Functional assessment of the lumbar spine through the optoelectronic ZooMS system

Clinical application

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Aim. **The radiographic method remains the main imaging technique for the physiological, anatomical and possibly pathological analysis of the spine thanks to its ease of use, precision and reliability. Despite this, the technique is inadequate for functional and dynamic studies. This paper aims to apply a dedicated noninvasive methodology based on optoelectronic techniques for the functional evaluation of the lumbar spine.**

Methods. **A reference data set for typical movements (i.e. flexion/extension, lateral bending, axial rotation) of the lumbar spine has been developed. Twenty healthy subjects have been recruited (10 males and 10 females) to create the databases of healthy subjects; one subject who suffers from lumbar spine diseases has been analyzed and his mobility has been compared to healthy subjects.**

Results. **Two databases have been created: in the former, the entire movement is normalized in time with respect to its duration; in the latter, all movements are classified in characteristic phases and each single phase is normalized to a defined duration. These databases include both the global movement of the lumbar tract of the spine and the movement of the single functional units (2 vertebrae, the intervertebral disk and the intervening surrounding soft tissues). Moreover, these databases are divided into male and female databases according to the natural differences in range of motion and pattern of movement. A clinical application for pathologic subjects is shown demonstrating the applicability and usability of this protocol.**

Conclusion. **This method allows to assess both the quality and the quantity of lumbar spine movement (both global and metameric level) of the subject and to distinguish the patient from the healthy subject.**

Key words: **Spine - Low back pain - Functional evaluation - Motion.**

In clinical medicine knowledge of the physiological, anatomical and possibly pathological characteristics of the lumbar spine of people suffering from low back pain is important for establishing the correct diagnosis and rehabilitation treatment. Clinical assessment is generally based on imaging techniques - RX, CT and MRI,[1-6] but functional analysis is arousing interest and importance because its evaluation is closer to subjective perception of pain and diseases. In fact radiological methods provide only anatomical and static information, and are generally based upon invasive techniques that do not allow frequent repetition of the examination, so limiting patient follow-up.[3, 4, 7] The result is that demand for a noninvasive alternative is really urgent. Among the functional parameters, mobility is the main one to support the physician in drawing diagnostic conclusions and identifying the rehabilitation treatment of the spine.[4, 8] Currently, the available devices are mostly based upon inclinometric technology [9-11] but they evaluate only the whole lumbar spine mobility (*i.e.* from L1 to L5) and do not

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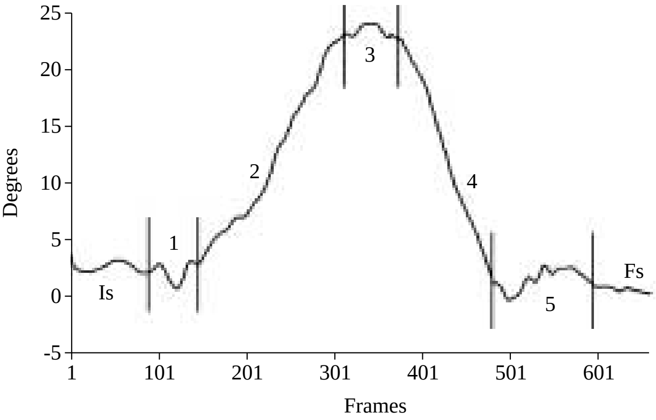

Figure 1.—Visualization of the phases of movement: Is) initial standing; 1) the preparation of the movement; 2) the forward movement; 3) the plateau; 4) the back movement; 5) the conclusion and the recovery of the erect posture; Fs) the final standing.

provide such accurate results. Moreover the device could interfere with the movement of the subject, so significantly affecting the measure and its reliability.

The optoelectronic systems for motion analysis are a valid alternative to the previous instruments. They record the position of a set of markers attached to the subject, which do not interfere with the movement.[12-16] Their noninvasive analysis is the main advantage, even if a loss of precision is intrinsic to the measurement because of the indirect assessment of the vertebral position, *i.e.* the external marking of the bone points of the spine.[17] In this frame a protocol called Zoom on Mobility of the Spine (ZooMS) was developed and validated on healthy subjects.[18, 19] It allows us to analyze the free movements of people in the 3 main body planes (sagittal, horizontal and frontal) and it assesses the mobility of the lumbar spine considering both the whole lumbar tract and each functional unit (FU: it consists of 2 vertebrae, the intervertebral disk and the intervening surrounding soft tissues: *i.e.* L4-L5) singularly. Continuing this research, this paper aims to verify the possibility of applying the protocol in clinical medicine, comparing the functionality of pathological people with the healthy subjects reference.

Materials and methods

ZooMS was implemented using an optoelectronic multicamera system for human motion analysis (EL.I.TE., BTS S.p.A. - Italy) [20] in an 8 TV-camera configuration as described in Andreoni *et al.* and validated in terms of accuracy and repeatability with good results.[19]

The experimental protocol requires the positioning of 28 markers (plastic hemispheres covered by reflecting film, 6 mm in diameter): 3 on each vertebra from the eleventh thoracic (T11) to the sacrum bone (S1) - 1 in correspondence to the spinous process and 2 geometrically on the left and right paravertebral points over the transverse processes, *i.e.* cranially on the paravertebral muscles 2 cm apart from the midline and equally distant from the 2 spinous processes - and 4 on the pelvis bone in correspondence to the superior iliac crests and the superior iliac posterior spines.

