spinal imbalance and degenerative kyphosis. As pelvic incidence, which is an anatomical angle, remaining constant throughout adulthood, is the only parameter requiring an X-ray measurement among those commonly used for the assessment of sagittal spine alignment, surface topography may integrate whole-spine radiography at the first examination and then surrogate it during the follow-up, reducing patients’ exposure to ionizing radiation.

Wearable sensors

While optoelectronic systems and surface topography are both based on an optical recording apparatus placed in a laboratory, many measurement systems are based upon skin-mounted devices that directly participate in the recordings. Most of these devices are portable, which increases their feasibility of use in the clinical practice, and allow not only the measurement of standing curvatures and range of motion during basic trunk movements, but also the continuous recording during the performance of daily life activities. On the contrary, a technical limitation of these systems is their dependence upon the maintenance of relationship between skin-mounted sensors and the underlying bony landmarks during motion (Table 1). In addition, due to the variability of sensors features and of procedures for patient preparation, data from different studies are not always directly comparable, and the devices cannot be used interchangeably without demonstration of a strong agreement.

Electromagnetic tracking systems

Electromagnetic tracking systems are six-degrees-of-freedom measurement devices consisting of a transmitter generating a low frequency magnetic field which induces current in a series of skin-mounted receivers depending upon their three-dimensional orientation. The accuracy of the measurement depends upon the distance between the transmitter and the receivers, with an optimal operational zone defined by the technical features of the instrumentation. Other sources of inaccuracy are intrinsic system errors in sensor position or angle and tip-offset calibration errors. Additionally, while some experimental evidence has been provided concerning the validity of this method compared to dynamic radiographic measurement on lumbar inter-vertebral and segmental motion, no optimization technique has yet been developed to minimize skin motion artefacts, nor a radiographic validation of multi-segmental spine models has been performed. Also, despite evidence has been provided in support of the feasibility of application of kinematical models employing screw displacement axes with electromagnetic tracking systems, no practical application has been proposed.

Electrogoniometers

Electrogoniometers are 3-D measurement devices consisting of potentiometers connected by lightweight bars, whose resistance changes give provide the angular measurement between the pair of body segments. As outlined for electromagnetic tracking systems, error measurement is prone to the
### Table 1.—Summary of the main technical and procedural features of each system.

<table>
<thead>
<tr>
<th>System</th>
<th>Identification of anatomical landmarks</th>
<th>Spine model</th>
<th>Radiographic validation</th>
<th>Minimization of skin motion artefacts</th>
<th>Posture analysis</th>
<th>Motion analysis</th>
<th>Operative procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optoelectronic</td>
<td>Skin markers</td>
<td>Chain of linked rigid body segments</td>
<td>2D: 34 3D: 6</td>
<td>Yes 6, 62</td>
<td>Limited to angles between rigid body segments</td>
<td>Yes</td>
<td>Time-consuming</td>
</tr>
<tr>
<td>Surface toplaphy</td>
<td>Automatic/skin markers</td>
<td>2D/3D/4D</td>
<td>3D: 61</td>
<td>No</td>
<td>Extended to calculation of spinal curvatures</td>
<td>No</td>
<td>Time-saving</td>
</tr>
<tr>
<td>Wearable sensors</td>
<td>Skin mounted devices</td>
<td>Chain of linked rigid body segments</td>
<td>3D: 99, 103</td>
<td>No</td>
<td>Limited to angles between rigid body segments</td>
<td>Yes</td>
<td>Time-saving</td>
</tr>
</tbody>
</table>

unavoidable skin motion artefacts. Moreover, most of these instruments was not validated against radiography but only against manual inclinometers, making their accuracy in relation to true spine angular movements unknown; even when assessed, agreement with radiography was controversial. In addition, the technical features of the sensors significantly affect reliability and accuracy of the measurements; hence, either electrogoniometer-based studies should be limited to longitudinal design, or device-specific normative range of motion should be provided; conversely, published database of both cervical and lumbar spine range of motion in asymptomatic subjects should be used cautiously. As far as concern the practical use in spine motion assessment, several authors reported good values for reliability of lumbar spine measurements, with rotation showing poorer repeatability than flex-extension or lateral bending, whereas reliability was less satisfactory for cervical and thoracic measurements.

**Inertial sensors**

Inertial and magnetic measurement systems are commercially available, low-cost, portable motion analysis systems, consisting of lightweight boxes containing a variable arrangement of 3-D accelerometers, gyroscopes and magnetometers. Through mathematical algorithms, the 3-D real-time orientation of each of these sensing units is calculated relative to a local coordinate system, without the need for optical cameras or equipped laboratory. Thanks to these features, these systems allow performing continuous measurements of movement in laboratory-free settings, such as daily life environments. Due to the use of the gravitational coordinate system, a calibration procedure is required for calculation of anatomical coordinate system for each body segment. Improvements of the accuracy of these systems are commonly obtained by use of additional sensors, allowing to reduce measurement error. For these wearable devices, skin motion artefacts are not only related to the relative motion between skin surface and the underlying...
bony landmarks, but also to the potential slippage, especially when using straps or belts, and loss of skin adhesion, when using adhesive or sticky tapes. While the greatest part of the published studies considers the spine as a single rigid body, a three-segment model including the cervical, thoracic and lumbar spine has been proposed. The small components size and the "occlusion free" measurement suggest that by use of additional sensors, the spine may further be divided into smaller regions; this would result in more accurate measurements, possibly allowing these systems to prevail over the optoelectronic ones in the assessment of spine motion.

