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A technique for assessment of torso kinesiology

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A technique is described for monitoring and analysis of the angular displacement of the human torso. The technique is based on the use of miniature electromechanical inclinometers and video recording. The system was developed for continuous measurement of the angular displacement of spinal segments in the sagittal plane during all stages of lifting. Angular displacements of the cervical, thoracic and lumbar regions were obtained from a dynamic lifting case study using a digital processing system. The geometrical changes of the torso during five prescribed stages were measured.

The system revealed good accuracy with high correlation coefficient scores for a wide range of lifting tasks in a comparative laboratory study. This paper describes the monitoring technique; the system's advantages, disadvantages and measuring accuracy are discussed.

Keywords: Musculoskeletal system, spinal flexion, lifting, sagittal movement, inclinometer

Introduction

Angular displacement of the spinal segments which determine the movement of the human torso is an important ergonomics measure in the study of work physiology. It has been of general interest in the field of occupational biomechanics during the act of lifting weights. The search for this geometrical determination of the human spinal system will help us to understand the phenomena of body balance, due to momentary external forces, and *in-vivo* reactions on vertebrae segments. Research is usually directed to the analysis of posture in the sagittal plane, where forces generated by object weights and object locations are studied. Important questions to be answered are: how does torso geometry really differ during the various methods of lifting (i e, torso lifting, leg lifting), and what is the relative role of each of the vertebral column segments during the different stages of the lifting act? Various studies in biomechanics of lifting indicated the issue that still remains: how does the geometrical response of the spine affect back pain (Chaffin *et al,* 1977; Davis and Stubbs, 1978; Tichauer, 1978)? More complex is the issue of how lifting postures are affected by workers' individual strength and mobility, and the reflection of object size on lifting kinematics, objectives which were discussed by Poulson and Jorgenson (1971) and by Park (1973).

Recent biomechanical evaluations of lifting performance have indicated that small changes in spinal column configurations while lifting can cause major changes in spinal column forces (Nordin *et al,* 1984). There is a wide agreement between researchers that the continuous measurements of torso segments during the lift motion is diagnostically important for health care studies, and ergonomically as an evaluation tool for improvement of working behaviour (Rizzi, 1976; Ayoub and El-Bassoussi, 1978; Hultman *et al,* 1984). It was Tichauer, one of the pioneers in ergonomics, who stated that the ever increasing number of low back injuries in industry has created the need for development of methods for the measurement of the response of the spinal column to lifting stress (Tichauer *et al,* 1973).

A literature survey indicates that the following methods – which differ conceptually, by levels of accuracy and by applications – have been reported:

(1) *The Accelerometer Method* uses a motion-sensitive electronic transducer to measure directly either the linear or angular acceleration of a body segment. The accelerometers are generally very sensitive to rapid changes in motion and are not preferred for measuring slowly-changing postures. This method is most often used to analyse high-speed motions and vibrations. Five accelerometers were used by Morris (1973) to study angular velocity and displacement of body segments.

(2) *The Goniometric Method* employs electronic or mechanical protractors to measure joint angles or relative linkage motions of specific axes. Complex goniometric systems using two or three orthogonally positioned rotary transducers with external skeleton support braces have been developed and used in laboratory and field studies. The main disadvantages of this method are the limitations involved in the use of the often cumbersome external skeleton, and the errors induced by soft-tissue motion around the skeletal frame. The use of this system is described in detail by Chao (1978).

