DEVELOPMENT AND APPLICATIONS OF A POLYNOMIAL METHOD FOR THREE-DIMENSIONAL ANALYSIS

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by

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In my father's memory

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Development and Applications of a Polynomial Method for Three-Dimensional Analysis

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Human locomotion is a complex and highly integrated form of activity. For this reason the accuracy of three-dimensional analysis is a significant factor for kinematic analysis of movement. Different techniques for three-dimensional reconstruction have been introduced, and the Direct Linear Transformation is the most frequently used. A polynomial method was developed to overcome the different shortcomings of previous methods concerning the calibration procedure and the accurate reconstruction outside the calibrated area.

To date, 16mm film has dominated as the medium used to record movement, but with the rapid development in technology, it is anticipated that video will be increasingly used for data collection in sports biomechanics. Therefore, the developed method has used video systems for 3-D reconstruction and kinematic analysis.

The developed method was examined for the 3-D coordinate reconstruction using spatial points with known 3-D coordinates. A small calibration plane (2.1 m W x 1.1 m H), relative to the calibrated volume, was implemented. The projection of any point on the calibration plane, viewed from two cameras, was computed using a first degree polynomial model constructed from local calibration points. Three-dimensional coordinates are computed using intersection techniques. The absolute measurement error ranged from 0.04% to 0.07% (of the field of view) in the X axis, from 0.05% to 0.06% in Y and from 0.05% to 0.07% in Z for control points inside the calibrated area (internal) and from 0.15% to 0.51% in X, from 0.16% to 0.42% in Y and from 0.15% to 0.46% in the Z axis for control points outside (external). The measurement error is significantly reduced compared to other video or film systems. Furthermore, this polynomial method allows linear extrapolation for coordinate reconstruction outside the calibration area and, therefore, is particularly useful in applications requiring large filming areas. In this method, there is no need to survey the camera locations and no assumptions are required for the internal camera parameters.

Panning techniques are the most appropriate methods for the analysis of athlete's movements, when these occurs in a large volume. The measurement error was considerably reduced compared with previous film or video panning studies, when the polynomial method was applied using the panning technique, ranging from 0.053% to 0.095% of the field of view. The image deformation correction algorithm used overcomes the effect of the recording angle during panning.

The accurate assessment of angular measurements was examined using the Biomechanics Workstation (BmWs) system and the developed polynomial method. The accuracy of BmWs when the zoom facility is implemented was also examined. A calibration plane with 19 markers was recorded in an underwater and an indoors environment. Five 90° angles formed by three non linear calibration points were used in the accuracy estimation of the above methods. The mean angular measurements for both environments ranged from 89.983° to 90.000° using the polynomial method, from 90.761 to 89.842 using the BmWs without zooming and from 90.700° to 90.090° using the BmWs with zoom facility. It was concluded that the polynomial method was superior to BmWs and produced accurate angular measurements in every screen location. Furthermore, there was no difference in the accuracy between the angular measurements in different environments when the polynomial method was used.

The analysis of dynamic images for the determination of skeletal deformation and joint kinematics using videofluoroscopy has been frequently implemented. However, image deformation is introduced in different stages of videofluoroscopy, reflected in the accurate reconstruction and consequently in kinematic analysis of dynamic images. The polynomial method, incorporating an image deformation correction method, was examined for the reconstruction of spatial points using videofluoroscopy. Different angles between image intensifier and calibration plane were used, as well as different sets of calibration points. The results indicate that the absolute mean error was considerably reduced compared with previous studies. The different amount of image deformation produced in every screen location has been effectively corrected. The number of calibration points affects the accuracy of the reconstruction. Thirty calibration points is the minimum number of calibration points required using this polynomial method, when the angle between object and X-ray ranges from 90° to 60°.

Determination of the optimal movement using accurate reconstruction methods affects athlete's performance and prevention of injuries. The knee kinematic parameters determined using the developed polynomial method, were within the range reported in previous studies. The estimated kinematic parameters for level and downhill running were: 20.9° and 17.4° respectively for the flexion angle in the footstrike, 36.2° and 43.1° for the peak flexion angle during the stance phase and 7.1 rad*s^{-1} and 7.4 rad*s^{-1} for the peak flexion angular velocity.

It can be concluded that the polynomial method presented is an accurate and easily implemented method for three-dimensional reconstruction and kinematic analysis. The main advantages of the method are the simple calibration procedure, image deformation correction and possibility for accurate reconstruction outside the calibrated volume.

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CHAPTER 1

INTRODUCTION

INTRODUCTION

Biomechanical analysis has a widespread application in the examination of human movement. Different techniques and standardized processes from other disciplines, such as mathematics, physics, anatomy, physiology and computer science, apply equally to biomechanics (Chaffin and Andersson, 1991). Different terms such as Biokinematics (concerning purely geometric descriptions of motion); Biodynamics (with special reference to the mass and forces); Bionetics (defined as the study of the structure and function of biological systems, see Hatze (1974)) have been used by researchers in an attempt to define this discipline. The term Biomechanics identifies the study of mechanical aspects of the structure and function of biological systems (Miller and Nelson, 1976; Subotnick, 1985; Enoka, 1988). Kinesiology is the subdiscipline of biomechanics which embraces the whole area of human movement (Miller and Nelson, 1976; Enoka, 1988; Winter 1990). It can be classified into kinematics and kinetics. Kinematics considers the motion of the whole body or body segments independent of the causes of these movements (Miller and Nelson, 1976; Robertson and Sprigings 1987; Cavanagh, 1990). In the study of kinetics, the forces that result in the movement of the body or segment are examined (Gagnon *et al.*, 1987; Enoka, 1988). Kinematic characteristics of a motion include the position and both linear and angular displacements, velocities and acceleration. Forces, energy and power are kinetic characteristics.