Feasibility of use in clinical practice

While some specific applications to the assessment of spine function will be illustrated below, it should be outlined that the distinctive benefit of wearable sensors is to allow clinicians to monitor patients over extended periods of time, providing data relative to patients' activity level and exercise compliance, effectiveness of pharmacological interventions, and ability to perform efficiently specific motor tasks.

The clinical applications of electromagnetic tracking systems are prone to some technical limitations: they are not suitable for patient with metallic implants, laboratory must be free from ferromagnetic materials - though the accuracy of the tracking system can be optimized in the presence of metal by careful choice of the sampling rate - and motor tasks to be investigated are limited by the restricted operational zone. Yet, normative data have been provided by assessing a large sample of healthy subjects during performance of basic trunk motion. Only few experiences comparing repositioning error and postural strategies between healthy subjects and both low back pain and post-stroke hemiparesis patients have been reported, still lacking of a widespread clinical application.

Similarly, application to scoliosis screening and diagnosis, by measurement of three-dimensional spine movements with a particular focus on abnormal rotation, has been proposed but not yet fully assessed. A good accuracy has been reported for the measurement of the rotations – not the translations – of the lumbar and lower thoracic spine in osteoporotic patients. Also, an adequate repeatability has been reported for the measurement of cervical spine range of motion in patients with ankylosing spondylitis, with limitation of cervical flexion yielding the strongest relationship with the clinical status, however, while it is assumed that the measurement of the rotation of the head with respect to the thorax has a satisfactory within-session reliability, data concerning the between-session variability are controversial, limiting the potential clinical applications.

Concerning clinical applications of electromyograms, measurements are commonly performed for basic spine movements, hence the role of these systems is limited to the assessment of changes in range of motion following intervention. However, a point of interest is represented by the easiness and fastness of the procedures for patient's preparation and recordings, even when dedicated skin fixation systems are used. Reduced lumbar range of motion and different profiles of flexion-extension velocity were reported for low-back pain patients compared to healthy subjects, and low-back pain classifications have been proposed based on a kinematical model including alterations of angular position, velocity, and acceleration of the lumbar spine during basic trunk movements. Moreover, displacements of the horizontal and vertical components of the instantaneous center of rotation of the skull relative to the thorax have been demonstrated to significantly differ between patients undergoing fusion for cervical disc degeneration and both normal subjects and patients with chronic cervical spondylitis.

In relation to ultrasound transmitters, reference values have been provided for neck motion, based on a high degree of test-retest reliability, and it has been demonstrated that sub-classes of patients with chronic neck pain (idiopathic vs. chronic whiplash) yield different limitation of cervical spine range of motion. No significant difference between low-back pain patients and control subjects relative to the amount of lumbar motion during walking has been found, whereas a higher kinematical variability was demonstrated for the former compared to the latter.

With reference to inertial sensors, several combinations of accelerometers, gyroscopes and magnetometers demonstrated to provide reliable and accurate data, comparable to high-quality optical motion analysis systems, relative to the spine kin-
Overview on current and potential clinical use

After reviewing all the instruments for spinal functional analysis used in medical papers in the last years, we have to face a critical clinical question: are they really worth for everyday clinical usage, or are they still confined to laboratory setting for research purposes? And, if so, can we envisage any clinical future for all these devices?

During a Consensus Session at the 2010 ISICO Meeting in Milan the authors of this paper confronted with a clinical audience on the topic. During the discussion some issues have been raised and some conclusions have been drawn.

It has been recommended to go beyond the possible appeal of such instruments as a consequence either of individual drive for high-tech solutions or of commercial implications in terms of advertising clinical activities. Both these situations will continue to confine these devices either to a passionate elite or to lucrative activities. On the contrary, we need to bring to the forefront of the debate their possible wider applications in different settings, as it has occurred for other imaging techniques. A major concern in everyday clinical use of these instruments resides in the costs/benefit ratio. We need in fact to consider: 1) direct costs of the instruments: some of them are costly and only an extensive use would balance costs; 2) need to involve expert personnel: many instruments are not user-friendly and require expert interventions; moreover, the interpretation of data is often complex and needs adequate training; 3) clinical applicability: almost all these instruments are time-consuming, either for data acquis-

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Institutional Measures of Spinal Function

A multifunction device consisting of an integrated circuit accelerometer which allows real-time measurement of pelvic tilt, and is supplied with an audible tilt alarm that can be custom set at flexion limits, has also been developed: despite this measurement method was intended to provide an approximation of lumbar flexion, the correlation between the two measures was poor; hence, the clinical role proposed for this device is to serve as a feedback to be used during rehabilitation and daily life activities in subjects affected by low back pain.