(3) *The Flexometer Method* involves the use of a gravity-sensitive measuring device, often referred to as an inclinometer, which is attached to a moving body segment. It measures the motion deviation relative to the gravity vector rather than an adjoining body segment. The system is basically a mechanical device using the readings generated by a pendulum attached to a low-friction protractor or electronic angle-sensitive transducer. Roebuck (1968) used this system in a survey of space-suit mobility. An electronic version of this device, referred to as a flexion analyser, was developed by Nordin *et al* (1984). This system was low in resolution and capable of measuring time durations in each of five 18-degree flexion intervals in the range of 0 to 90 degrees. An *Inclinometric Method* for continuous measurement of sagittal movement of the spine was recently introduced by Otun and Anderson (1988), and is aimed at recording quantitative physiological data for use in occupational related studies. The mechano-electrical inclination device is small in size and promises good results in laboratory as well as at site studies. The unit has a linear range of 0 to 110 degrees. This device is not yet commercially available.

(4) *The Photogrammetric Method* uses one camera when motion is in a single plane, and two or more cameras when motion is in three dimensions. Reflective markers are attached to body segments, which are photographed periodically throughout the motion. The location and movement of the markers is then measured from the photographs. The system is widely used in the study of human mobility (Gustafsson and Lanshammer, 1977), and was successfully adopted to model human torso mobility by Chaffin and Baker (1970) and Chaffin *et al* (1972).

(5) *The Photographic Chronocycleograph Method* is a photographic method which can accurately locate and record the path of a moving target. A flashing light is attached to the body segment of interest and a time exposure is made while the body is in motion. The location and movement of the segment is estimated from the series of dots on the resulting photograph. The method is widely used to conduct motion and time studies of hand and arm manipulations. Unfortunately, it is time consuming to digitise the photographs, and the method is not easily applied in three dimensions. Studies of lifting tasks using this method were conducted by Fletcher *et al* (1958) and Davis *et al* (1965)

(6) *The Lordosimetry Method* is based on a device designed to record the spinal configuration of subjects under varying conditions of static load. The device is essentially a pantograph, in which electronic circuitry and motion-sensing transducers replace the conventional mechanical linkage used to trace the outline of an object. The apparatus was introduced by Tichauer (1973) and was used in a laboratory study for the two-dimensional measurement of postural configurations used by people when performing materials handling tasks. A three-dimensional measurement study using the lordosimetry method was conducted by Gross (1981) who investigated spinal configuration in a scoliotic female during light, static lifting.

(7) *The Computerised Video Spot Location Method* uses a video camera to capture an image of a set of reflective markers or flashing LEDs which are then evaluated by a computer. Several systems exist which locate contrasting spots against a given background. Reflective markers with a flashing light are used to provide point images for some video based systems. Others rely on synchronised, rapidly pulsed infrared LEDs attached to the body segments. The light rays from these LEDs or from the reflective markers are detected by a special video camera which, when energerised by a light ray from each marker, outputs the ray's location in two dimensions to a computer. Advantages and disadvantages of such systems are discussed by Chaffin and Andersson (1984).

The effects of lifting stresses on the vertebral column are highly dependent on postural configuration, and vice versa. Accuracy of measurement, rapid ability of angular detection and its practicability for the study of spinal kinesiology are essential factors for an ergonomics diagnostical method. These significant factors led the authors to introduce a measuring system for the study of spinal flexion, based on a new detection device which is commercially available and relatively inexpensive. The miniature inclinometer and the proposed measuring technique were developed into an ergonomics assessment tool at the Center of Ergonomics at the University of Michigan. The objectives of this paper are: to introduce a new angular detection device – Miniature Inclinometer; to present the measuring system; to demonstrate the data obtained from the evaluation of lifting tasks; and to discuss this system's advantages.