Markers were placed by clinicians or skilled operators (biomedical engineer skilled and trained to recognize the anatomical repere points by manual identification: spinous and transversal processes).

During data acquisition, the subject was asked to perform free movements in the sagittal, frontal and horizontal planes: flexion, extension, left and right lateral bending, left and right axial rotation from standing to the maximum joint excursion and back; each acquisition included the initial and final standing. All tasks were performed three times at a natural speed chosen by the subject and with a continuous pattern, *i.e.* without a break at the end of the maximum joint movement.

The 3D position of each marker was acquired at a sample rate of 100 Hz; data were then filtered (low-pass Butterworth filter with adaptive frequency in general less then 5 Hz) and processed by specifically developed software implemented in MATLAB© (The MathWorks - Natick, USA) environment to compute the variables of interest: the absolute and relative rotations and the translations of each rigid body of the biomechanical model. The trajectories of the markers were therefore the basic data to compute vertebral movement through a biomechanical model defined by the position of the 3 markers corresponding to the bone itself. The absolute angles of each FU, its pattern of movement and the range of motion (RoM) were calculated considering the Euler convention (XYZ).

The basic result of an acquisition with this protocol is the absolute movement (position and rotation) of each observed bone (vertebra) with respect to the fixed reference system of the laboratory; with this information it is possible to compute the relative mobility of 2 consecutive vertebrae (metamer) or a larger spinal tract. The movements mostly involve a

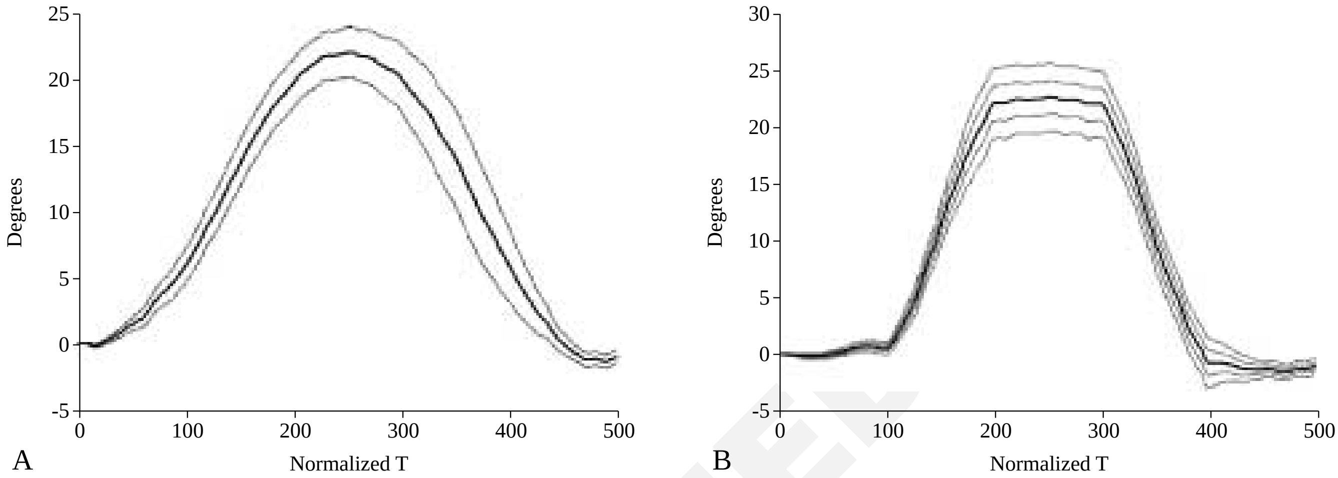

Figure 2.—Databases of healthy subjects. Relative rotation between T11 and the pelvis in the frontal plane during leftward bending: time database of healthy subjects (A), phase- database of healthy subjects (B). In the first database the 16°, 50°, 84° percentile are represented, whilst in the second one 2.5° and 97.5° percentiles are also shown.

specific axis of rotation, which defines a plane: in particular flexion and extension may be evaluated in the sagittal plane; left and right side bending in the frontal plane; left and right side axial rotation in the horizontal plane.

A pilot study was carried out to evaluate the efficacy of this protocol; 10 males (weight 72.3 ± 10.2 (SD) kg, height 175.5 ± 4.4 (SD) cm and age 27.5 ± 2.1 (SD) years) and 10 females (weight 57.3 ± 7.8 (SD) kg, height 163.7 ± 4.1 (SD) cm and age 24.8 ± 2.1 (SD) years) participated in this experimental protocol and constituted the reference population. All subjects were recruited on a voluntary basis and nobody ever reported muscle-skeletal pathologies.

