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ULTRASOUND-BASED SPINAL COLUMN EXAMINATION SYSTEMS

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Attila Zsidai, László Kocsis

Budapest University of Technology and Economics
Faculty of Mechanical Engineering
Department of Applied Mechanics, Biomechanical Laboratory
E-mail: kocsis@mm.bme.hu

Abstract: *Nowadays there is an increasing tendency for spreading modern ultrasound-based spine investigation systems supplementing traditional spine examination methods including X-ray scans, magnetic resonance investigations (MRI), and computer tomography (CT) scans. Their operation is based on the characteristic features of the propagation of ultrasound; therefore they do not load the human organism by harmful radiation. The new systems are mobile; they are also suitable for examining the mobility and loadability of the spine besides its structure. Furthermore, they can be complemented by other investigations such as sole pressure distribution, enabling the investigation of the interaction of several diseases. In present-day medical practice, ocular inspection and traditional diagnostic tests including X-ray, CT, and MRI are available for disclosing spinal diseases and deformations, the application of which depends on the severity of the illness and hospital conditions. These investigations result in the 2D (X-ray) or 3D (MRI, CT) image of the spine. It is time-consuming to process the results, and the harmful effects of the radiation load affecting the body are well known. Unfortunately, it is a further disadvantage that the patient has to stay still during screening, which is not always feasible and the resulting inaccuracies are difficult to correct. Nevertheless, it should be emphasized that these types of tests are indispensable for mapping up the entire shape of the spine. Several conceptions have been realized in practice to eliminate the disadvantages of common diagnostic procedures besides retaining their benefits. The joint objectives of tools and procedures are to increase accuracy, to achieve simpler and quicker usability, to provide additional information, to ensure reproducibility, and to avoid harmless radiation.*

Key words: *spine, ultrasound, motion analysis, X-ray, MRI, CT*

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1. INTRODUCTION

Nowadays there is an increasing tendency for spreading modern ultrasound-based spine investigation systems supplementing traditional spine examination methods including X-ray scans, magnetic resonance investigations (MRI) (Bauer, Harland, & Krappel, 2001), and computer tomography (CT) scans. Their operation is based on the characteristic features of the propagation of ultrasound; therefore they do not load the human organism by harmful radiation. The new systems are mobile; they are also suitable for examining the mobility and loadability of the spine besides its structure. Furthermore, they can be complemented by other investigations such as sole pressure distribution, enabling the investigation of the interaction of several diseases.

In present-day medical practice, ocular inspection and traditional diagnostic tests including X-ray, CT, and MRI are available for disclosing spinal diseases and deformations, the application of which depends on the severity of the illness and hospital conditions.

These investigations result in the 2D (X-ray) or 3D (MRI, CT) (Bergmann, Harrison, Kulig, & Powers, 2003) image of the spine (Figure 1). It is time-consuming to process the results, and the harmful effects of the radiation load affecting the body are well-known. Unfortunately, it is a further disadvantage that the patient has to stay still during screening, which is not always feasible and the resulting inaccuracies are difficult to correct. Nevertheless, it should be emphasized that these types of tests are indispensable for mapping up the entire shape of the spine (Asamoah, Klöckner, Mellerovitz, & Venus, 2000).

Fig. 1. Results of traditional diagnostic tests

Several conceptions have been utilized in practice to eliminate the disadvantages of common diagnostic procedures besides retaining their benefits. The joint objectives of tools and procedures are to increase accuracy, to achieve simpler and quicker usability, to provide additional information, to ensure reproducibility, and to avoid harmless radiation.

The first – and perhaps most widely spread – new type of diagnostic tool is the *triflexometer* (Figure 2), consisting of rollers. The triflexometer provides a distance-angle data pair to the processing unit at each 0.25 mm when driven along the line of the spine. The shape of the spine is displayed by converting the values of path and angle into mathematical functions. Benefits include a simple structure and being easy to use. A disadvantage is the difficulty of the mathematical processing of the angle-path data pair, therefore the inaccuracy of the system will increase. This tool does not provide any information on the structure and deformations of vertebrae.