Method

The detection system

The inclinometer detection system is based on a small angular detector manufactured by Spectron. The detection unit is an electro-mechanical miniature device consisting of a single axis electronic resistance potentiometer. It requires an AC excitation signal, and provides a proportional voltage output as the unit is tilted relative to the gravity vector. The inclinometers were designed by the manufacturer to control the gradient output while being subjected to a variety of motions and vibrations. The original use of this device was to input geometrical signals in missile guidance systems. The detector is a one-piece glass enclosure of approximately 1 cm diameter. It has internal platinum contacts and external terminals which are sealed into the glass chamber to prevent electrolyte leakage. The internal geometry is so designed that when the chamber is partially filled with electrolyte, a bubble results which maintains direct surface contact with six walls. This containment of the bubble gives stability to the performance of the detector as it is rotated. The miniature inclinometer provides a signal which is directly proportional to the inclination of the transducer from the horizontal plane. Its frame of reference is relative to the gravity vector. Changes in the curvature of the torso at a given level are measured as changes in the angle between the horizontal and the tangent to the spine at each inclinometer – i e, point of reference. The miniature inclinometer compares in size with a 1 cent coin and its chamber's simplified cross-section is demonstrated in Fig. 1.

The miniature inclinometer can be positioned on the skin of the trunk, over a reference point, using adhesive pads. The inclination angle is relative to the gravity vector,.

and the inclination angles are measured continuously in the range 0–120°. In order to be able to measure flexion and extension values during trunk motion, the inclinometer is calibrated so that its middle range of reference – i e, the zero point – will be at the halfway range of trunk motion. To be able to measure the inclination angle of more than one body segment, several inclinometers are to be mounted similarly on the subject's trunk. The electrical cables running from the inclinometers to the signal receiver will then be attached to the subject's body, using adhesive tape, in such a way that they would not interfere with his movements. A view of an inclinometer attached at the cervical region of a subject is seen in Fig. 2. In order to study the regional movements of spinal segments along the torso, three inclinometers were used. Locations of the inclination detectors along the trunk in the sagittal plane and the angles measured are shown in Fig. 3.

The instrumentation needed to utilise the miniature detection device was designed for a multi-parameter lifting study. It includes the Inclinometer Control Unit (ICU) which has integrated detection and amplification circuits with appropriate power supply. This provides an analogue output of suitable magnitude for input to an analogue-to-digital converter. The converter is connected to a minicomputer, which stores the raw data and converts it into x,y co-ordinates and angular values for torso configuration during motion.

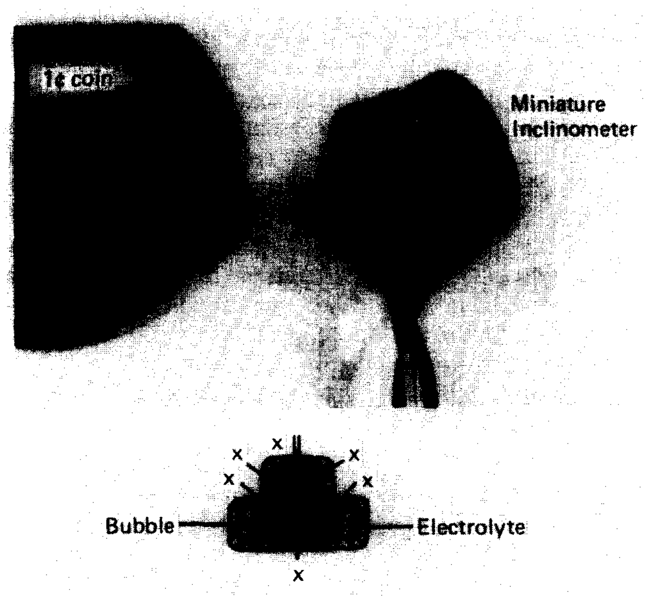

Fig. 1 Miniature inclinometer compared to a 1 ¢ (USA) coin and cross-section of the electrolyte chamber. The cross-sectional view shows a position of the bubble in chamber, X indicates bubble contact with six of eight walls