The processed data have been pooled to create 2 different databases of healthy subjects; the former is based on a temporal normalization of the whole movement to 500 samples, without considering the initial and final standing: the normalization in time is necessary to allow comparison among a series of data of different length (time database of healthy subjects); the latter is created through the normalization of 5 phases to 100 frames each (phase database of healthy subjects). The 5 phases are characteristic of the pattern of movement of the subjects (*i.e.* the quality of the movement) as reported in the result section; the choice of 500 samples is arbitrary but quite adherent to the length of the movement (about 5 s equal to 500 samples with a sample rate of 100 Hz).

The motor patterns have therefore been classified according to the different phases of movement observed in the relative rotations between T11 and the pelvis, *i.e.* the limiting bones of the analyzed region.

These 2 databases have also been divided into male and female ones: this is important because gender significantly influences RoM and pattern of movement.

Databases of healthy subjects are useful for analyzing the movement of people who suffer from lumbar back pain, *i.e.* to compare the RoM and the pattern of movement of a pathological subject with respect to the healthy data. To illustrate the clinical application of this protocol, the analysis of a representative patient (age 31 years, weight 90 kg, height 180 cm), who shows a discopathy at L5-S1 level, is described. This is used only as a representative example just to verify the efficacy and the potentiality of this protocol.

Results

Patterns of movement

The data analysis of healthy subjects provides some very interesting information for clinicians. In fact the quantitative assessment of movement is clinically integrated and completed by the kinematic description of the motor pattern of how the movement is performed

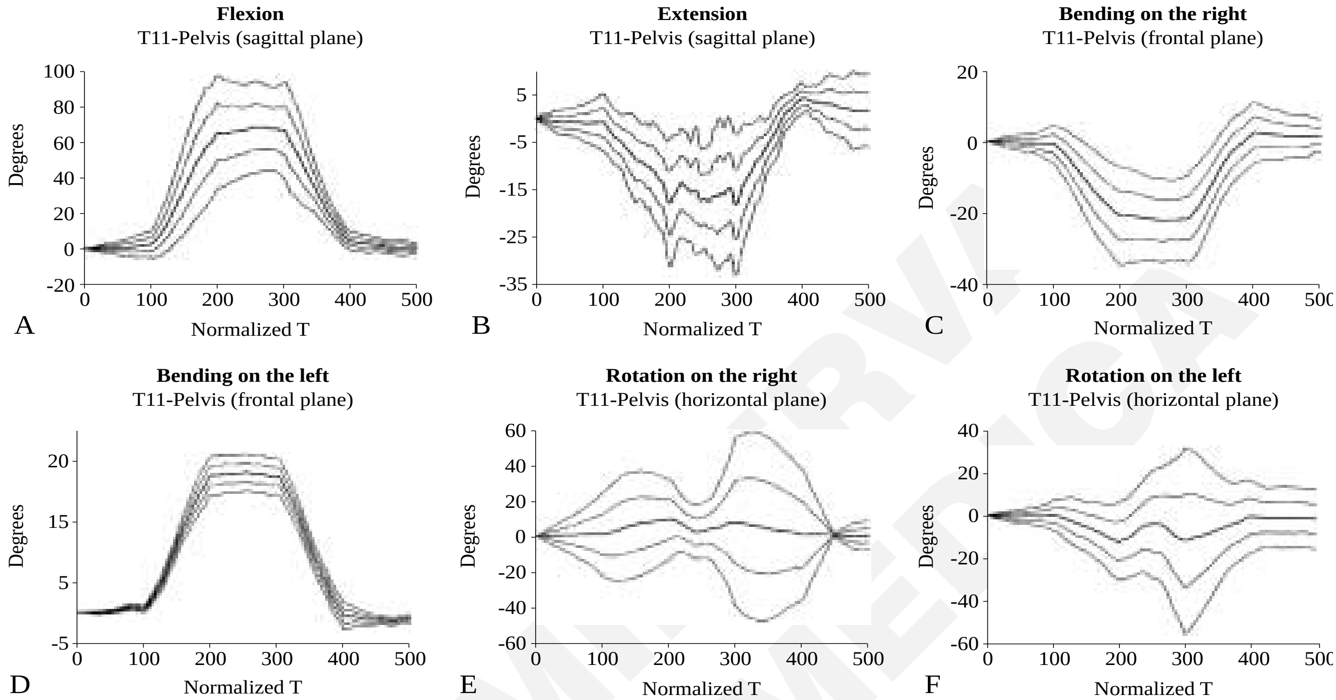

Figure 3.—Database of healthy male subjects for the global movement of flexion, extension, left and right side bending, left and right side axial rotation. Databases are normalized in the 5 phases of movement.