Medimouse (Figure 3) is theoretically similar in structure: the position of the "mouse" is specified using the signals emitted by the ultrasound beacon installed on it. A common feature of these tools is that the segments of the spine are in contact with a surface – the surface of cylinders – (surface to surfact contact), which may distort measurement results. The shape of the spine is easy to specify, but the tool is not suitable for more accurate tests. It is excellent for screening tests (Seichert, & Senn, 2002).

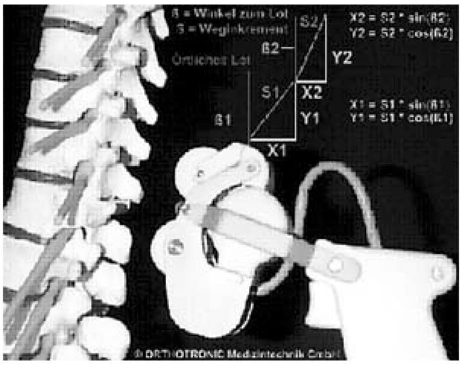

Fig. 2. Triflexometer

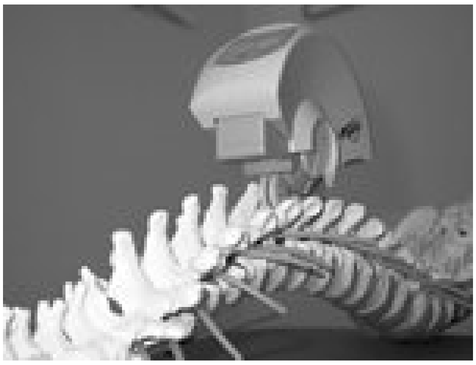

Fig. 3. Medimouse

2. Subjects and Methods

At the Biomechanical Laboratory of the Department, 52 patients have been examined so far by a new method still unique both in Hungary and in Europe. Subjects included both healthy people and patients with various spinal complaints (Scheuermann disease, Scoliosis). Test persons included 36 females and 16 males: 10 of them healthy, 26 with Scheuermann disease, and 16 scoliotics, with an average age of 14±3 years, height of 166±14cm, body weight of 49±13 kg. The patients undergo controls every four months in general, which ensures the traceability of various stages of recovery (Kocsis, Körmendi, Viola, & Zsidai, 2002).

Benefits of the CMS-HS system include more accurate processing of results, more widespread applicability, and compatibility with other products by the manufacturer (e.g. sole pressure distribution tests). System operation is based on the exploitation of ultrasound propagation characteristics. The WinSpine spine test module available at the Department, running in a Windows environment, is a program package of simple and logical structure.

The system consists of two basic units: 3 ultrasound beacons and ultrasound sensors, that is, microphones. The beacons constitute a plane. Three vectors are required to specify the spatial position of the microphones, meaning that the signals emitted from the beacons define the position of the microphones by the method of triangulation (Figure 4). Three signal sources can identify the position of the microphones with an accuracy of a tenth of a millimetre based on the following formulae (Jurák, Kiss, Knoll, & Kocsis, 2003):

$$Y = \frac{(d_1^2 - d_2^2)}{4 \bullet a}; \quad Z = \frac{(d_3^2 - 0{,}5 \bullet (d_1^2 + d_2^2) + a^2 - b^2)}{2 \bullet b}; \quad X = \sqrt{(d_1^2 - (Y+a)^2 - Z^2)}$$