Another potential problem is represented by the "too many data - no data" paradox: in fact most of these biomedical instruments allow gathering a critical mass of information, which makes extracting the really meaningful ones a complex task. Most of the time clinicians reach conclusions after an inductive process based on few key-data, as they are not used to deduce conclusions from a wide range of information. Such dualism, or in other terms the engineer-physician dualism, still hinders decision making, thus limiting the understanding and the applicability of the data obtained.

We also need to be aware of human factors, both on the side of final users and of developers. The first group, in fact, may show the well known "resistance to change". This is a typical behaviour in which any challenge requiring abrupt change of long-term habits and adoption of new and not totally acknowledged strategies/data is contrasted. On the other side, some developers prefer to maintain their personal role as the only and true interpreters of the "holy data", which is, paradoxically, in contrast with the commercial goals of dissemination of the instruments in everyday clinical use. Both these behaviours act as negative factors for an evidence-based dissemination of these instruments.

Finally, the attempt to mimic and surrogate other widely used, and probably not substitutable, instruments has further hindered the diffusion of these instruments. This has led to an inappropriate use of the instruments and spoiled their complete development. As an example, in the field of scoliosis, surface topography techniques have tried for years to represent an alternative to X-ray exposure. However, since bone deformity is what physiatrists treat and it can be seen only "from the inside", this is not possible. On the contrary, surface analysis of aesthetics, a very relevant issue for the patient, has been underestimated and not thoroughly developed.

Nevertheless, it is already possible to consider (and so it is in the everyday clinical experience of some of the authors) an everyday use of some devices and, specifically in: 1) sagittal plane deformities: there is a good correlation between the outside and inside in the sagittal plane reconstruction; as a consequence, once bone deformity has been defined with the first X-ray, patients can be non-invasively
followed-up by means of surface topography; 2) scoliosis in adulthood: this point is somehow related to the previous, since some severe progression of this condition with ageing is toward anterior trunk flexion, particularly at lumbar level. This must be carefully evaluated over time and surface topography can definitely reduce X-rays exposure; 3) spine diseases with a biomechanical pathogenesis (such as developmental spondylothesis, disc herniation, degenerative disc disease): evaluation of sagittal spine-pelvic alignment by surface topography, in addition to the radiographic evaluation of pelvic incidence, may contribute to establish appropriate treatment objectives and measure outcomes at follow-up, avoiding the need for whole spine radiography.

In other clinical situations, possible perspectives should be considered: 1) scoliosis during growth: in this field there is the clinical need of an aesthetic evaluation, which is presently almost ready to be used and spread. Another very important possible development is the 3-D evaluation: despite the evolution of radiological instruments and while awaiting for next-to-come very low dose X-ray, surface topography can presently offer less costly and invasive solutions. Hopefully, in the future, 3-D posture analysis will possibly represent a gold standard in spinal deformities evaluation, but much further research is needed; 2) back and neck pain: subgrouping the different type of pain is a hot topic for researchers. Some experiences concerning cervical spine movement analyses, also for occupational and forensic evaluations, are on the way, but not yet ready for a wide clinical application.

**Future developments**

Many specific technical approaches through different instruments have been proposed up to now for clinical measurements of spinal alignment and motion. Depending on the tool and the biomechanical model intrinsic to the clinical goal, different measurements can be obtained.

To get an effective clinical usefulness the spinal motion measurements must satisfy some basic requirements: 1) a reference range of motion or of postural attitude of healthy subjects should be provided independently of the measurement system. Comparative studies should be carried out to assess the performance of different systems. In fact, a biomechanical measurement system should be reproducible, stable (i.e., independent of personal factors), accurate, properly validated, able to distinguish between normal and pathological cases, should not impair function during measurement, provide results that have a clinical significance and have a good cost-effectiveness rate; 2) a validation work in terms of study of repeatability of measures intra-and inter observer and intersubjects should be performed for most relevant instruments and for each assessment protocol. This has been recently done for most common protocols for gait analysis providing the rate of reliability of different measurements; 3) the specificity of the measures: in order to escape from the huge amount of data produced by measuring systems, it will be necessary to identify "key parameters" that are strongly related to a specific disease. This is a relevant research activity, on which we need to concentrate our efforts to make the use of these instruments clinically helpful. The identification of "key parameters" should be based on the data we commonly evaluate by mean of observational analysis or by specific functional tests in different diseases. In this way the use of these systems may provide objective information for clinical diagnosis among different entities, in assessing the severity, extent or nature of the disease, to monitor progression associated to use or not of treatment and to measure the outcome.

**Conclusions**

Most of these instruments were born inside the specialty of Physical Medicine and Rehabilitation from the interest of clinicians for movement analysis and in the attempt of obtaining evaluation tools both for research and clinical purposes. Despite many years of researches and developments, very few tools are used today in everyday clinical practice. Given the considerations, recommendations and restrictions provided in this review, it is time for these techniques to spread out of the research laboratories and contribute to an evidence-based improvement of clinical protocols. To accomplish this ambitious goal, however, further considerable effort must be made from the clinical and biomechanical side to advance knowledge in this field, similarly to what had been successfully done with gait analysis.
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