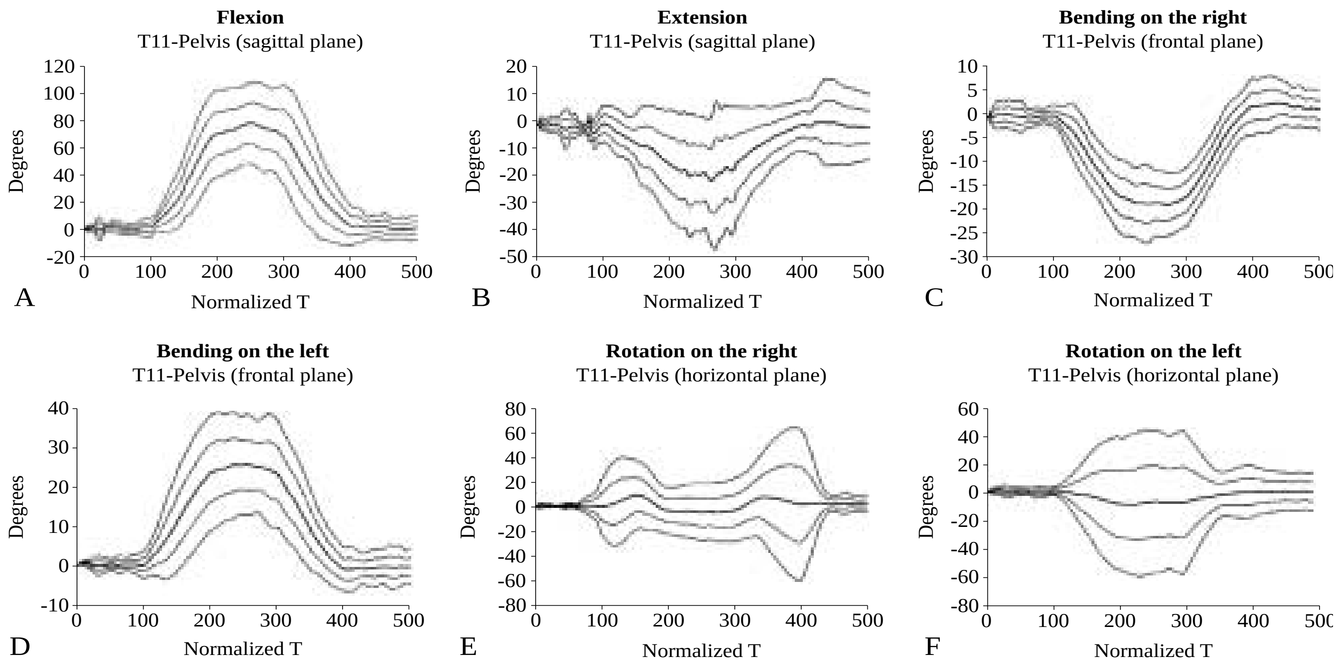

Figure 4.—Database of healthy female subjects for the global movement of flexion, extension, left and right side bending, left and right side axial rotation. Databases are normalized in the 5 phases of movement.