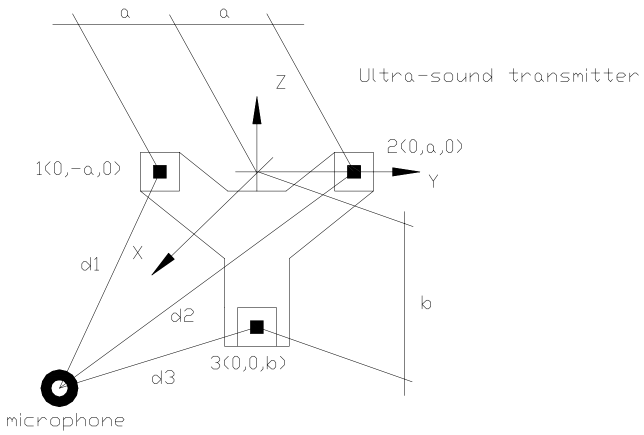

Fig. 4. Identifying the position of microphones

As a first step, a microphone was fastened to each vertebra in order to specify the shape of the spine. In the initial state, the shape of the spine can be determined accurately, but in the course of the movement of the trunk the microphones move together with the skin, rather than the vertebrae, therefore measurement information will not be accurate. It is difficult to exclude skin movements mathematically. Another arrangement yielded better results, where a reference microphone was placed on the sacrum of the patient and the position of each point of the spine and the required anatomical points were specified by a pointer (the pointer is an accessory; it has two ultrasound microphones installed, whereby the position of any anatomical points of the human body can be specified – Figure 5). The position of the pointer and thereby that of the respective anatomical point can be specified unambiguously by the two microphones installed:

$$\underline{R}_p = \underline{R}_{S1} + \frac{(a+b)}{a} \bullet (\underline{R}_{S2} - \underline{R}_{S1})$$

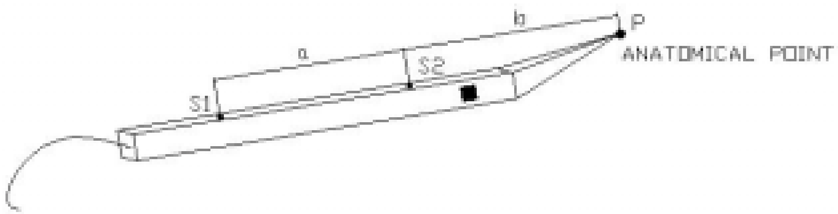

Fig. 5. Identifying the position of anatomical points using the pointer

Investigation of spinal structure: In the course of the test, the patient does not wear any clothing on the trunk; a reference microphone is fastened on the sacrum (Kaduna, McClure, & Michener, 2000). The doctor specifies the position of the processus spinosus of each vertebra using the pointer (Figure 6). He simply touches the pin of the pointer to the processus spinosus and fixes the position of the anatomical point by pushing the button on the pointer (Cholewicki, Radebold, & Siomons, 2000). In the course of the test, the patient has to assume various postures, and the position of the processus spinosus of the vertebrae is specified in each of these postures. The shape of the spine can be specified from three directions by a single measurement (Dvorak, Klein, Lanz, & Mannion, 2000).

Fig. 6. Test

Investigation of the mobility of the spine: The patient wears two sensors (groups of three microphones, that is, triplets) on the spinal section intended to be examined (Figure 7) and repeats three movements 10 to 15 times: leaning forward and backward, twisting the trunk, and bending the trunk (Badtke, Bittman, Kittel, & Luther, 2002). The microphone triplets are fixed as rigid bodies compared to the spine, therefore their displacement corresponds to the displacement of the spine, so skin movements can be eliminated (Kocsis, Körmendi, Viola, & Zsidai, 2003).

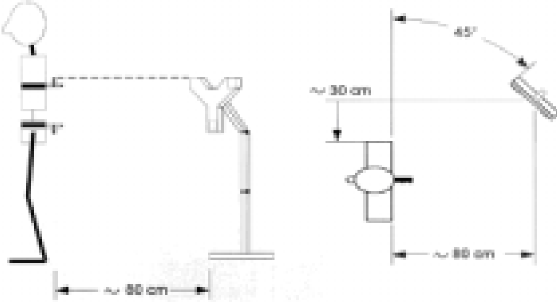

Fig. 7. Theoretical arrangement of the test

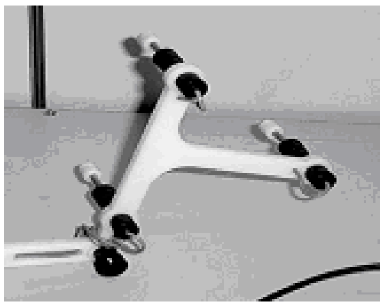

Fig. 8. Triplet

2.1 Parameters

Based on these two diseases, the following mechanical parameters can be defined in order to characterize illnesses (Csizmadia, & Nádori, 1997):

Relative angle: turn of two vertebrae compared to each other.