In examining any athletic or human movement, one must be aware of the limitations of data collection procedures. Movements can be captured by an observant eye. The eye is certainly an adaptable device, but it does have limitations. It is relatively slow, it can only concentrate on a small proportion of the great variety of visual information, and its usefulness is also limited by the small capacity, short - term memory to which it has access. Consequently if the eye is to be employed, efforts must be made to compensate for the weaknesses of this method of analysis, to establish good visual search strategies, to minimise the data gathered, and to organise memory aids. Therefore, where the properties of movement are to be determined with accuracy, the eye ceases to be adequate and other recording techniques must be applied. The data collection process in biomechanics is highly dependent upon technological advances and the rapid changes in this field, which are still taking place (Smith, 1975; Atha, 1984; Robertson and Sprigings 1987; Dainty *et al.*, 1987; Chaffin and Andersson, 1991; Yeadon and Challis, 1994). These changes facilitated the development of hardware, software and their applications. Furthermore, the development of rigorous data processing and analysis procedures has changed the whole concept of what should be valid in interpreting both collected raw and mathematically derived data. Continual advances in the field of microelectronics and high technology provide new instrumentation and techniques which offer more accurate and specific information for any kind of analysis. New sensors and recording techniques permit the measurement and evaluation of human movement parameters in a fraction of the time (Smith, 1975; Atha, 1984; Robertson and Sprigings 1987; Dainty *et al.*, 1987; Chaffin and Andersson, 1991). In recent years, such performance data has allowed applied biomechanics to be highly qualitative, in order to improve movement performance, prevent or reduce the risk of injuries and offer significant assistance in the rehabilitation from injuries. For instance, the extensive development of applied biomechanics in the field of exercise physiology and sports medicine have provided reliable evaluation and prediction methods for the functional assessment of joints, physical strength and flexibility (Miller and Nelson, 1976; Davis *et al.*, 1988; Andriacchi, 1990; Cappozzo and Gazzani, 1990; Chao and An, 1990; Paul, 1990), or the most appropriate joint rehabilitation treatment (Grimpy, 1985; Burnie and Brodie, 1986; Baltzopoulos and Brodie, 1989).

Due to the complexity of human movement, a large and accurate data-base is required for statistical evaluations and the total analysis of movement. The field of kinematic analysis has been enriched with a plethora of studies in two dimensional (2-D) analysis, considering the movement in one plane, and more recently with three dimensional (3-D) analysis, using the reconstructed image landmarks obtained from two different views. While some activities may be justifiably examined in two dimensions, the majority of analyses are three-dimensional, despite the increased information and processing requirements (Atha, 1994; Dainty *et al.*, 1987; Yeadon and Chalis, 1994).

Different 3-D methods have been introduced, but the most frequently used is the Direct Linear Transformation (DLT) presented by Abdel-Aziz and Karara (1971), which permits arbitrary camera placement, but requires that calibration points with known locations to be distributed throughout the activity space. The limitations in the calibration procedure (Chalis and Kerwin, 1992; Chen *et al.*, 1994; Yeadon and Chalis, 1994) and the inadequacy of the method for accurate reconstruction outside the calibrated volume (Shapiro, 1978; Wood and Marshall, 1986; Chen *et al.*, 1994) have resulted in the development of modifications to the DLT method (Miller *et al.*, 1980; Hatze, 1988) and polynomial methods (Andriacchi *et al.*, 1979; Woltring, 1980; Dapena *et al.*, 1982; Fioretti *et al.*, 1985; Woltring and Huiskes, 1990).

In the present study, an alternative 3-D method for kinematic analysis is introduced using video systems for the recording and analysis process, which can effectively overcome the shortcomings of previous studies in calibration procedure, deformation of the image and accurate reconstruction outside the calibrated volume.

Chapter 2 is a review of the literature, examining the development and present state of research and considering the instrumentational, methodological and mathematical limitations of previous 3-D studies.

The development of a linear polynomial method for 3-D kinematic analysis using a simple calibration structure and a correction technique for the image deformation, when video systems are used, is presented in Chapter 3. In this Chapter the reconstruction error of points outside the calibrated volume, is also estimated.

Since many human movements, especially in sports events, occur in a large field, a method to record the entire movement space is required. The rotation of the camera(s) about a vertical (panning) or horizontal axis (tilt) is the most frequently used technique to overcome the above shortcomings and has been applied for two and three dimensional analysis (Dapena, 1978; Chow, 1987; Gervais and Wronko, 1988; Hay and Koh, 1988; Gervais *et al.*, 1989; Yeadon, 1989; Chow, 1993; Yu *et al.*, 1993). In Chapter 4 the polynomial method presented in Chapter 3 was used to determine the 3-D coordinates of spatial points when a panning technique is applied.

A modification of the polynomial method proposed in Chapter 3, for 2-D analysis is implemented in Chapter 5 to determine angular measurements underwater (for swimming applications) and indoors. The polynomial method was compared with the respective values of angular measurements produced using the Biomechanics

Workstation (BmWs).

An application of the polynomial method in the field of joint kinematics for sports medicine or rehabilitation applications, is presented in Chapter 6. The method was implemented for the calibration of a videofluoroscopy system (continuous X-rays recorded on video), for image deformation correction and for measurement of joint kinematics.

Gait analysis techniques have been applied to a wide variety of human locomotion problems. Accurate 3-D kinematic analysis of the lower limb is a significant factor for the prevention of injuries and improvement of athlete's performance. In order to demonstrate the application of this method for kinematic analysis of movement, the 3-D polynomial method has been applied in kinematic analysis of level and downhill running. Joint kinematics and a comparison of the results with other published studies in the same field are presented in Chapter 7.

