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Applied Ergonomics 30 (1999) 543–553

APPLIED ERGONOMICS

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Development and evaluation of a microprocessor-based ergonomic dosimeter for evaluating carpentry tasks[1]

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Received 2 September 1996; accepted 9 December 1998

Abstract

This portable and self-contained lightweight microprocessor based Ergonomic Dosimeter is designed to collect continuously postural angles of the torso and the upper arm in the sagittal plane and the number of kneeling activities. Up to 4 h of task performance data can be stored in a non-volatile memory of the dosimeter, which can then be downloaded to a lap-top computer. The portable dosimeter was tested for test-retest reliability, compared with posture data obtained with a computer-based video analysis system and evaluated at a carpenter's apprentices school and at a construction site. The dosimeter was shown to be suitable for collecting posture and kneeling data for a prolonged period at construction sites. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Carpentry task; Posture Analysis; Kneeling activity; Egonomic dosimeter

1. Introduction

Most carpentry tasks are not as structured as those found in the manufacturing industries and generally have long cycle time. Therefore, the traditional methods of job analysis must be modified to fit the requirements for carpentry tasks (Silverstein, 1996). For this purpose first an ergonomic walkthrough checklist was developed and validated in order to gain preliminary understanding of postural effets and biomechanical loading on various body parts during carpentry task performance (Greathouse *et al.* 1993; Bhattacharya *et al.*, 1997). Based on results from the ergonomic checklist assessment on 21 carpenters, it was determined that the trunk, neck/shoulders and lower legs (knee, hip and ankle) are frequently positioned in an awkward postures during the performance of various carpentry tasks. Thus far these findings (Greathouse *et al.*, 1993) have been based on qualitative data obtained from our ergonomic walkthrough evaluations of 17 construction sites representing various specialties. Hence, in order to quantitate angular positions of certain body segments for a prolonged period and frequency of maintenance of these postures associated with the carpentry specialties, an ergonomic dosimeter was designed to meet certain criteria.

Several criteria had to be met for the development of such an ergonomic dosimeter including: (1) ability to store a "snap-shot" of multiple body link angles simultaneously and kneeling activities once every second for a prolonged period (at least 4 h); (2) lightweight and non-interfering with job performance; (3) ability to transmit data to a laptop computer at the field site; and (4) durable, sturdy and accurate while exposed to extreme environmental temperatures.

There have been previous reports of several instrumentation such as potentiometer-based goniometers, ultrasonic 3-D angle sensors, and opto-electronic devices which can measure human body link angles accurately (Pearcy, 1986; Aaras and Stranden, 1988; Hsiao and Keyserling, 1990). At a construction site, however, it is impractical to use any one of these tools for continuous measurement. For example, the ultrasonic 3-D system (Hsiao, 1990) is accurate for laboratory-based measurement of postural angles but it is impractical and is not feasible to use it at a construction site while the worker is carrying out his/her tasks. The video-based system (Keyserling, 1986) has been shown to be reasonably accurate but requires significant amount of training of the

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PII: S0003-6870(99)00006-X

operator and the video processing time is high. In a study performed by Keyserling (1986) it was shown that the time taken to carry out a frame-by frame analysis of a 74 s video segment was about 2 h. Since the construction related tasks have a relatively longer cycle time our experience has shown that it is necessary to collect data for prolonged periods (number of hours) which will require an inordinate amount of time to carry out a frame-by-frame analysis. The video based analyses in Keyserling's study were carried out on tasks from a automobile assembly line where it is relatively easy to obtain clear view of the worker for videotaping purpose. However, at the construction sites, it is not easy (sometimes even impossible) to obtain clear view of the tasks being performed. The use of checklist-type methods have been devised and used by us (Bhattacharya 1997) and by several other investigators (Mattila, 1993; Ahasan, 1996; Bucholtz, 1996) to obtain posture and repetition data at construction sites. Most of these methods rely primarily on the expertise of the observer to identify the posture observed and compare it to the list of weighted postures in the checklist. This process requires significant amount of time for training and it is also not possible to obtain continous collection of postures assumed by the worker at the workplace which may be critical for obtaining a representative sample of postures associated with construction tasks with longer cycle time. For such tasks, it would be useful to have an instrument which can collect continous "snapshots" of postures at a predetermined time interval which can be directly downloaded to a computer. Therefore, an ergonomic dosimeter was designed, developed and tested for the continous measurement of postures and kneeling activities associated with carpentry tasks at construction sites. The ergonomic dosimeter described below was an extension of a Lower Extremity Dosimeter built earlier by our group for analysis of carpet layer's tasks (Bhattacharya, Teuschler, *et al.*, 1988; Bhattacharya, 1985). The details of dosimeter hardware design are given in the appendix.

2. Testing and evaluation

The dosimeter was tested and evaluated to compare the posture data collected with the dosimeter with those obtained with a video-based motion analysis system. Also, the reliability and field worthiness of the dosimeter was evaluated.

2.1. Methods

2.1.1. Calibration and reproducibility test

The transducer was calibrated in the laboratory to determine the relationship between the sensor readout and actual angle with respect to gravity. The sensor was attached to one end of a plexiglass arm whose other end was pivoted at the center of a circular board placed in the sagittal plane. With a protractor 180 diameter lines were drawn at 2° interval on the circular board. The sensor attached to the plexiglass was carefully (removing parallex between the diameter lines and the center line of the sensor) rotated at 2° interval through $\pm 180°$ (360°). The sensor values at each of the 2° positions were recorded in analog/digital counts from the dosimeter. The data from three repeat trials were obtained. Fig. 1 shows the calibration data, R^2 value (0.9999), and 95% confidence limits for the working range of interest ($-20°$ and $+180°$) in this project as per the posture definition described later in this article. As the relationship between the posture angle and the analog/digital count was not linear, a best fit curve was obtained. The relationship between the angle and the observed dosimeter output is given by the following ninth degree polynomial:

$$\begin{aligned}\text{Dosimeter} = {} & 4.6 + 3.0\text{Angle} - 0.024\text{Angle}^2 \\ & - 9.6\times10^{-4}\text{Angle}^3 + 4.0\times10^{-5}\text{Angle}^4 \\ & - 6.7\times10^{-7}\text{Angle}^5 + 6.2\times10^{-9}\text{Angle}^6 \\ & - 3.3\times10^{-11}\text{Angle}^7 + 9.3\times10^{-14}\text{Angle}^8 \\ & - 1.1\times10^{-16}\text{Angle}^9.\end{aligned}$$