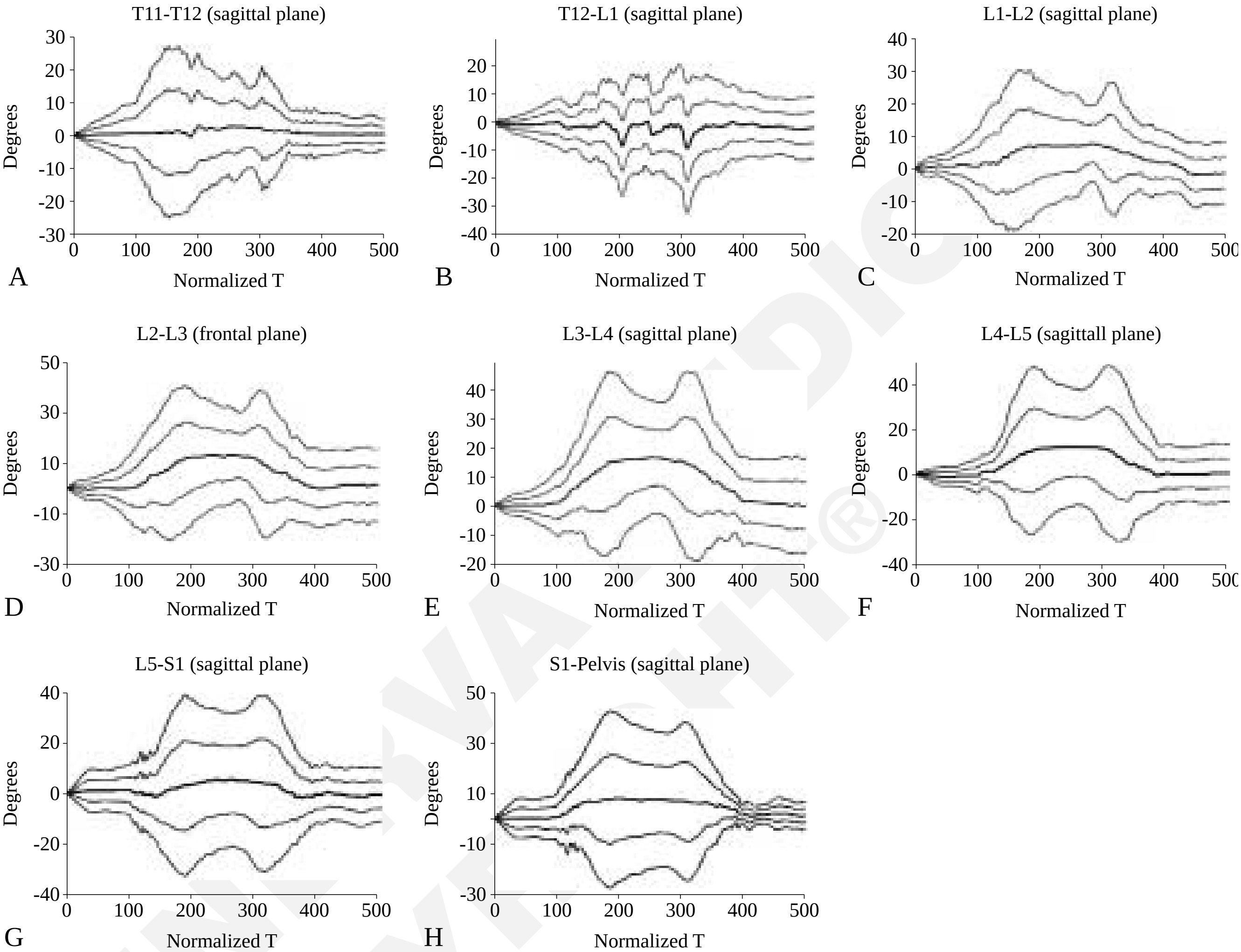

Figure 5.—Phase database of healthy subjects at the metameric level for male flexion movements.

by the subject. Thanks to that, it has been possible to identify specific phases in the execution of movements observing the relative rotations between the 2 extreme bones (T11 and pelvis). The most general and common strategy adopted by people is a five-phase movement (Figure 1): starting from the initial standing (Is) we have:

1) the preparation of the movement;
2) the forward movement;
3) the plateau;
4) the backward movement;
5) the conclusion and the recovery of the erect posture.

After the initial standing (Is), some oscillations describe the preparation of the movement (1), where acceleration and speed begin to assume non void values. The forward movement (2) is easily identified through the pronounced increase in the inclination of the curve: during this phase the acceleration is approximately null, because the movement is performed at constant speed. When the subject approaches the limit of the joint RoM, the angular speed decreases to zero: the curve of the movement becomes a nearly flat plateau (3). Then the backward movement starts with the same inclination of the angle curve with respect to the forward movement but with a decreasing pat-

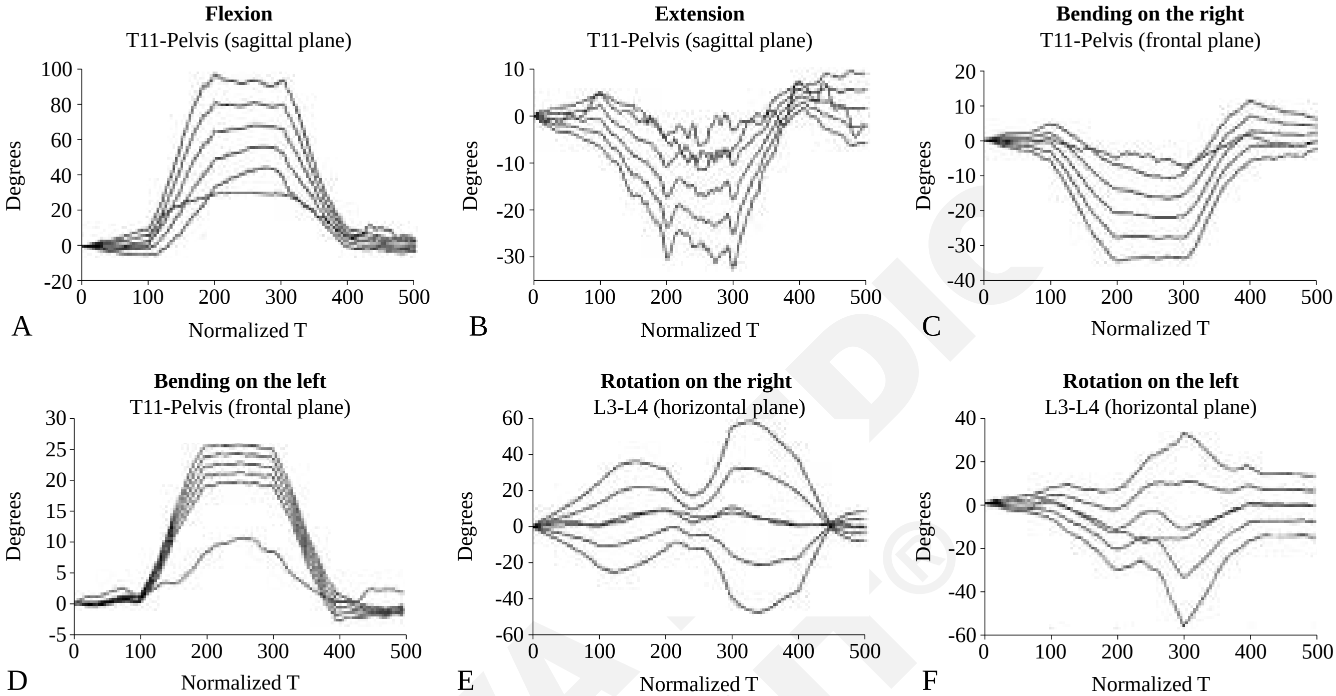

Figure 6.—Pattern of movement and range of motion of a pathological subject with respect to database of healthy male subjects for movement of flexion, extension, left and right side bending, left and right side axial rotation. The movement is normalized in the 5 phases.

tern (4). Recovery of the final standing (Fs) is only reached after the final phase of the movement (5), where oscillations are damped, because of the compensations of the inertial movements, the awareness of having almost reached or gone beyond the initial position and the wish to return with small swings. These phases are generally present in all subjects, even if different behaviors may be detected.