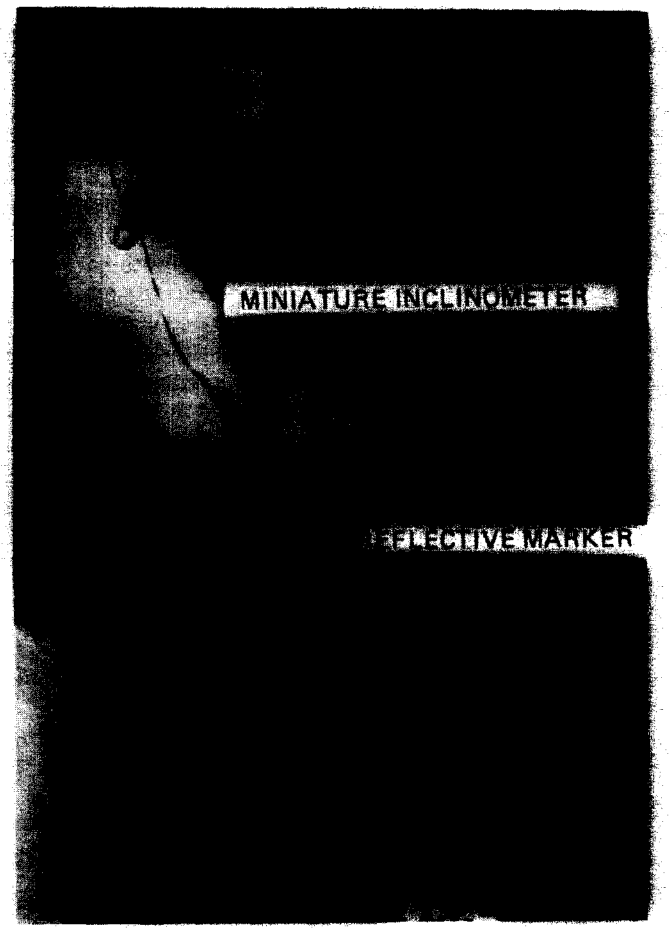

Fig. 2 The miniature inclinometer on a mounting post as attached to a subject at the cervical region

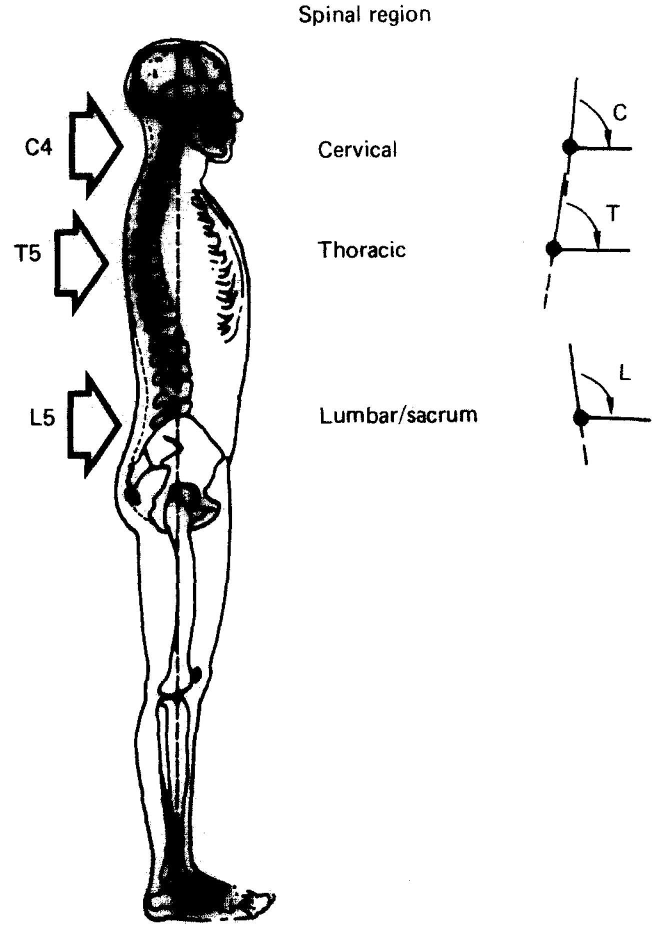

Fig. 3 Location of inclinometers along the spine in the lifting study and angles of tangent as measured by these detection devices at three spinal regions

A lifting study

A methodological study of the biomechanics of lifting usually employs a wide range of lifting parameters, such as object's weight and size, horizontal distances, vertical heights, methods of lifting, etc. In many studies of this nature, a factorial design of lifting experiments is conducted, which makes the management of data an important issue vital to the investigation.