This polynomial was considered to be optimal because all coefficients up to the ninth degree term in the model were statistically significant ($p = 0.0001$). On the other hand, coefficients for higher-order polynomials could not be estimated because the design matrix is too close to being singular. For additional verification of reproducibility of data collected in calibration Trials 1–3 an interclass correlation Coefficient (ICC) was calculated. The value of ICC obtained was almost equal to 1 implying that virtually all variability in dosimeter measurements (or outputs) was due to difference in angles and the proportion of variability generated by difference in measurements at the same angle (within angle variance) was minimal. A pairwise Pearson Correlation Coefficient for data from three trials gave a value of 0.999 which further confirms the reproducibility of data.

2.1.2. Posture definition

Fig. 2 shows schematic of arm and back posture definitions used for describing the postures measured by the dosimeter. The 0° position refers to upright back and arm on the side, respectively. The 90° position for the torso refers to flexion in the sagittal plane and parallel to the floor (Fig. 2A). Similarly, for the arm 90° refers to arm raised at shoulder height (in the sagittal plane) and parallel to the floor (Fig. 2B). The negative angles in Figs. 2A and 2B refer to extension of torso and the backward extension of the arm, respectively. As sensor provided the angles with respect to the vertical gravitational field (in the sagittal plane), the angle measured with the sensor attached to the upper arm were converted to give the

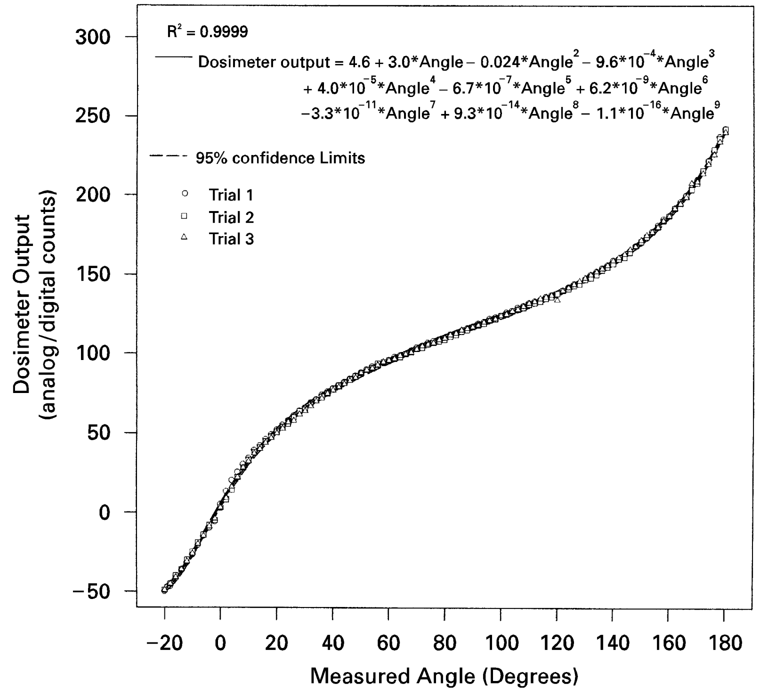

Fig. 1. Calibration graph for the sensor.

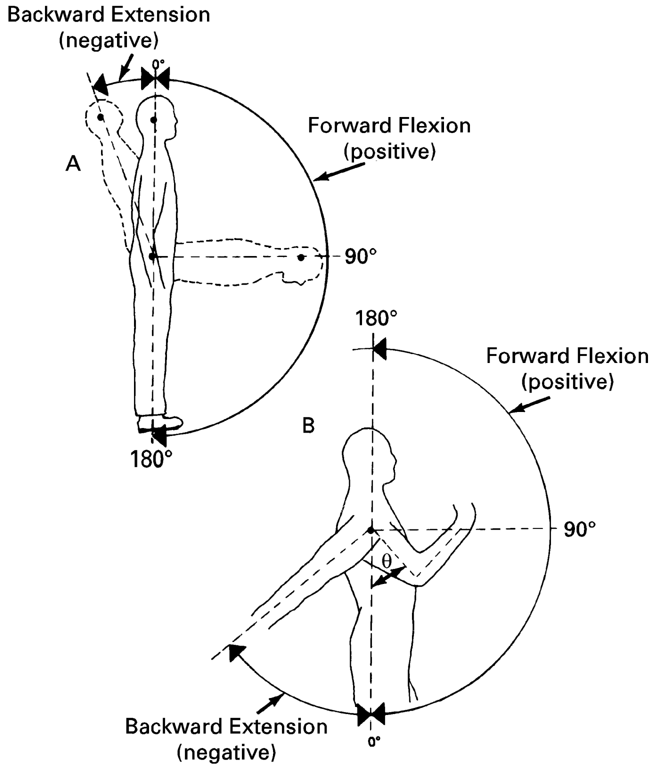

Fig. 2. Definitions of (A) back (torso) and (B) arm postures.

subtended arm angle Θ between the torso and the upper arm (Fig. 2B). The torso (back) angle was used as measured reference to the vertical gravitational field.

The sensor data were processed to determine the workers' posture profile for the upper arm and back. The information from the kneeling meter was recorded to determine the number of kneels and the duration of kneeling. The information from the arm and torso sensors were divided into various postural regions based on the ergonomic risk levels defined in the literature (Keyserling, 1986; Genaidy and Karwowski, 1993; Genaidy *et al.*, 1994). The levels of ergonomic risk for posture used for this dosimeter were as follows:

Upper arm	Torso (Back)
Neutral:- 20–20°	−20–20°
Low: 20–45°	20–45°
Medium: 45–90°	45–90°
High: 90–135°	>90°
Very high: >135°	

A "very high" category was added to the upper arm posture to provide additional separation for ceiling workers who were expected to spend more time with their arms higher than the other specialties being studied.