Databases of healthy subjects

Figure 2 shows 2 databases of healthy males concerning the relative movement T11 - pelvis during a leftward bending: the former (on the left) is the time database of healthy subjects, the latter (on the right) is the phase database of healthy subjects.

In the following paragraphs only the phase databases of healthy subjects for typical movements (flexion, extension, bending and rotation) are presented. This decision was made because these databases are more useful for comparing pathological mobility with respect to healthy patterns, as described later. Figure 3 and Figure 4 show the phase databases of healthy males and females for the global movement (T11-pelvis).

Close to the global evaluation of the lumbar spine, FU assessment of rachis movement plays an important role in characterizing and selectively identify the local mobility of each metamer. In Figure 5 the phase database of healthy subjects concerning all the FU for male flexion movement is shown.

Application of ZooMS protocol to a pathological subject

In the analysis of the pathological subject, data show a meaningful reduction in the mobility of the lumbar spine in the sagittal and frontal plane. In fact the most compromised movements are flexion-extension and left and right side bending.

In particular global flexion mobility is around 25°, a lower value with respect to the healthy male RoM (about 60°). Also the extension seems to be compromised even if the movement is not so limited as flexion.

As for lateral bending, the subject performs small

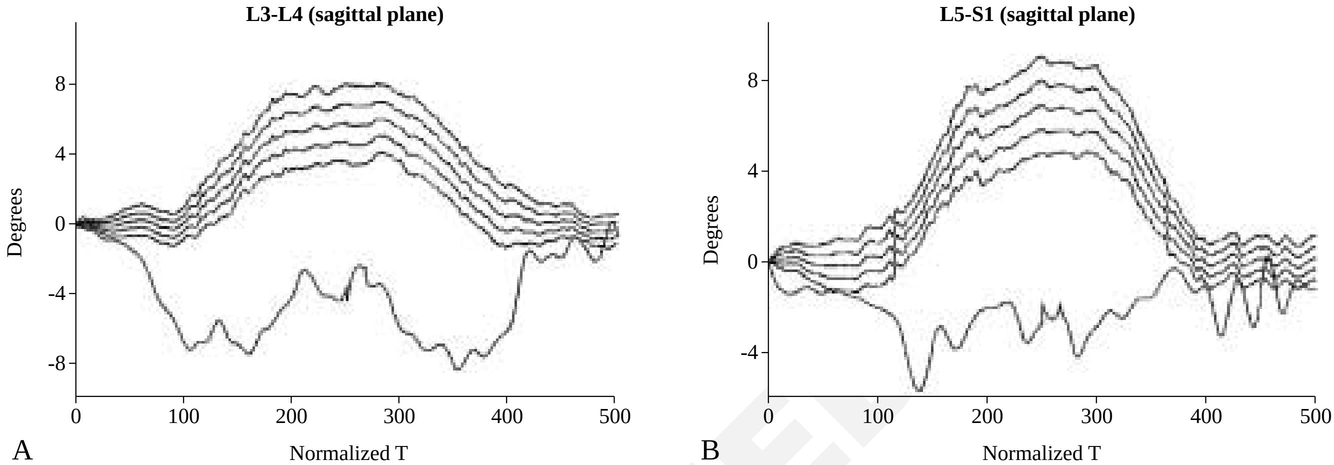

Figure 7.—Example of functional limitation of rightward bending movement on the L3-L4 (on the left) and L5-S1 (on the right) FUs.

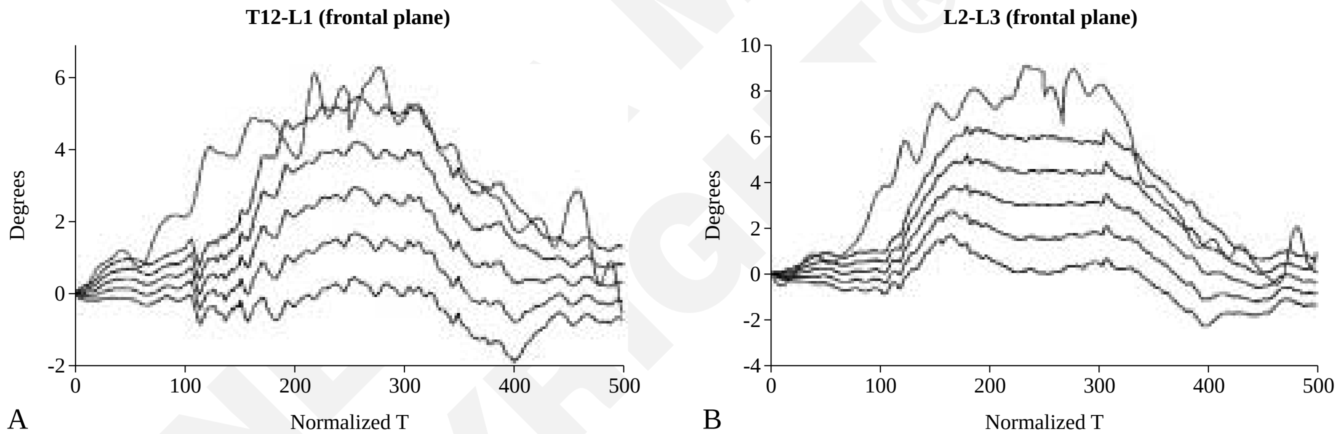

Figure 8.—Example of functional recovery of rightward bending movement on the T12-L1 (A) and L2-L3 (B) FUs.