To control the various parameters assigned to the lifting study a video recording system was employed parallel to the angular detection system. Video Camera and Video Cassette Recorder (VCR) were set on line with a computer-video synchroniser and video effects generator (Telecomb-1000) attached to a microcomputer. This was used to impose the lifting assignment parameters on a video control monitor. The multiple lifting parameters and the lifting motion picture were synchronised, presented and recorded by the VCR. To observe the exact locations of the inclinometers on the video control monitor, reflective markers were attached to the post on which the miniature inclinometers were positioned. Position of the detection device and the marker on the post at a given reference point (C4) are seen in Fig. 2. The reflection of the marker on the video monitor is seen in Fig. 5.

This system enables the researcher to record and obtain a list of geometrical values for momentary torso flexion, assigned to the set of lifting parameters and thus, at the same time, observe the continuous change of the torso kinesiology. Fig. 4 outlines the system component layout and Fig. 5 presents the lifting image, as it appeared on the video control monitor, during the dynamic lifting study. Anatomical differences may exist between males and females due to the forward tilt of the female pelvis (Tichauer, 1978) which produces differences in biomechanics of the lifting act between males and females. To cover possible differences in lifting kinematics due to sex, two subjects – one of each gender, of the same age and close stature – were selected for the study.

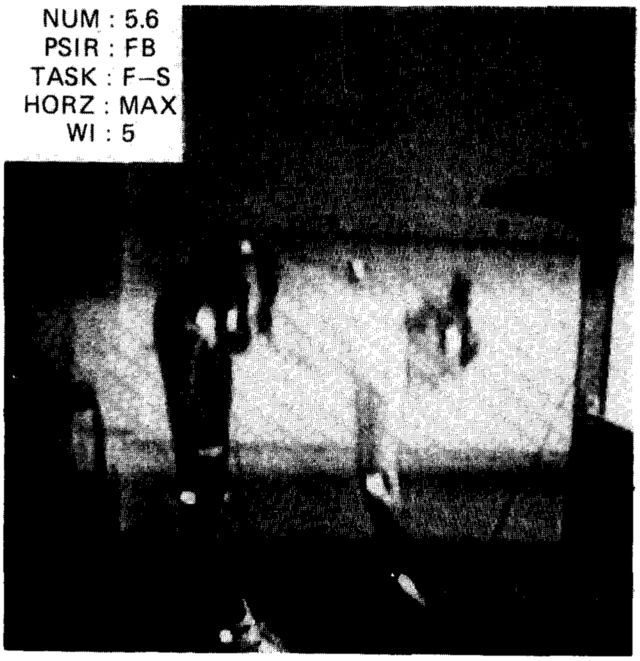

Fig. 5 Lifting assignment parameters and subject's image during lifting study as it appears on the video control monitor

Results

Momentary angular displacement values, at each spinal level over time, have been obtained using a microcomputer. A set of three geometrical diagrams (Figs. 6a, b, c) presents the angular displacement of the torso's three regions: The Cervical spine at C4 level (Fig. 6a), the Thoracic spine at T5 level (Fig. 6b), and the Lumbar spine at L5 level (Fig. 6c). These angular presentations are of the female subject who performed dynamic liftings with straight back–flexed knees, floor to knuckle height; the lifting weight was 7 kg, with maximum horizontal reach distance between torso and weight. Time scale in these diagrams is 10 ms (1/100 s) intervals on the x-axis. Inclination angles are presented on the y-axis.