Cobb degree: Serving to measure the degree of bend on the postero-anterior X-ray shot and defined by drawing an intervertebral line above and below the bend, respectively, where the intervertebral spaces are already parallel, and then drawing a perpendicular thereto. The Cobb degree will be the angle enclosed by the two perpendiculars.

Movement function: the r = r(t) vector-scalar function, specifying the actual position of the material point.

Velocity function: the first derivative of the r = r(t) vector-scalar function (that is, the movement function) according to time is $v(t) = \frac{dr(t)}{dt}$. The value assumed at any moment is the actual velocity.

Angular velocity: $\omega = \frac{d\phi}{dt} = \dot{\phi}$ change in time of the polar angle φ. That is, angular velocity can be defined as a vector.

3. Results and Discussion

The primary objective of the investigations is to familiarize with the system, to map up the opportunities provided by the system. Spinal movements with scoliotic patients (Table 1): New information is provided by dorsal and lumbar spine investigations performed in several planes and separately (Vízkelety, 1994). Spinal (both dorsal and lumbar) extension increases. Deflection of the dorsal spine to the right is reduced in the sagittal plane and increased in the rotational plane to the left; deflection thereof to the left is increased in the sagittal plane and decreased in the rotational planes. Deflection of the lumbar spine to the right is reduced in every plane; deflection to the left is decreased in rotation to the left and increased in rotation to the right. Analysis in the rotational planes yields different results from those in a purely sagittal plane. Scoliotic spines are unstable in every plane.

Table 1. Spinal movements in AIS

Flexion-extension (degrees)												Deflection (degrees)											
Dorsal spine						Lumbar spine						Dorsal spine			Lumbar spine			Dorsal spine			Lumbar spine		
flexion			extension			flexion			extension			right deflection						left deflection					
S	JR	BR	S	JR	BR	S	JR	BR	S	JR	BR	S	JR	BR	S	JR	BR	S	JR	BR	S	JR	BR
13	–4	4	5	10	1	30	23	30	7	10	7	7	11	25	7	2	–1	27	30	6	12	16	10
32	25	14	2	12	12	45	30	32	27	8	4	27	11	17	10	13	15	22	41	18	11	10	18

Rotation (degrees)			
Dorsal spine		Lumbar spine	
J	B	J	B
25	34	17	12
28	25	18	13

Legend: S: sagittal plane; JR: right rotational plane; BR: left rotational plane
Upper data: AIS; Lower data: healthy
J: right; B: left

Spinal movements at Scheuermann patients (Table 2): Dorsal spine flexion and extension are reduced both in the sagittal and the rotational planes. Our general perception is that the movement path of the spine is narrowed down in the sagittal plane, except for an increasing ability to lean to the left. Rotation is decreased to the right and increased to the left on the dorsal spine. Movements already show differences in rotational planes. On the dorsal spine, right deflection decreases in rotation to the right and increases in rotation to the left; left deflection decreases in the rotational planes of both directions. Right deflection of the lumbar spine is reduced in rotation to the right and increased in rotation to the left; left deflection thereof increases in rotation to the right and decreases in rotation to the left. In the rotational planes, a spine with Scheuermann disease is unstable. Increasing left deflection in the "stable" sagittal plane explains that scoliosis associated with SD is mainly characterized by bending to the left.

Table 2. Spinal movements in SD

Flexion-extension (degrees)												Deflection (degrees)											
Dorsal spine						Lumbar spine						Dorsal spine			Lumbar spine			Dorsal spine			Lumbar spine		
flexion			extension			flexion			extension			right deflection						left deflection					
S	JR	BR	S	JR	BR	S	JR	BR	S	JR	BR	S	JR	BR	S	JR	BR	S	JR	BR	S	JR	BR
28	10	10	–4	–4	8	38	30	30	–4	–4	8	22	4	31	8	9	21	28	20	–3	11	14	5
32	25	14	2	10	12	45	30	32	4	8	4	27	11	17	10	13	15	22	41	18	11	10	18

Rotation (degrees)			
Dorsal spine		Lumbar spine	
J	B	J	B
24	36	17	12
28	25	18	13

Legend: S: sagittal plane — Upper data: AIS — J: right
JR: right rotational plane — Lower data: healthy — B: left
BR: left rotational plane

Scoliosis symptoms: The spine deflects laterally; there is a rib hump on the back; the trunk is asymmetrical; and the movement of the spinal section affected is reduced. Scoliosis means the lateral deflection of the spinal column accompanied by torsion. As a consequence of torsion, a rib hump is developed on the convexity side. Lateral deflection can be associated with humpback, a breakage of the dorsal bend of the spine, as well as the spinal column leaning forward.