RoMs on both the left and right side: the reduction is about 50% with respect to healthy subjects; this limit is most pronounced on right side bending.

The axial rotations, on the other hand, are similar to databases of healthy subjects with a slight alteration in normal strategy in the left side rotation (Figure 6).

FU analysis underlines that the most involved metamers in the functional limitation of flexion movements are L3-L4 and L5-S1, as shown in Figure 7. Moreover a compensation with a hypermovement can be observed in comparison to the normal one in T12-L1 and L1-L2 districts, above all for bending tasks (Figure 8). This is probably due to an attempt by the subject to recover his whole mobility, increasing the RoM of sound regions of the lumbar spine.

Discussion and conclusions

Nowadays, the radiographic method remains the principal source of information for the analysis of the spine thanks to its easiness, precision and reliability. Despite this, the technique is inadequate for functional and dynamic studies.

The spine mobility considered in terms of both quantity and quality has recently been introduced into clinical practice for a more complete evaluation.[2, 3, 7, 10, 21, 22] A lot of researches have been carried out mainly through radiographic investigations; for instance, in subjects affected by serious spinal pathologies, dynamic radiographies are commonly used, but these are limited to analyzing the positions assumed by the subject at the beginning and at the end of the movement, so losing the functional information on the pattern of the movement. This limit can be overcome using cine-radiographic methods that, however, are made highly invasive by the massive usage of X-rays.

On the contrary, noninvasive methods prove not to be sufficiently accurate, not to allow free movements, not to provide FU assessment, and not to allow routine everyday use. Therefore, from a scientific point of view, despite all these efforts no conclusive data on living subjects are available in literature either for the metameric movements or for the modification of the RoM due to age or pathology.

The method here presented, ZooMS, is based on the optoelectronic technique and on a simple and repeatable protocol. The most important advantages of ZooMS are to be noninvasive and dynamic so allowing them to be frequently used (when required), *i.e.* in clinical applications this protocol could be useful for evaluating the follow-up of rehabilitation treatment. ZooMS represents the first noninvasive structured systematic approach to evaluate the vertebral mobility in the single FU and considers the free natural strategy of the execution of movements. Its application requires a system for human motion analysis, but its relative simplicity (studied in close connection with the clinicians) makes it suitable for daily use in clinical practice. Moreover RoM gives quantitative and qualitative results which reflect the subjectivity of people in executing the movement: in fact the analysis consists of the evaluation of simple, free and usual movements of subjects without any constraints so as to better analyze the common movements daily performed by people. Another positive characteristic is the 3D assessment of the spinal movements considering all the contributions to the motion by each rotation axis (principal and secondary). This is surely an innovation with respect to any other previous reported methods.

This protocol is already validated on a sample of healthy people [18, 19] with successful results in terms of accuracy and repeatability.

Also the information related to patterns of movement is a fundamental and innovative outcome of ZooMS methodology; it could be very useful for clinical diagnosis and, in fact, it can evidence the limitations and strategies adopted to compensate for the functional limitations in the execution of the movements.

The informative content of the motor patterns is preserved in time databases of healthy subjects, as shown in Figure 2; in fact it is possible to distinguish the strategy adopted not only by observing if the subject respects the classical sequence of phases, but also its speed of execution. On the contrary, the phase database of healthy subjects completely looses this information concerning the motor strategy, but lets the clinician analyze in detail behavior during every single phase and makes it possible to compare mobility quantitatively. In fact, the main advantage of this second database consists in the computation of the RoM; in fact the high dispersions caused by the different duration of the phases are removed, and small standard deviations are obtained with respect to the time normalized database. All things considered, only 64% of the population (percentile ranges from 16° to 84°) are represented in the time databases of healthy subjects, whilst in phase databases of healthy subjects 95% of population are shown (percentile ranges from 2.5° to 97.5°).

Here we have presented some results of this protocol and its application in the analysis of the global and metameric movement of the lumbar spine of a pathological subject.

This method enables us to assess both the quality and the quantity of movement of the subject in a precise and accurate way and to discriminate a patient from healthy, also characterizing the most affected FUs and FUs where a recovery of motor ability is present.

With respect to the radiographic methods, ZooMS combines and balances the absolute noninvasive approach with quite high accuracy (this last characteristic is due to the indirect assessment of the movement through superficial anatomical points) and allows for frequent exam repetition during treatment and follow-up; with respect to the other noninvasive methods it also offers the possibility to assess the single FU contribution as well as complete spine mobility.