In order to evaluate the various trends in angle trajectory of torso kinematics during lifting, the motion diagram was divided (by vertical lines) into five phases, as seen in Figs. 6 and 7. These five phases of lifting are defined in Table 1, where the beginning point, ending point and motion description are explained.

From the analysis of the complete set of liftings, the following points of interest are recognised: the frequent angular changes of the cervix, and of the thoracic spine, especially in the 'straight back–flexed knees' lifts, indicating the role of the head and the cervical region, which acts as a counter-balance weight for body stability. The location of the zero reference line differs in every region due to precalibration of the inclinometer detectors. This is of importance since every region tends to produce different

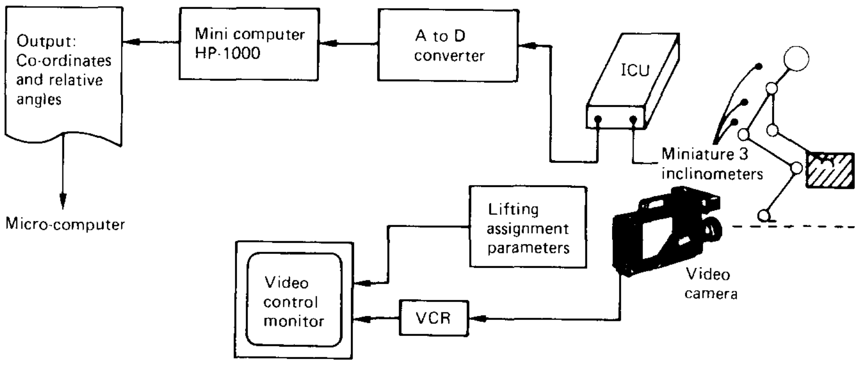

Fig. 4 Component diagram of the inclinometer detectors and the instrumentation set-up