The development of a computer program and detailed explanation of the function of the software procedures implemented in the above studies, is presented in Chapter 8.

The detailed description of the computer program is presented in Appendix I.

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CHAPTER 2

REVIEW OF THE LITERATURE

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INSTRUMENTATION IN KINEMATICS

The classical recording instrument of motion is the camera. It has been used for recording not only of the slowest but the fastest of movements. As the technology in the field of recording methods progresses, more sophisticated and automated techniques are being developed (Mitchelson, 1975; Leo and Macellari, 1981; Cappozzo *et al.*, 1983).

The most frequently used technique in bioinstrumentation for the measurement of kinematic variables is cinematography. Recording frequencies in excess of 10,000 frames per second may be achieved with modern high speed cameras (Hennig, 1988). For most applications in biomechanical movement analyses, frame rates from 100 to 400 Hz are appropriate (Smith, 1975). High quality camera lenses should be used to reduce lens distortion of the film image (Phillips *et al.*, 1984; Wood and Marshall, 1986). With the use of a good quality zoom lens, maximum image size can be achieved. For the accurate determination of the film data points, it is important to have high quality film analyzers and digitizers. A quality analyzer should provide film magnification in excess of 25 times the film size and should register each frame precisely in the grid for consistent analysis (Dainty *et al.*, 1987). The resolution (the ability of a system to distinguish fine detail in a screen that is being recorded) achieved using this system is high (usually measurement error ranges from less than 0.1 mm to 0.5 mm) and consequently, produces accurate results in movement analysis. However, cinematographic analysis is time-consuming, and therefore tends to be confined to the study of transient phenomena, since quantification of movements over longer periods is rarely practical (Atha, 1984;

Hennig, 1988; Nike Sports Research Laboratory, 1991). Furthermore, results are never immediately available for inspection, thus, there is no feedback of information and serious recording faults may pass unnoticed until the film has been developed and viewed days later. A serious problem in cinematography is the synchronization of the cameras during the recording procedure, reflected in the increase of measurement error (Miller *et al.*, 1980). Different techniques have been used to effectively overcome this source of error, such as the flash bulb (Noble and Kelley, 1968; Ben-Sira *et al.*, 1978; Miller *et al.*, 1980), or the electric sweep-hand clock technique (Elliot *et al.*, 1986). For perfect shutter synchronisation, the cameras should be phase-locked (Yeadon and Challis, 1994). The developing and replacing costs of filming, have also become important considerations. Film stock can be used only once, so erroneous and outdated material is not re-usable. In addition, artificial light is required for indoor filming.

Optoelectronic systems (i.e. CODA-3, EXPERTVISION, SELSPOT II, WATSMART, ELITE) are generally comprised of passive or active light-emitter(s) attached to the point of interest on the body, a remote receiver and a microprocessing system designed to compute the displacement function of the body (Mitchelson, 1975; Leo and Macellari, 1981; Cappozzo *et al.*, 1983). When the image of an infrared light source is projected and focused through a lens onto the surface of the photodetector, current will originate from this point. The resolution of the sensors is very high and the distortion produced by the sensors lens is negligible (measurement error 1: 32,000 and standard deviation less than 1: 10,000 for stationary markers) (Furnee, 1990). This type of system permits instantaneous analyses and is able to determine a large number of points (14,400 in Ball and Pierrynowski, 1988a). In spite of the excellent technical data produced, the reflecting lights present a problem that must be seen as a severe limitation. Optical reflection from a single marker may produce more than one light image on the photodetector and this will result in erroneous outputs. Furthermore, any measurement system that comes in direct contact with the subject (such as the optoelectronic systems), may hinder the normal movement pattern and so this must be considered. These systems can be used only in laboratory conditions.

In classical cinematographic studies, such as aerophotogrammetry (Yeadon, 1989), cameras of which the internal characteristics are completely known (metric cameras) are used. The internal characteristics are so-called parameters of interior orientation: position of the image plane with respect to the optical axis and the image distortion. Other characteristics of this camera are the fixed focus and the diaphragm shutters located within the lens. Although metric cameras may be available, they are often considered too expensive for routine use in biomechanichal analysis. In biomechanics, both cinematographic and optoelectronic non-metric cameras are usually implemented (Winter *et al.*, 1974; Woltring, 1974; Shapiro, 1978; Karara, 1980; Woltring, 1980; Dapena *et al.*, 1982; Fioretti *et al.*, 1985). A non-metric camera's interior orientation is completely or partially unknown and frequently unstable. The advantages of non-metric cameras (compared with the metric) are: the flexibility of the focusing range; their usual smaller size, lighter weight, handling; orientation in any direction; availability of film, and considerably reduced price.

Interfacing video cameras with computer systems has provided a method of acquiring kinematic data much more rapidly and conveniently than the above systems. It allows instantaneous feedback of the subject's movement during data collection, using TV monitors and also immediate playback and picture "freezing" of the recorded data, for the analysis process (Winter, 1979; Atha, 1984). The camera tubes are more sensitive compared with cinematography systems (have variable speed shutters to accommodate the various light levels) and so can be used in low light conditions. However, retro-reflective markers and an intensive light source must be used when the contrast of landmarks to background is not sufficient, affecting digitization accuracy, or for recording high speed movement. Furthermore, the running cost for video systems is low because the video tapes are re-usable. This allows mistakes in the recording procedure to be erased and tapes containing outdated data to be used again. Furthermore, additional information from other sources (EMG, force platform, other video) or text can be included or superimposed on the same video tape, before or after the recording task. This permits simultaneous analysis of different kinematic parameters of the same movement in different planes. Block (1982) highlighted the contribution of video systems in the reduction of injuries.