The data files were processed by a computer program utilizing the calibration curves. The calibration curves converted the dosimeter readings to actual angles measured in the sagittal plane. The angles found in each region of interest were counted. Each count represented a duration of 1 s based on the data sampling rate of the dosimeter. The computer program also calculated the subtended arm angle. The average, maximum, and minimum angles were also calculated.

The kneeling sensor was a force sensing resistor type (FSR). The FSR sensor was used primarily as a pressure sensitive switch attached inside the kneeling pad. The FSR sensors were calibrated with a strain gauge-type force platform (Model OR6, AMTI, Watertown, MA). The kneeling information, the number of kneels and duration of time spent kneeling, were used to determine the percentage of monitoring time spent kneeling and the average kneeling time.

2.1.3. Laboratory evaluation

The dosimeter was evaluated in the laboratory by simultaneously measuring torso and arm posture angles and kneeling activities with an existing video-based computerized motion analysis system (PROTEK 2000) as well as with the dosimeter. For this evaluation a subject wore the coveralls with the dosimeter attached inside the coveralls. Passive reflective markers were placed at the following anatomical sites: shoulder joint, elbow joint, wrist joint and the hip joint. Each session was video taped to allow a separate calculation of back and arm angles from the video for comparison with the dosimeter measured angles. The session was started by having the individual stand erect with both arms at the side. This position represented the reference point for the data collection. A calibration reading was taken and recorded to ensure the dosimeter was operating properly. Next, the arms were raised to 90° in the sagittal plane to obtain another calibration reading. Next, a reading was taken with the subject bending forward approximately 90° at the waist with the arms positioned 0° from the body (Fig. 2). A final calibration reading was collected with the subject retured to the reference position (standing erect with arms at the sides). These calibration values were compared to the calibration curves to ensure the dosimeter was working properly. The subject was then asked to perform following static posture tests: (1) Stand erect with arms at the sides. (2) Bend at the waist approximately 45° in the sagittal plane but keeping arms at the sides. (3) Bend at the waist approximately 90° in the sagittal plane but keeping the arms at the sides. (4) Stand erect with arms at the sides. (5) Bend at the waist approximately as far as comfortably possible in the sagittal plane but keep arms at the sides. (6) Stand erect and raise

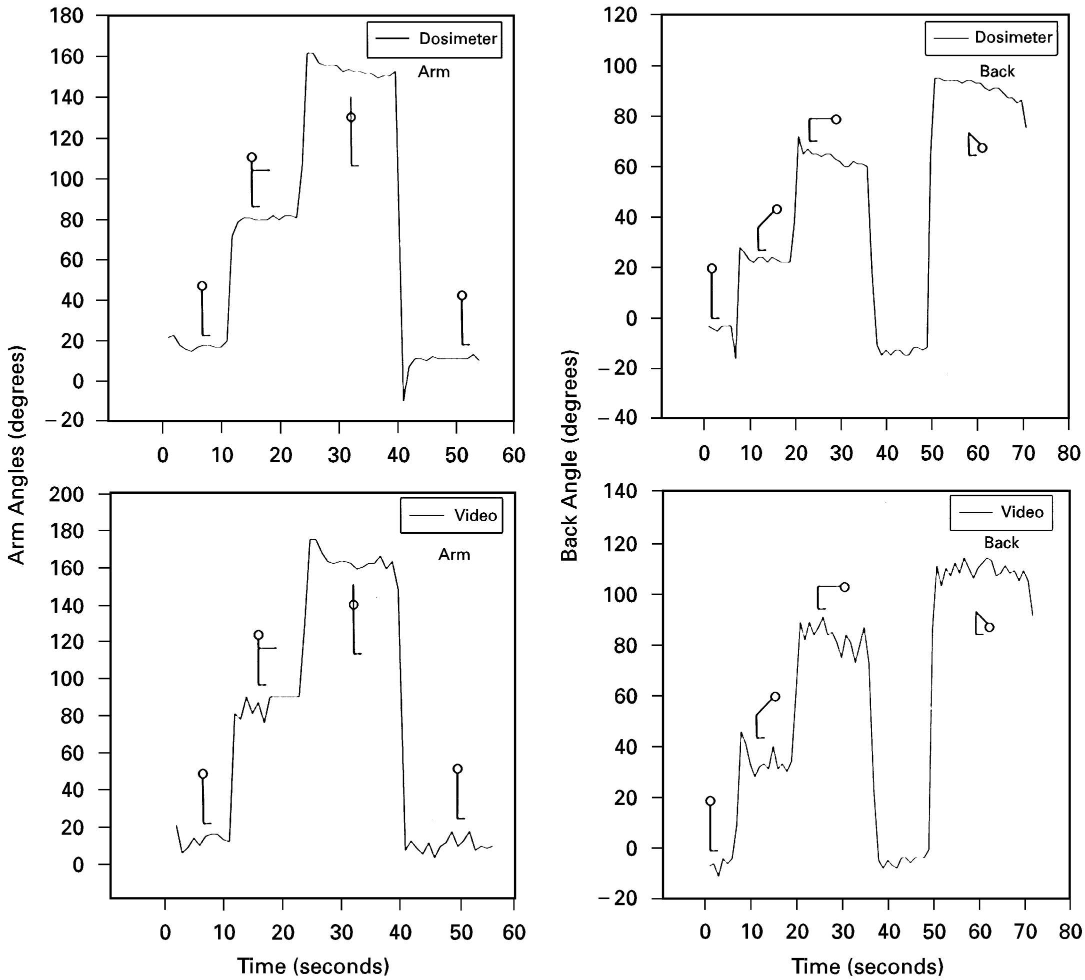

Fig. 3. Comparison of static posture angles for the back (torso) and the arm between the dosimeter and the video-based posture analysis system.