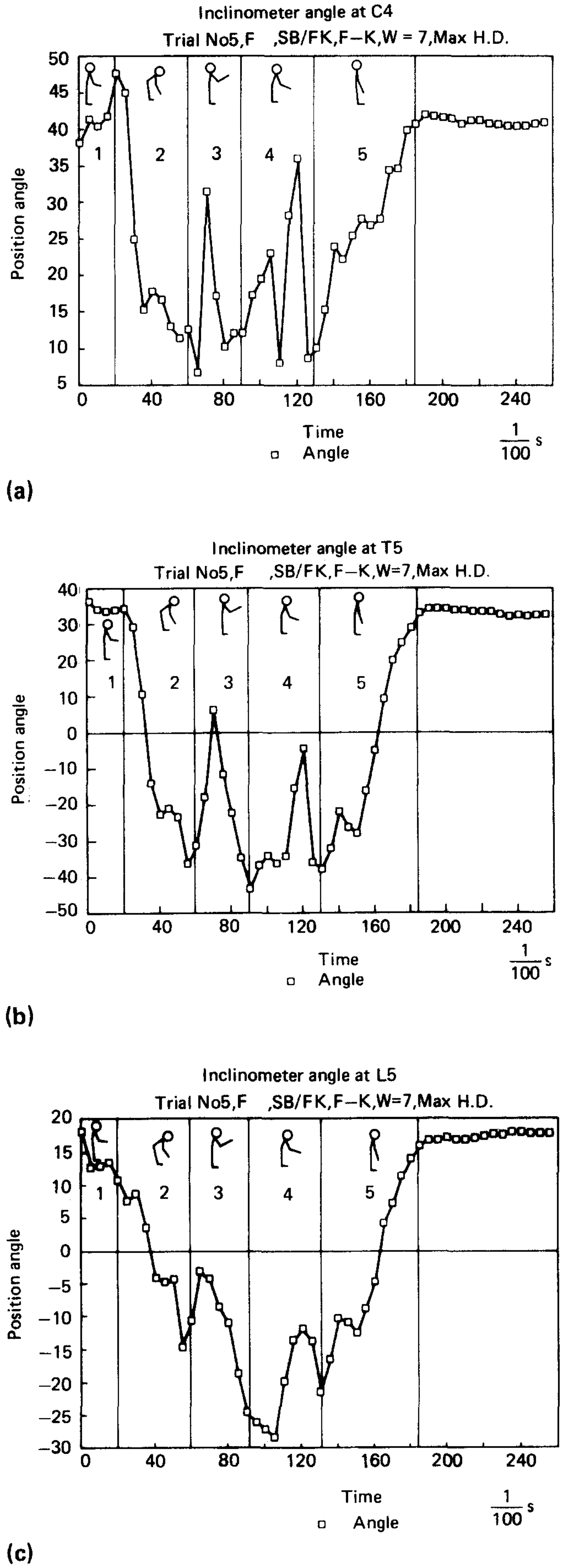

Fig. 6 Graphical presentation of angular displacement (a) C4, (b) T5 and (c) L5 levels as obtained from the inclinometer detection system

angular displacements on the relative reference frame. The technique provides a comparison of the momentary regional displacement of the torso during the continuous act of lifting, and an evaluation of each of the segments during the five phases of the act. The vertical reference scale (y-axis), which presents the momentary angle value, has therefore been plotted on a different scale for each graph to present the angular displacement to the maximum size of the graph. In case smoothness of line is required, simple statistical methods, which are available for microcomputers, can be performed. This will allow minor angular changes to be ignored and will present only significant changes of angular displacements of the referenced region.

Discussion

The accuracy and reliability of the miniature inclinometer detection system was evaluated in a separate comparative study where the readings obtained were compared to the Selspot computerised spot detection system. This reference system was chosen, from among other methods available in the market, for its proven ability to produce accurate estimates of geometrical values. The Selspot System provides about 5 mm accuracy for each spot location on 2-D co-ordinates (Gustaffson and Landshammar, 1977).

For system evaluation, a complete set of lifting tasks was investigated where angular displacements of torso were compared through linear correlation analysis between the two methods (Gilad *et al,* 1988). The reliability of the miniature inclinometer technique was tested over three different lifting techniques: straight back–flexed knees (SB), flexed back–straight knees (FB), and free unconstrained lifting (FREE). The miniature inclinometer system showed, overall, a very good accuracy compared with the well established Selspot System in lifting performances.

The similarity between the Selspot system and the inclinometer technique is presented in Fig. 7 which demonstrates a momentary angular displacement of the spine for a female

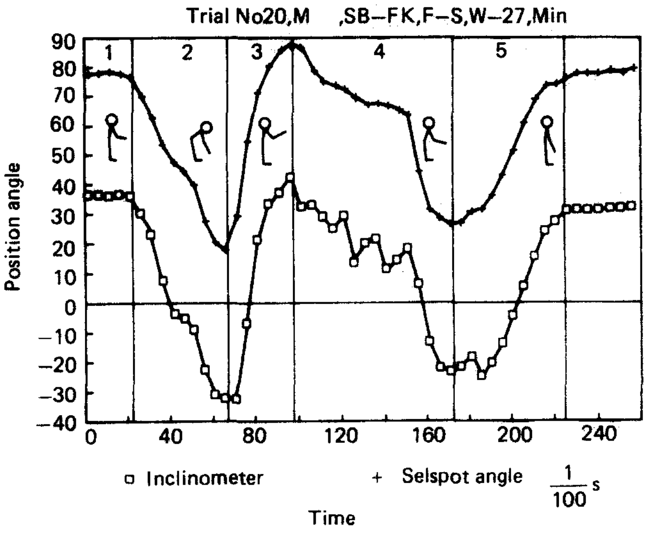

Fig. 7 Selspot *vs* Inclinometer at T5. Comparison presentation of angular displacement as obtained simultaneously from the Inclinometer detectors and the Selspot detection systems