Generally video systems permit a sampling rate of 25 Hz (30 Hz in USA), with ability to increase the recorded frames to 50 per second (60). However, modern high speed video is available at rates in excess of 1000 Hz (Shapiro *et al.*, 1987). The SP-2000 video system has a framing rate of 2000 Hz and can record continuously for one minute to produce 120000 frames of data (Paisley, 1981). Winter *et al.* (1972) provided an early system of video scanning for examining slow human motions such as gait. Recently improved video systems use reflective points for digitizing purposes (i.e VICON). The introduction of the mechanically shuttered and the strobe-effect non-mechanically shuttered video cameras provide a less costly option. With a shutter to control exposure times, this type of camera, although still limited to 50 (or 60) frames per second, can provide adequate output for biomechanical analysis of movements including walking, running and jumping, but may not be appropriate for highly detailed studies requiring investigation of impact, such as in tennis, or the rapid action of any limb, such as the movement of the arm during ball release in throwing.

The low resolution of video systems compared with cinematography presents another limitation. The resolution in video systems is determined by the number of pixels or lines which make up the screen display. When the number of pixels or lines is increased, higher screen resolution is achieved. The horizontal and the vertical screen axes have different number of pixels or lines. Different graphic adaptor cards for the standard IBM - compatible computers provide a choice of different resolutions (Ohlsen and Stoker, 1989). Recently new types of video systems (high definition video cameras) have been introduced with higher resolutions, minimizing the limitation of the video systems due to the low resolution (Hennig, 1988; Kerwin and Maybery, 1993).

Previous studies compared the accuracy in coordinate reconstruction produced by video and cinematography systems, in two and three-dimensional coordinates reconstruction (Shapiro *et al.*, 1987; Kennedy *et al.*, 1989; Kerwin and Templeton, 1991; Angulo and Dapena, 1992). These studies indicate that film systems are more accurate than video, but this difference is not significant considering the measurement error as a percentage of the field of view in a large filming volume (Kennedy *et al.*, 1989). Consequently the use of video or cinematography systems depends on the requirements of each study.

SMOOTHING TECHNIQUES - ERROR REDUCTION

Type and sources of error

Two main types of error can be identified: measurement error and computing error (Hatze, 1990). The measurement error may be classified into systematic and random error (D'Amico and Ferringo, 1992). Systematic measurement errors introduce artificial signal (noise) into the data which may be difficult to detect and eliminate. This type of error is produced by the high frequency components included into the main signal of the observed data. These are difficult to eliminate effectively since these oscillations (cased by artificial high frequency components included in the signal) are in the frequency range of the signal to be analyzed. An important source of systematic error is the linear and non-linear lens distortion of the cinematographic, optoelectronic and video systems (Shapiro, 1978; Andriacchi *et al.*, 1979; Winter, 1979; Miller et al., 1980; Woltring, 1980; Wood, 1982; Hatze, 1990; Chaffin and Andersson, 1991). Lens distortion is either radial which causes displacement of image coordinates radially to or from the centre of the image field; or tangential which causes displacement of image coordinates in a direction perpendicular to radial lines from the centre of the image field resulting in "pin-cushion" or "barrel" distortion (Woltring, 1975). Both types of lens distortion deform the image and therefore affect the accuracy of movement analyses. In many studies the error produced (by lens distortion) in the analysis process, is higher in the periphery than in the centre of the screen (Woltring, 1975; Atha, 1984; Phillips *et al.*, 1984; Wood and Marshall, 1986; Pigos and Baltzopoulos, 1992). However, Whittle (1982) has reported no clear accuracy differences in the different locations. Therefore, various techniques have been developed in order to reduce lense distortion (Andriacchi *et al.* 1979; Miller *et al.*, 1980; Woltring, 1980; Hatze, 1988).

Another source of systematic error is the shift of body markers positions with respect to anatomical landmarks. This could be caused by the movement of additional equipment placed on the skin near the markers during the recording process, or a faulty perception of where an anatomical point or joint centre lies (these factors vary with movement) (Ronsky and Nigg, 1991).

Random error is produced primarily by the digitization process (D'Amico and Ferringo, 1992), but is also caused by film deformation and movement of the camera or projector. This type of error is usually assumed to be additive, normally distributed with a mean error of zero (zero-mean noise) and independent of the main signal (McLaughlin *et al.*, 1977).

The topic of computing errors is an important section of numerical mathematics. Computing errors result mainly from the conversion (analog to digital), truncation and rounding of numbers, and from algorithmic approximations (mathematical models) in the computing process.

Smoothing Techniques

Since applied biomechanics has emerged as an important of human movement analysis, specifically in sport activities to permit the distinction between movement of high-level performers, accurate measurement of human movement is required. Therefore, the measurement error must be eliminated or reduced by incorporating appropriate correction algorithms. There are several different methods for data smoothing utilized in biomechanics. In the past, researchers have used manual plotting methods to draw smooth curves connecting the average point for every two neighbouring data points (line of best fit). These procedures have evolved into a more sophisticated form using digital computers and appropriate software.

Polynomial smoothing

When smoothing method using different order of polynomials, the basic assumption is that the trajectory signal has a predetermined shape. However, the selection of the appropriate order of polynomial is a significant limitation of this method. In many studies an arbitrary order is choosed, usually third or fifth (Zernicke *et al.*, 1976). Moreover, the polynomial smoothing method produces highly over-smoothed and unrealistic second derivatives (Pezzack *et al.*, 1977; Hatze, 1981).