Symptoms of the Scheuermann disease: Increased dorsal hump, breakage of the dorsal bend, or flattened lumbar bend forward; limited movement of the spinal section, spontaneous pain, fatigability, sensitivity to pressure may be generated.

The current phases of the investigations can be traced on the monitor continuously (on-line); and the results can be promptly viewed and analysed in the Report function (Figure 9). The first part of measurement results shows the structure of the spine from various directions, containing the angular deviations of vertebrae compared to each other; the data measured can be compared to average values on the diagrams.

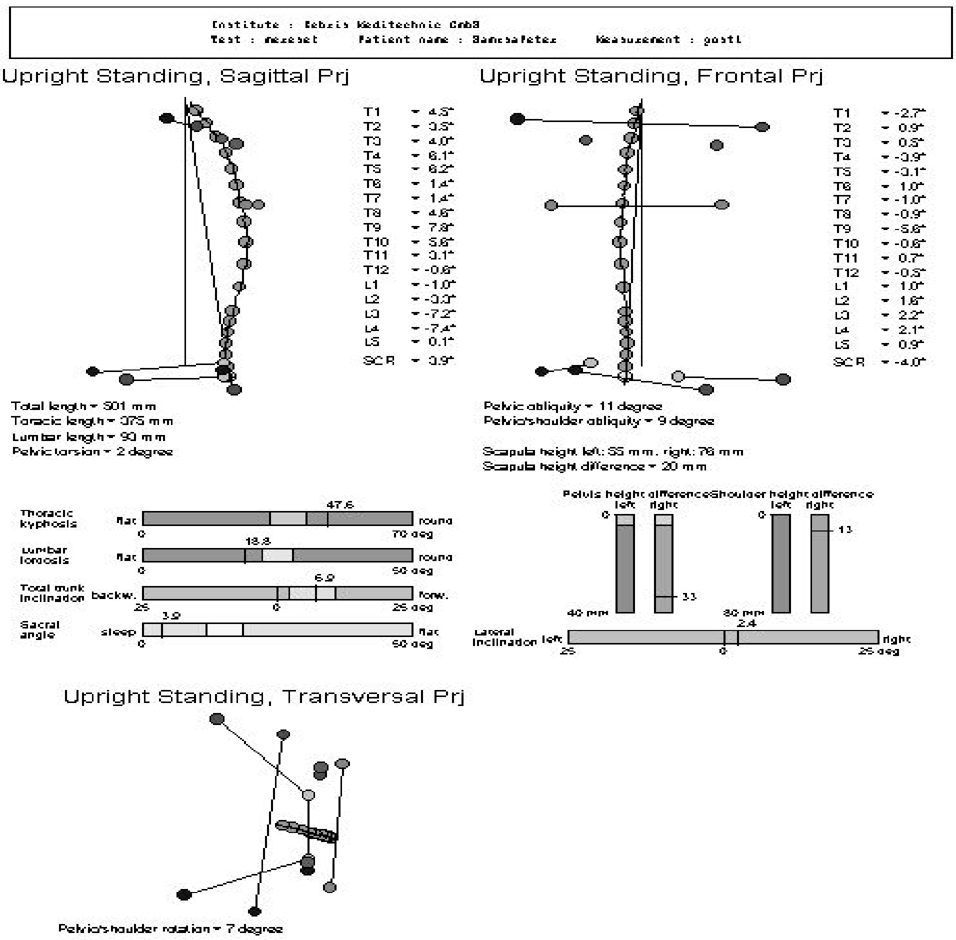

Fig. 9. Measurement results of the shape of the spine

It should be mentioned as a major deficiency that the degree of spinal disorders is not measured in Cobb degrees used in traditional medical practice. Therefore supplementary software was developed at the Department to define the missing data (Figure 10).