Table 1: Definitions of five phases during the lifting act

Lifting phase	Beginning point	Ending point	Motion description
1. Preload position	Angle of normal standing posture	Angle of posture at the moment of bending to weight origin	Operator takes natural standing before lifting task is performed
2. Bending to weight origin	Angle of posture at the moment of bending to weight origin	Angle of posture at the moment of hand contact with weight to lift	Operator is bending his back to hold the weight on origin location
3. Lifting to destination	Angle of posture at the moment of hand contact with weight to lift	Angle of posture at the moment of loading the weight on destination	Operator lifts the weight to load on the destination location
4. Return to origin	Angle of posture at the moment of loading the weight on destination	Angle of posture at the moment of loading the weight back to origin	Operator holds the weight again and then returns the weight back to origin location
5. Back to preload	Angle of posture at the moment of loading the weight back to origin	Angle of normal standing posture	Operator straightens his torso and returns to his normal standing posture lift

subject at straight back–flexed knees, floor to shoulder height lifting of 27 kg, with minimal horizontal reach distance. The vertical difference in angular reading is due to the differences in the angular output methods. In the case of the inclinometer system, the angular frame indicates the relative angle, while the Selspot system provides the absolute angle.

A clear similarity between the two systems can be observed during all stages of the lifting act. Quantitative comparison between the two measuring systems revealed that both systems display similar torso angle measurements for a large variety of lifting conditions. Time series correlation-coefficient analyses indicate overall high r values, significant at 0·005 levels up to 0·97 for the Cervical spine with low scores for SB posture, up to 0·98 for the Thoracic spine, and 0·96 for Lumbar spine (Gilad *et al,* 1988). Analysis of variance indicated better performance for the system at the Thoracic in all three lifting postures, which is also logical because of the limited flexibility of action at this region during all movements of lifting.

Advantages and disadvantages of the proposed measuring technique are:

Accuracy – the accuracy of the new inclinometer system was evaluated by comparison with the well established Selspot detection system, as previously mentioned. A cross-correlation study between angular estimations of the two systems suggested that the miniature inclinometer technique performed with high accuracy over a wide variety of dynamic lifting tasks.

Repeatability – during the extended set of lifting tasks, the investigation revealed that the system generated reproducible sets of results, which positively supported its high repeatability abilities.

Ease of use -- careful calibration of the miniature detectors, is required during the set-up of the system. Data retrieval is easily achieved and relatively simple to analyse with graphical software packages used by microcomputers, like 'Lotus 1-2-3' and 'Chart Graph'.

Safety of use – there are no physical effects to human health during any phase of subject preparation or data recording. The system is therefore totally safe as a diagnostic tool for purposes of the health care industry, ergonomics or biomechanical studies.

Practicability – the proposed technique is relatively easy to set up and the raw data are manipulated in a straightforward manner. The miniature detectors were designed to perform accurately in a manner unbiased or influenced by high velocity, according to strict military standards. The measurement functions were not obscured by outside environmental factors such as illumination, magnetic or acoustic radiation. Also, errors from optical distortion do not exist in the measuring technique. The system is relatively inexpensive. The estimated cost of the system, as used in the previously mentioned lifting study, is about US $10,000, including the microcomputer, which is about 25% of the cost of the 'Selspot' detection system.

Measurement flexibility – the inherent limitation of the miniature inclinometer restricts the continuous detection of angular range to 120°, which is more promising than the two other inclinometers mentioned in Paragraph (3) earlier. From the results of the lifting study, measuring the angular displacement of torso segments, the whole range of spinal motion can be measured with this system, though one should consider this range of angular detection as a capability limitation for different more complex types of motions.

Conclusion

A technique for the measurement of torso inclination in the sagittal plane at three levels has been described. The technique is based on a new miniature inclinometer device, and an evaluation system which was instrumented for the study of dynamic lifting. The system provides an on-line 2-D spinal motion detection method for continuous measurements of torso inclination. The system provides, over all, good accuracy in a lifting study for three different lifting postures.

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