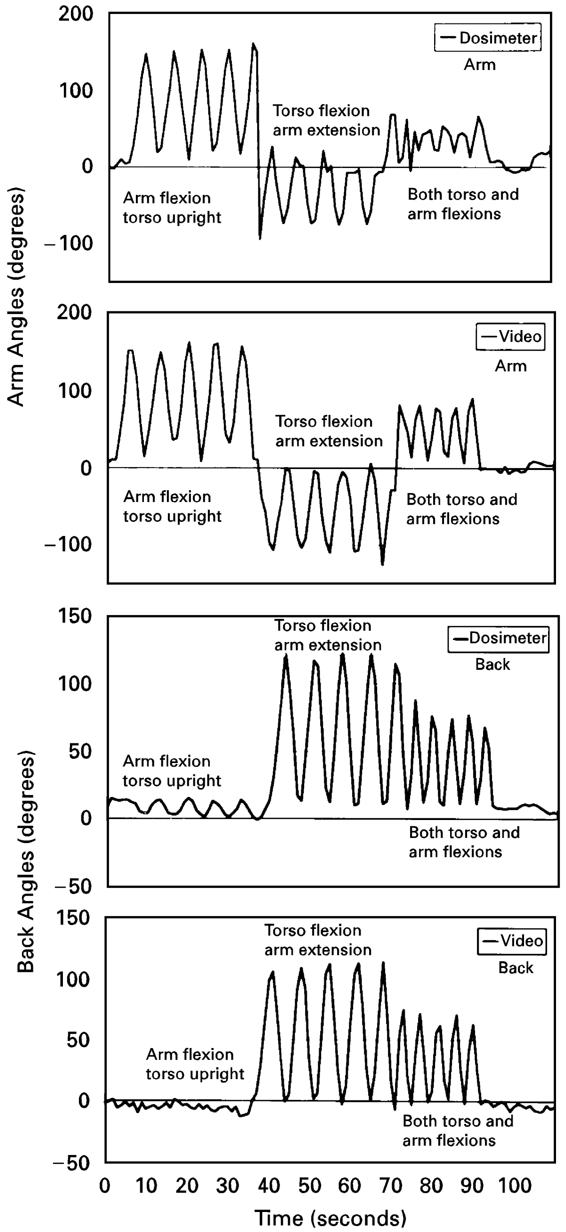

Fig. 4. Comparison of dynamic posture angles for the back (torso) and the arm between the dosimeter and the video-based posture analysis system.

arm to 90° in the sagittal plane. (7) Stand erect and raise arms to 180° in the sagittal plane. (Fig. 3). In addition to the static test, the subject also assumed predefined dynamic postures for torso and the arm in the sagittal plane for a specified period of time. Three major movements were performed: (1) Cyclic arm flexion with torso in the upright position. (2) Cyclic flexion of torso with some extension of the arms. (3) Cyclic simultaneous flexions of torso and arm (Fig. 4). These postures were repeated during three test sessions. Each session was video taped for later analysis. The dosimeter recorded the angles of the upper arm and back. At the end of each session, the dosimeter was downloaded into a lap-top computer using a transmission interface box. Measurement were taken from the video every 30 frame (approximately once a second) to match the sampling rate of the dosimeter. The video data was also analyzed to obtain arm and torso angles with respect to vertical gravitational axis for each video frame.

Table 1
Kneeling sensor testing data

Data	Kneels	Duration of kneeling
Video	26	3 min, 25 s
Dosimeter	26	3 min, 14 s

Figs. 3 and 4 demonstrate the comparison of posture angles for the torso (back) and the arm between the dosimeter data and those obtained from the video-based posture analysis system. In Figs. 3 and 4 it can be seen that the nature of the time-dependent posture angles for the arm and the back measured with the dosimeter were comparable to those measured with the video system.

The knee-pad was tested to determine the reliability of measurement and the effects of accidental contact of the knee against an object. A subject wore the knee-pad and performed a standardized number of kneels and simulated accidental contacts. The protocol called for kneels each lasting between 5 and 10 s. The session was video taped and the number of kneels from the video were counted and timed using a stopwatch. The final readout from the dosimeter display was recorded and compared with video data. Table 1 summarizes the results of the kneeling meter tests. The results were comparable to findings from the video analysis. Accidental contact with objects for durations greater than one second, however were counted erroneously based on the hardware design criteria.

2.1.4. Evaluation at the carpenters apprenticeship school

At the carpenter's apprenticeship school, the following issues were addressed: attachment of the body segment angle sensors and kneeling sensors to the worker, durability, adaptability, stability and functionality of the dosimeter for field use. These issues were addressed by taking a prototype unit to the carpenters apprenticeship school where apprentice-carpenters wore the dosimeter and performed their normal day's activity. At the end of the day, integrity of the dosimeter and its components and the apprentice's subjective comments regarding any problems (such as difficulty in wearing the dosimeter, interference with their task, etc) were used to further refine the durability and field functionality of the dosimeter. The temperature sensitivity of the dosimeter was evaluated by exposing it to extreme temperatures, and it was found that the data remained accurate and reliable.

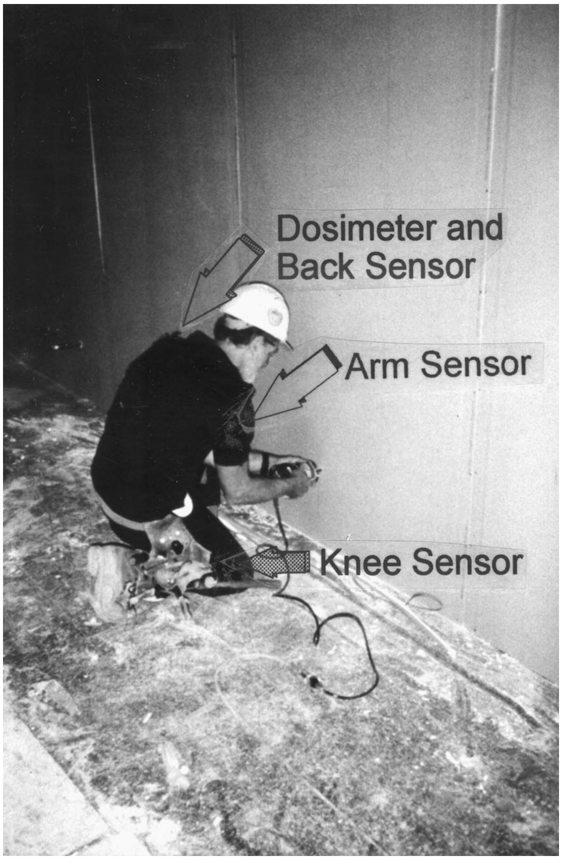

Fig. 5. A carpenter performing drywall task while wearing the ergonomic dosimeter.