Mobility test results show the extreme values of various movements (leaning forward and backward, twisting the trunk, and bending the trunk), compared with ideal values. Velocity - angular velocity diagrams are circular - progressing along a single track - in the case of healthy people. The radii of the circular diagrams refer to the limitations of movements (Figure 11).

Movement curves can be specified in the function of time; reproducibility of movements in the case of several measurements (Figure 12).

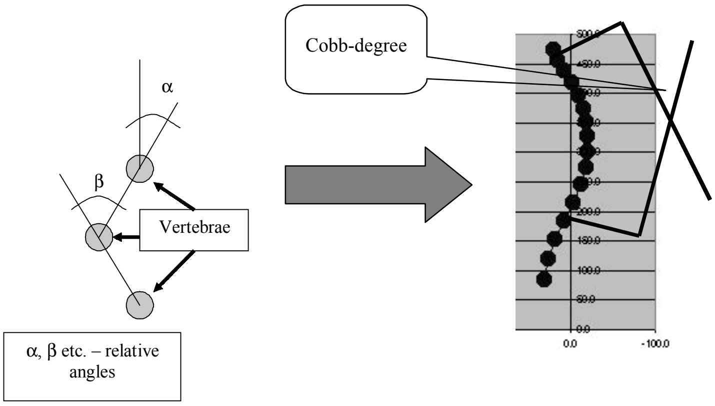

Fig. 10. Determination of the Cobb degree

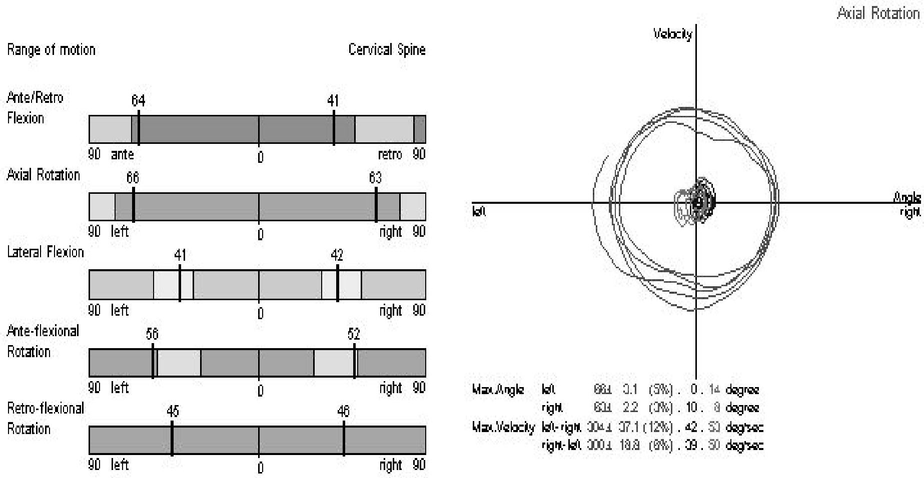

Fig. 11. Comparison of the actual and ideal values of movements; the velocity – angular velocity diagram.

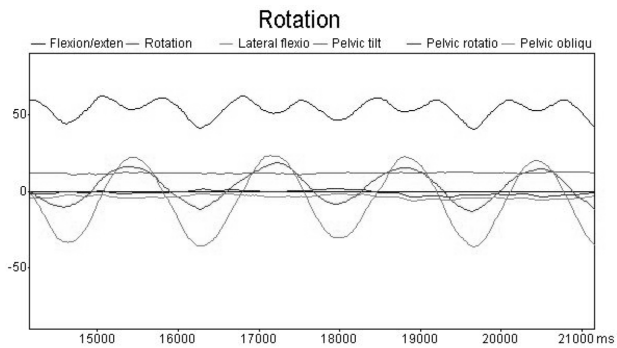

Fig. 12. Movement curves

4. CONCLUSIONS

A major benefit of the system is that the tools make it possible to check the design and fitness for proper use of the corsets individually prepared for patients, which has not been enabled by other systems so far. The suitability of corsets can be characterized by numerical data.

Moreover, measurements can also be complemented on the basis of individually customized conceptions. Using such supplements, the everyday loads and movements of the spine can be modelled. As each of the patients were schoolchildren, the tests were performed with a schoolbag in both hands to study the impact of schoolbags on the spine (Figure 13). It was identified how each of the patients carry their schoolbags in order to load their spine to the least possible degree; in some cases, passive correction was also managed to be achieved (Bender, 1999).