In the near future, ZooMS protocol is to be applied to the evaluation of rehabilitative treatment for pathological people who suffer from lumbar spine diseases for a customized approach to therapy and follow-up. In fact the results are based on an easy, low-cost and above all noninvasive analysis which may be repeated several times during the clinical rehabilitation to evaluate its efficacy.

Finally this method may be easily applied to the study and modeling of the whole spine. A pilot study of the mobility of the cervical spine has already been developed in our laboratory with promising preliminary results.[23]

References

1. Begg CA, Falconer MA. Plain radiography in intraspinal protrusion of lumbar intervertebral disk: a correlation with operative findings. Br J Surg 1949;36:225-39.
2. Cholewicki J, McGill SM, Wells RP, Vernon H. Method for measuring vertebral kinematics from videofluoroscopy. Clin Biomech 1991;6:73-8.
3. Pearcy M, Portek I, Shepherd J. The effect of low back pain on lumbar spinal movements measured by three dimensional X-ray analysis. Spine 1985;10:150-3.
4. Tallroth K, Alaranta H, Soukka A. Lumbar mobility in asymptomatic individuals. J Spinal Disord 1992;5:481-4.
5. McGregor AH, Anderton L, Gedroyc WM, Johnson J, Hughes SP. Assessment of spinal kinematics using open interventional magnetic resonance imaging. Clin Orthop Relat Res 2001; (392):341-8.
6. Miyasaka K, Ohmori K, Suzuki K, Inoue H. Radiographic analysis of lumbar motion in relation to lumbosacral stability. Investigation of moderate and maximum motion. Spine 2000;25:732-7.
7. Putto E, Tallroth K. Extension-flexion radiographs for motion studies of the lumbar spine. Spine1990;15:107-10.
8. Waddell G, Somerville D, Henderson I, Newton M. Objective clinical evaluation of physical impairment in chronic low back pain. Spine 1992;17:617-28.
9. Keeley J, Mayer TG, Cox R, Gatchel RJ, Smith J, Mooney V. Quantification of lumbar function. Part 5: Reliability of range-of-motion measures in the sagittal plane and an *in vivo* torso rotation measurement technique. Spine 1986;11:31-5.
10. Mayer TG, Tencer AF, Kristoferson S, Mooney V. Use of noninvasive techniques for quantification of spinal range of motion in normal subjects and chronic low back dysfunction patients. Spine 1984;9:588-95.
11. Saur PM, Ensink FB, Frese K, Seeger D, Hildebrandt J. Lumbar range of motion: reliability and validity of the inclinometer technique in the clinical measurement of trunk flexibility. Spine 1996;21:1332-8.
12. Assente R, Ferrigno G, Pedotti A, Santambrogio GC, Viganò R. AUSCAN System: a new procedure to evaluate spinal deformity. In: Jonsson B editor. Biomechanics X A. Champaign, IL: Human Kinetic Publish; 1987. p. 207-11.
13. Assente R, Ferrigno G, Pedotti A, Santambrogio GC, Viganò R. AUSCAN System: technological features of the new 3-D version. In: Alberti A, Drerup B, Hierholzer E editors. Surface topography and spinal deformity. Stuttgart: Gustav Fischer Verlag Publish; 1987. p. 395-401.
14. Esola MA, McClure PW, Fitzgerald GK, Siegler S. Analysis of lumbar spine and hip motion during forward bending in subjects with and without a history of low back pain. Spine 1996;21:71-8.
15. Gill K, Krag MH, Johnson GB, Haugh LD, Pope MH. Repeatability of four clinical methods for assessment of lumbar spine motion. Spine 1988;13:50-3.
16. Porter JL, Wilkinson A. Lumbar-hip flexion motion. A comparative study between asymptomatic and chronic low back pain in 18- to 36-year-old men. Spine 1997;22:1508-14.
17. Leardini A, Chiari L, Croce UD, Cappozzo A. Human movement analysis using stereophotogrammetry. Part 3. Soft tissue artifact assessment and compensation. Gait Posture 2005;21:212-25.
18. Andreoni G, Negrini S, Mazzoleni P, Ciavarro GL, Santambrogio GC, Pedotti A. ZooMS: a non invasive analysis of global and metameric movement of the spine. Proceedings of the 2nd European and Biological Engineering Conference, 2002; December 4-8, Vienna, Austria.
19. Andreoni G, Negrini S, Ciavarro GL, Santambrogio GC. ZooMS: a non invasive analysis of global and metameric movement of the lumbar spine. Eura Medicophys 2005;41:7-16.
20. Ferrigno G, Pedotti A. A digital dedicated hardware system for movement analysis via real-time TV signal processing. IEEE Trans Biomed Eng 1985;32:943-50.
21. McGregor AH, McCarthy ID, Hughes SP. Motion characteristics of the lumbar spine in the normal population. Spine 1995;20:2421-8.
22. White AA 3rd, Panjabi MM. Clinical biomechanics of the spine. Philadelphia: J.B. Lippincot Company; 1990.
23. Ciavarro GL, Colombo S, Curami M, Andreoni G, Santambrogio GC. Functional analysis of the cervical spine mobility in people with whiplash syndrome. Proceedings of the Mediterranean Conference on Medical and Biological Engineering, 2004 July 31-August 15, Isle of Ischia, Naples, Italy.