Splines

Reinsch (1967), Greville (1969), McLaughlin *et al.* (1977) and Woltring (1985) introduced the use of spline functions to smooth experimental data. A spline function consists of a number of polynomials, all of low degree, which fit through groups of N data points and join at points called "knots" in such a way as to provide a continuous function with continuous derivatives (Wood, 1982). It is a piece-wise differentiable polynomial function satisfying certain continuity conditions on the derivatives of the data points (Vaughan, 1982). When using this method, the degree of the spline, the required accuracy of the fit (least-squares criterion), and the number and position of the knots must be specified. That means that the investigator is required to select a parameter that controls the extent of smoothing. This parameter is reported as the smoothing factor and specifies how close the curve is to the original data (Phillips and Roberts, 1983). A smoothing factor that is too low results in undersmoothing of the data, whilst a smoothing factor that is too high has the opposite effect. The most frequently used spline polynomials are the cubic (third order polynomials) and the quintic spline (fifth order polynomials). According to previous studies (Hatze, 1981; Vaughan, 1982) cubic are inferior compared to quintic spline.

The difference between the spline and the polynomial smoothing method is that the least square error using spline, may be varied continuously as an input parameter by the operator whereas using polynomials, it is restricted to a given value.

Fourier series

This method is based on the assumption that any periodic waveform can be presented as sum of sine and consine functions with increasing frequency. In order to analyse a periodical signal, the frequency content must be expressed in terms of the fundamental frequency (Winter, 1979; Wood, 1982). The first sine and cosine terms represent functions describing one cycle in the total time period and subsequent terms represent functions whose frequencies are multiples of the fundamental frequency. These functions are called harmonic components of the signal (Winter, 1979; Wood, 1982). A fourier filter cuts off any high frequencies (noise) that are above the selected cutoff frequency and thus the filtered signal will then be composed by the low frequency harmonics. In practice this is achieved by multiplying the high frequencies (above the cutoff frequency) by 0.0 and the low frequencies with 1.0.

Digital filter

Another smoothing method is the digital filter method. Filtering of any "noisy" signal is achieved through the selective rejection, or attenuation, of certain frequencies. Thus, in this method only the lower frequency components of the signal pass unattenuated. With this technique, there is a problem with the selection of the cutoff frequency, especially when there is a region where the signal and the noise overlap. If the cutoff frequency is too high, a high percentage of noise is allowed to pass through and if it is too low, the noise is drastically reduced, but at the expense of increased signal distortion.

It is evident (Winter, 1979; Wood 1982) that using the above techniques in order to minimize the measurement error, the higher-frequency noise can be severely reduced but can not be completely eliminated. The evaluation of smoothing techniques has been reported in several studies with different conclusions (Hatze, 1981; Lanshammar, 1982; Vaughan, 1982; Garhammer and Whiting, 1989). It can be concluded that the type of smoothing method adopted should depend upon the data being analysed. Digital filters have been frequently implemented for human movement analysis and especially in gait analysis (Williams and Cavanagh, 1983; Winter, 1983; Buczek and Cavanagh, 1990; Hamill *et al.*, 1992; van Woensel and Cavanagh, 1992). For this reason digital filters were implemented in the present study.

TWO AND 3 DIMENSIONAL TECHNIQUES

2-Dimensional - Single plane technique

In a 2-dimensional (2-D) recording and analysis procedure, the kinematic characteristics (i.e position, velocity, acceleration) are analyzed by assuming that the entire movement pattern occurs in a single plane, perpendicular to the camera axis. For this recording method, a single camera, in conjunction with a simple calibration structure for vertical and horizontal scaling are sufficient to provide movement data analysis. Furthermore, the mathematical models required are generally simple. Two dimensional linked segment models and inverse dynamics methods have been used in biomechanics, in order to provide kinetic and kinematic analyses of human movement. The appeal of single-plane motion recording lies in the immediacy of an attractive representation of the movement sequence. The most significant disadvantage of the 2-D technique is that it allows analyses only in a preselected single plane of movement (Winter *et al.*, 1974; Dainty *et al.*, 1987; Yeadon and Challis, 1994). Thus, although normal running or walking can be well presented in a single plane, if the runner has any limb rotation, the two-dimensional procedure is inadequate for accurate analysis.

3-dimensional - (Space) technique

In contrast to the rather simple 2-D methods, three dimensional (3-D) analyses require significantly greater measurement sophistication. Humans use two eyes to view objects in space. Working together, the eyes establish depth perception, in order to provide three dimensional images. A similar procedure is required for 3-D image reconstruction. With the use of 3-D procedures, non-planar movements can be estimated with accuracy. Thus, measurement errors, such as the perspective error, are minimized. The move from two to three-dimensional analysis involves a considerable increase in the data to be handled, and this is an important problem which must be overcome. In 3-D analysis, all joint and mass centre locations must be resolved with respect to a reference axis system. The movements are defined using a 3-D Cartesian coordinate system. A Cartesian coordinate system is comprised of three perpendicular axes: X, Y, Z with a common origin. Generally two or more cameras must simultaneously record individual segment markers. Accurate 3-D analysis can not be performed by the limited information provided by a single camera (Winter *et al.*, 1974; Miller *et al.*, 1980; Whittle, 1982; Atha, 1984). However, the three dimensional procedures demand greater time to set up the (usually) complex calibration structure and additional equipments (camera(s), measurement equipment) (Yeadon and Challis, 1994). In the analysis process more sophisticated mathematical models with the incorporation of more complex computing programs were required (Smith, 1975; Dainty, *et al.*, 1987; Ball and Pierrynowski, 1988a).

Improvements in accuracy for 2- and 3-dimensional procedures may be gained in a number of ways: through better data collection hardware (camera design, high quality lenses); assessment of improved data recording procedures (camera placement, use of multiple cameras); and improved techniques for the collection (calibration methods, different type of recording equipment) and analysis of kinematic data (using mathematical models).