2.1.5. Evaluation at a construction site:

Once it was evaluated at the laboratory and apprentice school, the dosimeter was further tested for "field worthiness", at two construction sites on two carpenters while performing typical carpentry tasks. Fig. 5 shows a photograph of a carpenter performing drywall task while wearing the dosimeter. The results from the evaluations are described in the following.

The dosimeter was used to record the postures of a worker hanging drywall for 41.5 min. A worker installing a ceiling grid was observed for 112.75 min. The dosimeter data were downloaded to a laptop computer via a serial interface. Fig. 6 shows an example of raw time dependent postural data obtained from the arm sensor. A frequency distribution of the postural data was divided into regions representing neutral, low, medium, and high-risk areas for ergonomic problems based on the posture definition given earlier (Fig. 7a and b).

The drywall worker spent 0, 18, 36, 32 and 14% of the time with arms in the neutral, low, medium, high and very high-risk posture regions, respectively (Fig. 7a). The ceiling worker spent 0, 12, 39, 13 and 36% of the time in the same regions of arm elevations. The drywall worker spent 16, 45, 21, 18 and 0% of the time in the neutral, low, medium, high and very high-risk back-posture regions, respectively (Fig. 7a). The ceiling worker spent 46, 44, 4, 5 and 0% of the time in the same back flexion regions. Based on the kneeling sensor data, the drywall worker knelt 28 times which resulted in a total kneeling time of 180 sc. The ceiling worker did not perform kneeling activities. During these construction site evaluations, no problems associated with dosimeter data collection and downloading was experienced. In a future publication we will present findings and implications of posture data collected with this dosimeter from 22 carpenters performing ceiling, drywall and formwork tasks.

3. Discussion

The ergonomic dosimeter described herein allowed continuous measurement every one second "snap-shot" of changes in torso and upper arm postures and kneeling events while performing carpentry tasks. This type of measurement tool was desirable for obtaining posture data for nonstructured tasks that usually have long cycle times such as those found in the construction industry. Unlike paper–pencil methods, where posture information is captured visually by the observer, the dosimeter data provides a quantifiable sample of postures at a rate (1 Hz) which is not feasible to accurately document with the human eye. A video-based system can provide posture data at a rate higher than that provided by this dosimeter. However, the labor-intensive nature of video processing task and impracticality of following a carpenter with a video camera for a prolonged period at a construction site suggests the need of a portable posture measurement dosimeter such as the one described in this article. The dosimeter method of pseudo-continuous measurement of body segment postural changes provided a better characterization of cumulative postural loading associated with task performance by carpenters. In a prospective study, the cumulative postural loadings will be useful for investigating their potential association in developing work related musculoskeletal discomfort and/or disorders.

The modified coveralls provided a useful means of attachment of the dosimeter and its posture and kneeling sensors. The coveralls also provided the flexibility to attach the sensors to monitor the postural changes of torso, dominant arm and knee for each subject. The coveralls also served to protect the dosimeter and the connecting wires for the arm sensor and kneeling meter and were lightweight, durable and short-sleeved to minimize worker discomfort.

The kneeling meter in the laboratory testing phase was found capable of correctly counting the number of times pressure was exerted on the sensor; however, this included any accidental contacts lasting greater than one second. In the laboratory evaluation phase, the dosimeter

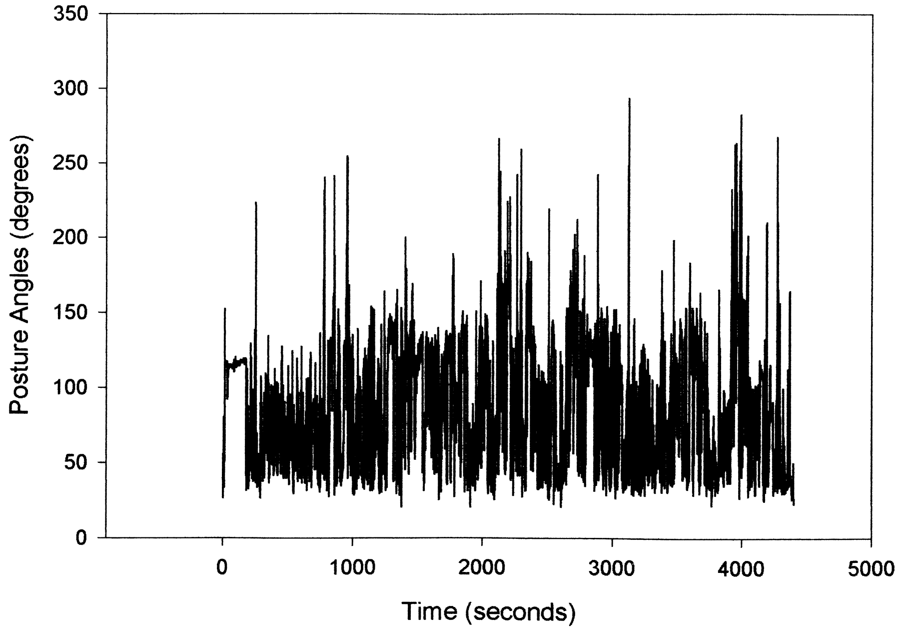

Fig. 6. An example of raw time-dependent postural data obtained from the arm sensor.

was tested on a human subject by comparing the dosimeter data to the results obtained by video analysis. The results showed good agreement between the dosimeter and the video based results. The time dependent temporal patterns of the arm and back postures were comparable between the dosimeter and video based data (Figs. 3 and 4). The average difference from three test sessions for the dynamic postures between dosimeter and video-based data were 6° for the arm sensor and 11° for the back sensor, respectively. The back angles measured by the dosimeter indicated a more (than arm) consistent posture; however some variation would occur due to postural sway and muscle fatigue. Similarly, for the static posture tests, the average difference from three test sessions between the dosimeter and video-based data were 6.5° for the arm sensor and 12° for the back sensor.

In summary, the dosimeter was shown to provide a practical, reliable and easy to use method for obtaining continuous time-dependent postural data on carpenters at construction sites.