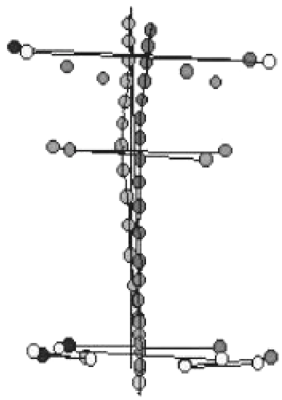

Fig. 13. Position of the spine in the case of standing upright and holding a schoolbag in the right hand

Traditional examination procedures – X-ray, CT and MRI – cannot be replaced by new procedures. New procedures do not provide any information on the accurate location of the spine within the body. As opposed to traditional methods, they do not load the human body with harmful radiation. Measurements can be repeated at optional intervals; tracing as well as the comparison of measurement results prove to be much simpler. They are not only suitable for static examinations: they provide opportunities for determining the mobility of the spine as well, and they can be supplemented individually. The 3D ultrasound device can map up the real topography and the entire movement track of 3D deformations. The system is suitable for being linked with other investigations (gait analysis, electromyography) Tests can be really performed in 3D, and measurements can be made in lifelike movement circumstances. It is suitable for research and diagnostics purposes based on our series of measurements; it provides new information (Cholewicki, Polzhofer, & Radebolt, 2000).

Due to the size of the tools, measurements can be performed anywhere, in a rapid and simple manner, providing perfect opportunities for screening tests. Their application is reasonable in rehabilitation, orthopaedics, rheumatology, traumatology, sports therapeutics, school and industrial medical practice, ergonomy, fitness centers, and first class sports as well (Banzer, & Vogt, 1999). Further advantages include the fine reproducibility of examinations, IT compatibility, and an excellent service background. Their spread may be hindered by high investment costs (Kingma, & Van Dieën, 1999).

The main objective of our investigations is to test a complete screening and control examination system and prepare it for implementation in everyday medical practice. In the course of cooperation with outpatient clinics and universities of medical sciences, tests and the system are continued to be developed.

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ISTRAŽIVANJA KIČMENOG STUBA BAZIRANA NA ULTRAZVUKU

Attila Zsidai, László Kocsis,

U današnje vreme postoji povećana tendencija za širenje modernih sistema za istraživanje kičme baziranih na ultrazvuku, kao dopuna tradicionalnim metodama pregleda kičme, uključujući i skeniranje X-zracima, istraživanje magnetnom rezonancom (MRI) i skeniranjem kompjuterskom tomografijom (CT). Taj rad je baziran na karakterističnim obeležjima širenja ultrazvuka, jer on ne opterećuje ljudski organizam štetnom radijacijom. Novi sistemi su mobilni i pogodni za ispitivanje opterećenosti kičme bez obzira na strukturu. U savremenoj medicinskoj praksi, vizuelni pregled i tradicionalni dijagnostički testovi uključujući X-zrake, CT i MRI su dostupni za otkrivanje bolesti i deformacija kičmenog stuba. Rezultati istraživanja su 2D (X-zraci) ili 3D (MRI, CT) slike kičme. Treba dosta vremena da se rezultati obrade, a i postoje štetni efekti radijacijskog opterećenja, što je poznato. Na žalost, još jedna mana ovih metoda je što, tokom skeniranja, pacijent mora da ostane miran, što nije uvek moguće, pa verovatni pogrešni podaci se teško ispravljaju. Ipak, treba naglasiti da su ovi tipovi testova preko potrebni za beleženje čitavog oblika kičme. Realizovano je nekoliko koncepcija da bi se eliminisale mane uobičajenih dijagnostičkih procedura, uz zadržavanje njihovih beneficija. Zajednički cilj sredstava i procedura jeste da se poveća tačnost, jednostavnost, brža iskorišćenost, dodatna obrada informacija, osiguranje reproduktivnosti i da se izbegne štetna radijacija.

Ključne reči: *kičma, ultrazvuk, analiza, motivacija, X-zraci, MRI, CT.*