Human activities often combine directional changes with simultaneous twisting or bending in space. It is evident that the use of 2-D recording procedures for three-dimensional movement are only appropriate for a small range of movements and generally present significant problems in interpretation (Bergemann, 1974; Winter *et al.*, 1974; Smith, 1975; Dainty *et al.*, 1987). The easy implementation of single camera and the simple mathematical models required in a 2-D technique, has deceived many investigators to use the 2-D technique. In the majority of these studies many parameters are estimated using scaling techniques. The measurement error in these studies is high and consequently inadequate for accurate movement parameters estimation. Consequently, the 3-dimensional analysis can be applied in a wide variety of human movement and it is more accurate than 2-D analysis.

CLASSIFICATION OF 3-DIMENSIONAL KINEMATIC TECHNIQUES

Several three dimensional reconstruction techniques are available. These will be categorized in this thesis according to the instrumentation implemented and the analysis technique.

Number of cameras

Although, more frequently two or more cameras are used, some researchers have developed 3-D single-camera procedures.

3-D single-camera technique

Miller *et al.* (1980) have reported a 3-D single-camera technique which can determine the kinematic parameters using three (at least) body markers of known 3-D coordinates relative to the origin of the calibration structure. However the results from the implementation of two cameras (placed left and right relative to the filming area) indicated that the accuracy using only either the left or the right-hand camera (for the estimation of 8 markers) was significantly lower than these of both cameras. Similarly, Bourgeois (1983) used a method for estimation of kinematic and dynamic parameters pertinent to crawl swimming using only one camera. However, this method is only valid when the 3-D coordinates of at least one marker are known relative to the inertial coordinate system. In addition, it was assumed that the shoulder motion was parallel to the long side of the swimming pool, where the camera had been positioned.

The mirror technique is a different type of 3-D single-camera method. In this procedure a plain mirror is placed in such a way that the object and its image by the mirror, can be recorded by a single camera (Bernstain, 1967). Although this method has the advantage of the perfect synchronization in the recording procedure, is limited because of the mirror distortion and it can be used only in a laboratory environment.

Multiple-camera 3-D techniques

Stereographic technique

In this technique two photogrammetric cameras are positioned side by side a known distance apart and on the same level, with their optical axes horizontal, parallel and perpendicular to the baseline. The three dimensional coordinates of any point can be determined by the effective lens-image distance, the baseline of the cameras and the measured coordinates of the image (Bullock and Harley, 1972). This technique requires metric cameras with precisely known (and preferably the same) internal characteristics. However, these cameras are still and very expensive, and consequently this method can not be widely implemented.

Fioretti *et al.* (1985) have described an alternative stereophotogrammetry method using a highly accurate polynomial model with non metric cameras. The accuracy of the model was tested using two parallel planar calibration grids forming an area of 200 x 200 x 88.75 mm. However, this method requires ideal cameras (with known inter-camera distance) and the model has been empirically produced and consequently is a black box approach, more appropriate if the observation volume is sufficiently small (smaller than 0.5 m^3).

Direct Linear Transformation (DLT) method

In 1971, Abdel-Aziz and Karara developed the DLT method that allowed the use of non-metric cameras. Although, the initially developed method required the use of still cameras, with the development of computer methods, the procedure can be applied using any type of cinematographic, optoelectronic or video camera. The innovation in the DLT technique is the concept of the direct transformation from comparator coordinates into object space coordinates, thus by passing the intermediate step of transforming image from a comparator system to a photograph or screen coordinate system. The position and orientation of the cameras are estimated using control points mounted on various types of three-dimensional calibration structures. Two linear equations with 11 unknown parameters (for each camera) are used to define the camera coordinates and subsequently the position of every point using the U, V coordinates of its image.

$$U+\delta U+\Delta U=\frac{L_1 X+L_2 Y+L_3 Z+L_4}{L_9 X+L_{10} Y+L_{11} Z+1}$$

$$V+\delta V+\Delta V=\frac{L_5 X+L_6 Y+L_7 Z+L_8}{L_9 X+L_{10} Y+L_{11} Z+1}$$

where : X, Y, Z are the coordinates of the point (must be determined) in space.

U, V are the digitized coordinates of the point.

L_i (i = 1..11) are coefficients called transformation coefficients.

δU, δV are nonlinear systematic error.

ΔU, ΔV are random errors..

Therefore, a minimum of six non-planar control points must be detectable by each camera, for the solution of the DLT mathematical expressions. Additional parameters were used in order to express the linear (symmetrical) and non-linear (asymmetrical) lens distortion. With later studies only one parameter is required (Karara, 1980) for modelling lens distortion and film deformation.

The evaluation of the DLT method and its applicability in high-speed cinematography using two cameras was investigated by Shapiro (1978). A 3-dimensional calibration structure formed by 48 calibration (control) points with known coordinates relative to an origin (centre of the base) was used, but only twenty of them were selected to estimate the 11 DLT parameters. The average measurement errors were approximately 4 mm for X and Z axes, and 5 mm for Y. In the dynamic test the acceleration of the ball in free fall ranged from -9.5 m/sec^2 to -10.0 m/sec^2. Miller *et al.* (1980) examined the DLT method and determined directly the position of a rigid body without using a 3-dimensional calibration structure. This method can be applied using only one camera and three (at least) points, with known coordinates relative to a local coordinate system attached to the body. However, this method can not be easily applied outdoors and further, accuracy can be improved by the use of multiple cameras.