Appendix A: hardware development

To meet the lightweight and power requirements, the dosimeter was developed using CMOS technology for the microprocessor system. This technology allows small battery powered lightweight units to be fabricated. Fig. 8 shows a schematic of various components and their relative positions inside the dosimeter box.

A.1. Sensors for body link angle measurement

The sensors chosen for the postural angle detection are (diameter: 2.2 cm, thickness: 0.318 cm, weight: < 5 g) angle detectors (Micro ARC Transducers series 0728 Fredericks Co. Huntington Valley, PA). The sensor is a miniature glass circular ring with symmetrical gold plates placed on both side of the junction. The glass ring is half-full of fluid when rotated causing a change in the capacitance between the transducer circuit. Due to the nature of the sensor, the transducer response is V-shaped curve ranging between $\pm 180°$. The apex of this curve is at 0° of tilt of the sensor representing minimal capacitance between the two gold plates. The angles are measured with reference to the gravitational axis in the sagittal plane.

One sensor was used for the measurement of the torso (back) angle and the other was used for the measurement of upper arm angle. The upper arm sensor was sandwiched between two plexiglass plates (Fig. 9A). The torso angle sensor was mounted inside the dosimeter case which was mounted on the back at the thoracic level of the subject (Fig. 9B and 9C). Information from the sensors were converted to digital signals through a 8 bit analog to digital converter (A/D National ADC 0844). The resolution was 240 counts for every 180° of angular motion. The sensor was calibrated between 10–12 counts at minimum angular reading and 245–250 counts at the maximum angular reading. The system is designed to store 32,0000 bytes of information for each sensor. The data from each sensor are collected at a sampling frequency of 1 Hz.

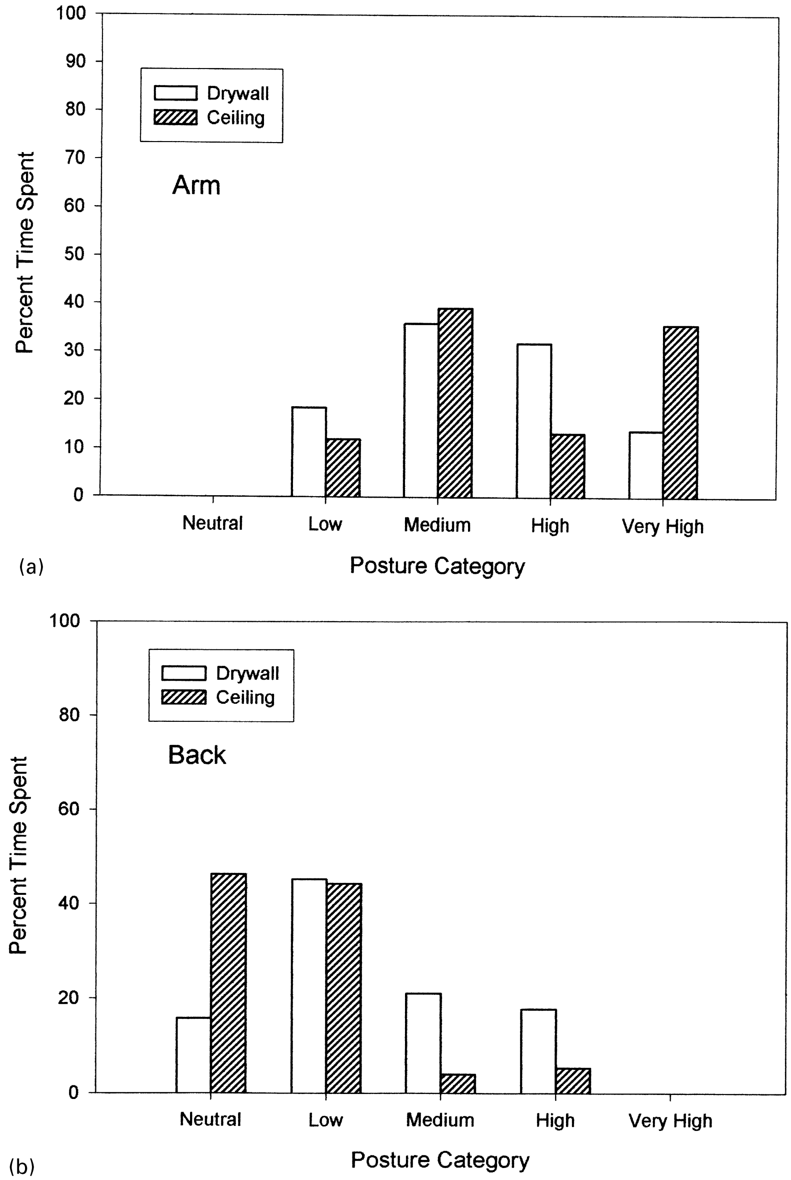

Fig. 7. A frequency distribution of postural data for the (A) arm and (B) back.

A.2. Sensor for kneeling activity measurement

The knee sensor is a force sensing resistor (FSR, Interlink, Inc.) which responds to kneeling pressure. The resistivity of the FSR drops as an increasing force is applied over a known surface area. The FSR is calibrated (using a strain gauge type force platform) to count number of kneels once a "real" (as opposed to slight bending of knee during walking) kneeling event has occurred (Fig. 9A).

It was important to differentiate between false and true kneeling events. A true kneel was defined as the activation pressure resistance level applied for a minimum of one second. The FSRs' are calibrated to only respond to a kneel when at least half of the body weight is acting through the kneeling knee joint. False kneeling events due to slight bending of the knee during walking were eliminated by decreasing the sensitivity of the activation pressure resistance level.