The determination of any point using the DLT method is limited outside the calibrated volume (extrapolation technique) when a small calibration structure relative to a large filming is used. Wood and Marshall (1986) have used different control point configurations, different camera positions and mathematical procedures for lens distortion correction, and concluded that poor accuracy is achieved when the DLT technique is used for extrapolation. Furthermore, it was reported that better results were produced when the ratio of the distance between the cameras and the base of cameras and object was approximately 1:2, than with 1:1; and that more accurate results were obtained without correction for non linear distortions, when few control points were used.

Two modified (linear and non-linear) DLT methods were presented by Hatze (1988). In order to examine the accuracy of the 3-dimensional reconstruction using the two modified DLT algorithms and compare them with the results produced using the DLT technique a three dimensional rectangular calibration frame was constructed. In this method the calibration coefficients were constrained so that the orientation matrix of the object-to-image coordinate system to be orthogonal. The accuracy was improved using either linear or non linear algorithms compared with the DLT method. The non linear algorithm produced an accurate polynomial approximation of the control points inside the calibrated area (internal) but very low for the control points outside (external). The linear modified DLT method was accurate in the estimation both of the internal and the external control points. Further, in this study lens distortion correction was effectively achieved.

Another modified method of DLT is presented by Ball and Pierrynowski (1988b) using optoelectronic devices. In this study three different stages for the reconstruction of 3-D coordinates are used. The advantage of this method is that the 3-D calibration structure can be removed from its initial position, covering large filming areas. The new position, relative to the initial, can be determined using singular evaluations (for the 3 rotations and 3 translations). The error introduced when 3-D coordinates of points are outside of the calibrated area is minimized using nonlinear equations. However the absolute measurement error reported was 10.2 ± 5.8 mm, for a total of 3149 markers. Furthermore, the number of calibration points to be digitized is much greater than for a single calibration frame for the same level of accuracy.

Direct Linear Transformation method was used by Kennedy *et al.* (1989) in order to compare the accuracy of film and video systems. The results of this study supported the validity of video analysis and the DLT method (measurement error 0.24% and 0.29% for the film and video respectively). Similarly, accuracy estimation for a wider field of view was investigated by Angulo and Dapena (1992). In this study low accuracy was reported in the determination of the external markers (measurement error 1% and 1.3% for the film and video system), confirming the results of Wood and Marshall (1986).

The requirement for implementation of large 3-dimensional calibration structures (rather unwieldy in non-laboratory environments) for accurate analysis when the movement analyzed is performed in wide field of view, have resulted in the investigation of more convenient and flexible calibration designs. Challis and Kerwin (1992) examined the reconstruction accuracy using different calibration objects with different 3-dimensional forms and calibration points. They concluded that it is more appropriate to surround the space in which the activity is to take place than to have control points inside the space, although there may exist other control point configurations which could result in high reconstruction accuracy.

The accuracy of the DLT method for 3-D reconstruction using video systems was also reported by Chen *et al.* (1994). The results indicate that the best accuracy was achieved when the control points were evenly distributed throughout the calibrated volume (Yeadon and Challis, 1994). They also demonstrated that the measurement error is decreased as the calibration points increased and that the accuracy is reduced in the periphery of the calibrated volume (due to the lens distortion). The measurement error of the points outside the calibrated volume ranged from 1.2 mm to 14.9 mm (the distance of external points form the calibrated area ranged from 0.3 m to 0.9 m).

Other 3-dimensional techniques

Noble and Kelley (1969) used three cameras to determine the three dimensional coordinates of a moving ball in a path of a right circular helix. Two cameras were placed in the horizontal plane, 90^0 out of phase with one another. The third camera was positioned directly above the apparatus with its optical axis facing down the axis of revolution of the cylinder. The synchronizing of the cameras was achieved using a flash bulb. The determination of the coordinates of the ball was achieved using scale factors. The accuracy of this method was very low (mean error 35% of the criterion value in acceleration).

Bergemann (1974) emphasized the significance of camera placement for accurate reconstruction. In this method, two cameras were placed in the horizontal plane with their optical axes intersecting at a common origin. For the placement of the cameras, standard surveying equipment was used. Scaling techniques were used for the determination of the camera positions. Equations were derived to calculate the position of several arbitrary points on a coordinate grid. The 3-D coordinates of any digitized point is determined as the intersection points of the cameras optical axes. A similar technique was reported by Van Cheluwe (1975), for the estimation of the errors caused by misalignment of the cameras.

Van Gheluwe (1978) reported a technique involving camera placement in any position relative to the subject being filmed. The main advantage of this method is the explicit mathematical reconstruction of the position of the cameras in space, using the known actual and the image coordinates of certain reference points. A three dimensional calibration structure (calibration "tree") was positioned in the filming area in order to provide appropriate information for the camera orientation and subsequently coordinate determination of any point included in the calibrated area. Although, the accuracy of this procedure was acceptable for 3-D reconstruction (measurement error ranged from 2.0 mm to 0.0 mm) there is no information concerning the points chosen for the reliability test. Furthermore, there is no appropriate algorithm for lens distortion correction.

An alternative technique for 3-D reconstruction using a simple and flexible 2-dimensional calibration structure, and optoelectronic cameras was presented by Andriacchi *et al.* (1979). The 3-D coordinates of any point are estimated as the intersection point of the two camera optical axes. A second degree polynomial was utilized to determine the projection of any point on the calibration plane, viewed from the camera. The coefficients of the projected point on the plane were determined by minimizing the sum of the squares of the error between the approximate and the actual location of the calibration points (least square regression analysis). This portion of the calculation contains the calibration and image deformation correction. The average measurement error at 45 test locations was decreased with the increase in number of the calibration points (4.5 mm for 29 point cluster, 5.6 mm for 19 and 5.7 mm for 10) and when the distribution of the calibration points was in random locations throughout the calibration structure. This method is adequate for the reconstruction of internal points, it is particularly useful, when a large degree of optical and electrical distortion is presented and does not require the assumption of a theoretically perfect camera. However, it is not adequate for the estimation of external points due to the non-linear algorithm used. Furthermore, using this type of camera, the coordinates of each camera position must be in a known position relative to the global origin using surveying or manual measurements.