A.3. Microprocessor and peripherals

The heart of this device is a Motorola 6800 series 8 bit microprocessor which controls all functions of the dosimeter (Fig. 9A). This series was selected for its versatility, CMOS compatibility, and analog to digital integration capability. The microprocessor has 4 K of EPROM available for program storage. It has 128 bytes of internal scratchpad RAM and a 64 K external RAM chip is used for data storage. CMOS logic inputs/outputs

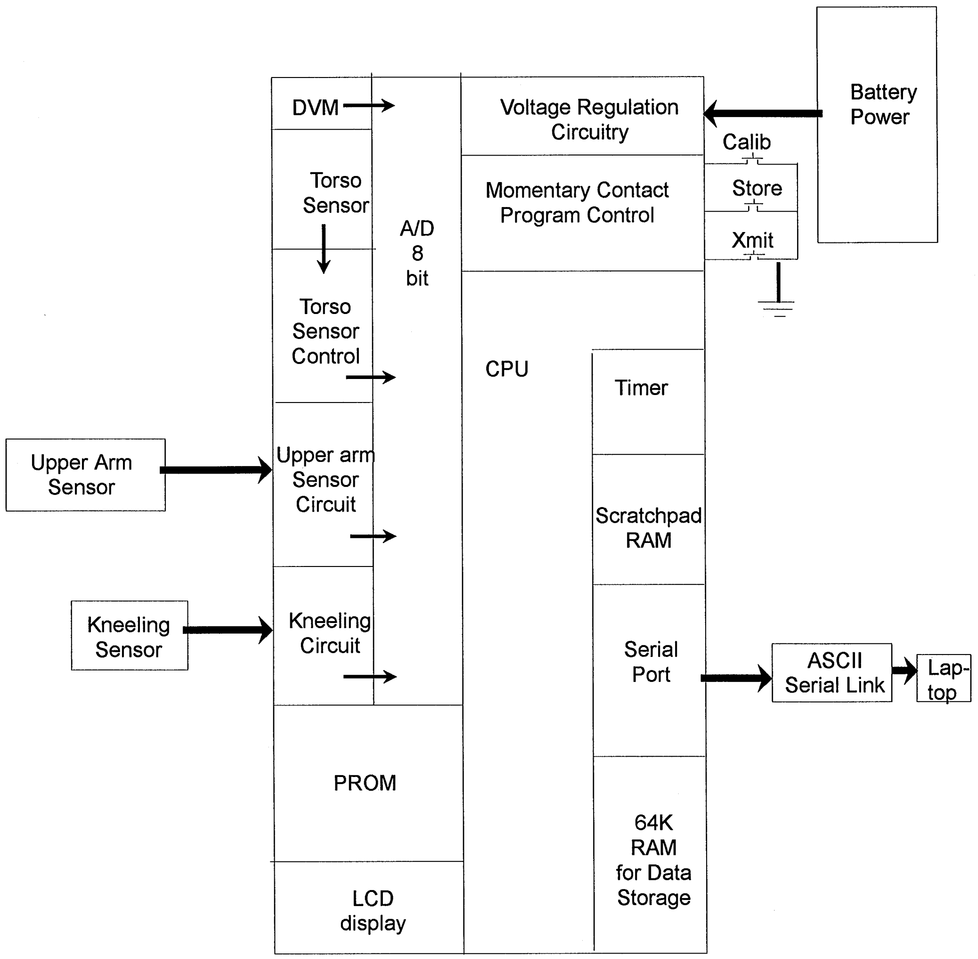

Fig. 8 Schematic of various components within the ergonomic dosimeter

(I/O) were connected directly to the Central Processing Unit (CPU) digital I/O.

The programming language is Motorola 6800 8 bit assembly code. The microprocessor instructions are burned into the EPROM which furnishes the CPU with the necessary programming information. Motorola 6800 timer/interrupt handling codes are implemented to insure timing accuracy.

The display panel used is a LCD type which is a low-power device with 40 character by four line display. The size of the character is 1.01 cm. The functions of the dosimeter are selected via three momentary contact switches operating in conjunction with the LCD display. The screen is designed to display calibration information, real time angular posture data, kneeling events and total kneeling period. The battery status is also displayed.

Two 12 V battery packs each consisting of eight AA alkaline or carbon/zinc cells are used for the operation of the dosimeter. The dosimeter is designed to operate for a 10 h period with AA size cells. The dosimeter requires about 0.075 and 0.045 A of current on the positive and the negative sources, respectively.

A.4. Data downloading features

The dosimeter is designed to allow transferring of collected data (upto 64 kbytes) through an interface box and a standard RS-232-C ASCII link to a IBM PC/AT or compatible computer (Fig. 9D). Data transmission checking is included in the microprocessor communication code design. A standard nine pin PC AT compatible serial connector is mounted on the dosimeter housing to facilitate transmission to an IBM PC compatible serial port.

A.5. Hardware operation

Fig. 8 shows a schematic illustrating the relative relationships of all the components within the dosimeter. The dimension of the dosimeter box is 17.8 cm × 8.9 cm × 3.8 cm and weighs less than 0.5 kg. As the power switch to the dosimeter is turned on, the system performs an internal memory check on installed RAM and displays the results of this operation. If the voltage of the power source falls below 8.8 V, a "Battery Low" message is

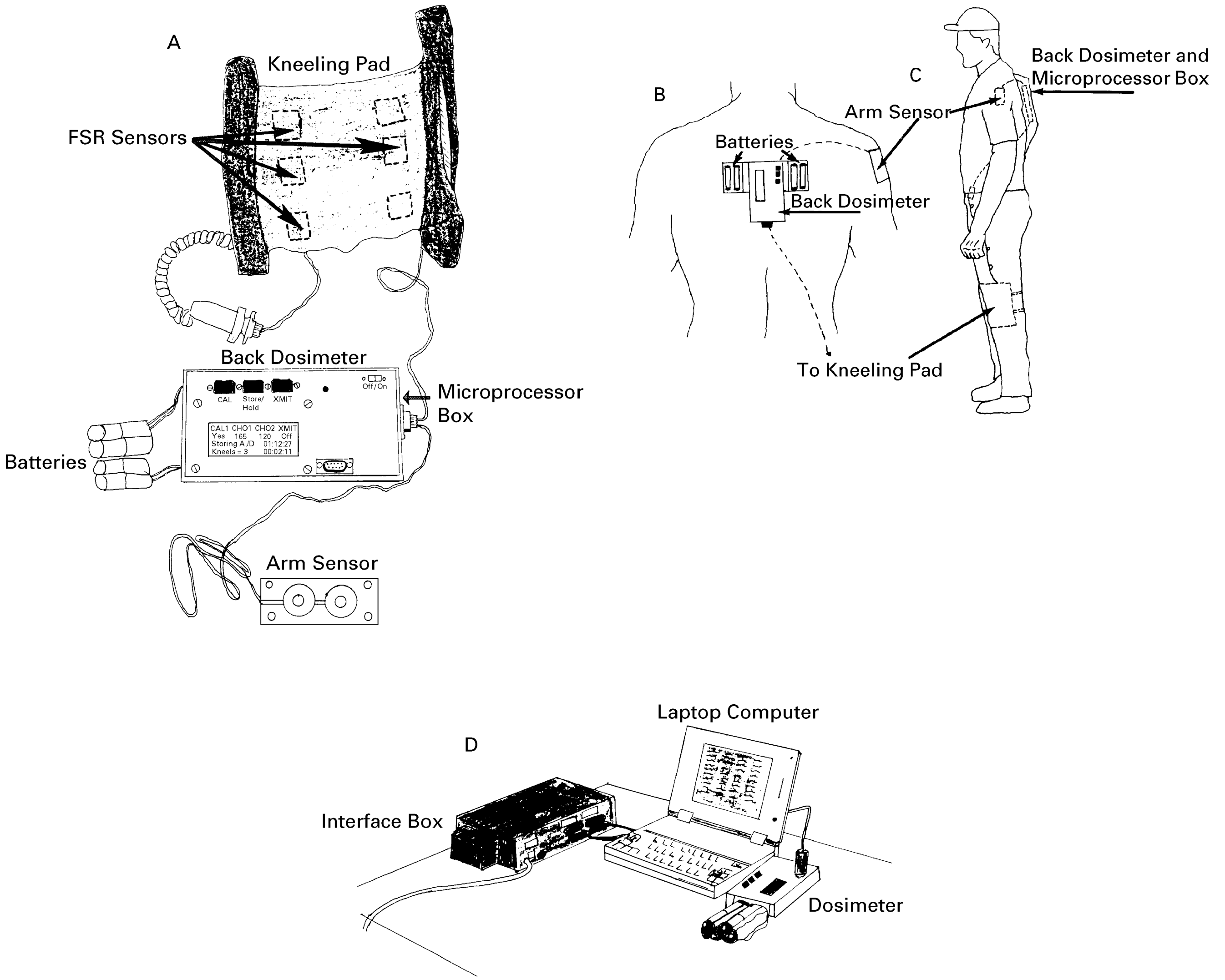

Fig. 9 (A) Kneeling pad, back (torso) sensor, arm sensor, and microprocessor box with battery. (B) Location of attachment of the back (torso) sensor. (C) Relative positions of back and arm sensors and kneeling pad inside the work- coverall. (D) Ergonomic dosimeter connected via interface box to the lap-top computer for data transmission.

flashed on the display screen. Three momentary contact control switches, "calibrate", "store/hold" and "transmit" provide complete operation of the dosimeter (Fig. 9A). The "Calibration" switch on the front panel (above the display screen) of the dosimeter activates a single data conversion from the angle sensors. This conversion is used to verify the predicted position of the sensor. The activation of "Calibration" switch also clears the RAM of the previously generated data set making the display screen to show zero collected values. The "Collect Data" switch initiates the collection of data from all three sensors at 1 Hz frequency. The timer information in seconds, minutes and hours is displayed continuously as long as the data acquisition is active. To terminate the data acquisition the "Collect Data" switch is again depressed. This stops the collection of data and the number of collected values are displayed on the LCD screen. All sensor information is retained in the RAM.

To transmit the stored data dosimeter is removed from the subject and connected to the transmission cable from the dosimeter to the serial port of the microcomputer via the serial ASCII interface box (Fig. 9D). Next, the transmission button is depressed to transmit a starting sequence, all collected data, and an ending sequence. The same data can be re-transmitted if necessary. Software programs have been written for the IBM PC which verify correct transmission of the data.

A.6. Parameters measured

The following parameters were measured with the dosimeter: Angles of limb with respect to gravity, total number of times body part(s) assumed a posture, total length of time body part(s) stayed at a posture and number of kneels and total length of kneeling time.

A.7. Method of attachment

The dosimeter was attached to individuals using a pair of modified short sleeve work-coveralls made of a lightweight fabric (Fig. 9B and 9C). The coveralls were modified with pockets for each dosimeter sensor (arm and back). Coveralls were selected to protect the connection wires and allow an individual wearing normal work clothes to step into the coveralls and have a comfortable fit. The lightweight fabric was chosen to minimize risk of heat stress. The coveralls provided the most rapid method of attachment and could easily be adjusted to fit a wide range of sizes.

The pant legs of the coveralls had ankle slits and equipped with velcro strips. The slits allowed the coveralls to be slipped over work boots. Pockets sewn into the inside of each sleeve held the upper arm sensor. The arm sensor was placed on the dominant arm of the worker being monitored. The sleeves have adjustable velcro strips to hold it securely to the side of the arm being monitored. The pockets were lined with vinyl plastic for moisture protection.

A pouch sewn into the back of the coveralls consisted of three separate pockets (Fig. 9B). Two of the pockets contained the battery packs used to power the dosimeter. The main pocket held the device containing the dosimeter microprocessor and torso (back) sensor. These pockets also were lined with vinyl plastic for moisture protection. An outer layer of fabric was attached over the main pocket to protect the plastic and provide a window to observe the dosimeter display readout. The window allowed the dosimeter to be periodically checked during monitoring sessions. Velcro strips were sewn across both shoulders to help support the weight of the dosimeter and to hold the dosimeter tightly to the back so that the back angle sensor was properly oriented to measure angles in the sagittal plane. Prior to donning the coveralls, the kneeling meter was attached with adjustable velcro strips sewn across the top and bottom of the knee pad and was wrapped around the knee. The connection wire clipped into a belt loop located about waist high on the inside of the coveralls. The inside of the coveralls were equipped with velcro strips running across the shoulders and down to each hip to hold the excess wires connecting the sensors and kneeling meter to the microprocessing unit located in the back dosimeter. The exterior of the coveralls also were sprayed with Scotchgard^{tm} for further waterproofing to protect the electronic components of the dosimeter.

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