A similar 2-dimensional calibration structure was utilized by Woltring (1980). The implementation of this method requires a plane which is free to rotate about an axis. This plane was positioned and filmed at various angular positions (throughout the observation field) thus constituting a 3-D calibration area. The 3-D coordinates of any point were determined via the fractional linear transformation, similar to the mathematical expression used in the DLT technique. This method may be sufficient for the study of movements that cover relatively small volumes, but is not appropriate for large filming areas, because it would require filming of the calibration plane in a large number of overlapping positions, or use of an a very large calibration grid.

A technique for 3-D reconstruction which permits the determination of coordinates in large filming volume, was developed by Dapena *et al.* (1982). In this method the determination of the 3-D coordinates of the point (within the large area) can be accomplished without the stress deformation and transportation problems associated with the use of a large calibrated 3-dimensional structure in the DLT method. The calibration of the cameras is achieved by the use of two calibration crosses and a set of vertical poles apart from each other to form a calibration area of a large volume (approximately 5 m x 5 m x 1.5 m), of unknown exact shape, but at least one known length. For the validation of this method using a calibration grid, only 15 points of the calibration grid from the total 24 available was used. The root mean square error averaged 0.5% (of the calibrated volume) in X and Z, and 0.7% in Y axes. Three different lenses were tested in the same procedure with no significant difference in the improvement of the reconstruction accuracy. This method did not provide any lens distortion correction technique in order to minimize the image deformations in a large filming area. Furthermore, the corrected version of this procedure produced a measurement error of 1.1% (Dapena, 1985).

Whittle (1982) developed a method for 3-D kinematic analysis using a television system, connected to a digital computer. Two television cameras which were positioned in four different placements (working together as a convergent stereopair), and a 3-D calibration structure were used to view the subject. The synchronisation was achieved by one camera's internal synchronisation generator. Different calibration structures were used to estimate the magnitude of the error due to the optics and scanning system, and the accuracy for relative measurement (the error in measuring the distance between two or more points). The position of any point was estimated by the point at which the lines from the two camera views intersect. Two calibration procedures in the horizontal plane (for X, Y point coordinates) and the vertical plane (for Z) were also used. The error in measuring a distance between two spatial points ranged from 1.0 mm to 3.8 mm.

Woltring *et al.* (1989) reported a method which the calibration procedure accomplished using four markers on each body segment. Although in this method the calibration procedure is simple and not time consuming, the disadvantages are the requirement of a rigid marker configuration and the decreased accuracy of the method for the large field of view. The measurement error using this method has not been reported.

PURPOSE OF THIS STUDY

It is evident that there are limitations in the accurate 3-D reconstruction using the above methods (in calibration and analysis). The importance of the accurate reconstruction in kinematic analysis of human movement have resulted in the extensive investigation of more adequate methods. A polynomial method for 3-D coordinate reconstruction which can be implemented for kinematic analysis of every human movement and is also accurate for analysis in large field of view is proposed.

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CHAPTER 3

A POLYNOMIAL METHOD FOR 3-D KINEMATIC ANALYSIS USING VIDEO SYSTEMS

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ABSTRACT

A number of different algorithms for three-dimensional (3-D) kinematics have been reported, but the most frequently used is the Direct Linear Transformation (DLT) technique. However, the inadequacy of the DLT method for large filming areas has resulted in the development of a number of DLT modifications. The purpose of this study is to evaluate a polynomial method for the correction of image deformation and 3-D coordinate reconstruction using video systems for large filming areas. A small calibration plane (2.1 m W x 1.1 m H), relative to a calibrated volume, with 47 calibration points was used. The projection of any point on the calibration plane viewed from two cameras is computed using a first degree polynomial model constructed from local calibration points. Three-dimensional coordinates are computed using intersection techniques. The absolute measurement error ranged from 0.04% to 0.07% (of the field of view) in the X axis, from 0.05% to 0.06% in Y and from 0.05% to 0.07% in Z for control points inside the calibrated area (internal) and from 0.15% to 0.51% in X, from 0.16% to 0.42% in Y and from 0.15% to 0.46% in the Z axis for control points outside (external). The measurement error is significantly reduced compared to other video or film systems. Furthermore, this polynomial method allows linear extrapolation for coordinate reconstruction outside the calibration area and therefore is particularly useful in applications requiring large filming areas.

INTRODUCTION

Biomechanics research, including kinematic analysis of human movement, requires accurate three-dimensional (3-D) analysis. Although simple planar movements can be represented adequately using 2-D kinematics, the complexity of human movement in three dimensions requires a 3-D approach in the majority of kinematic investigations. However, these techniques require a complicated and time consuming calibration procedure, additional recording equipment and more complex steps in the analysis process (Dainty *et al.*, 1987).

The measurement of kinematic parameters is accomplished using one (Miller *et al.*, 1980; Bourgeois, 1983), two or more (Noble and Kelley, 1966; Whittle, 1982; Williams and Cavanagh, 1983; Wood and Marshall, 1986; Woltring *et al.*, 1989; Cappozzo and Gazzani, 1990) video, film or optoelectronic cameras. The use of one camera for 3-D reconstruction is appropriate only under restricted conditions and the accuracy is improved with the use of two or more cameras (Miller *et al.*, 1980; Whittle, 1982; Atha, 1984).

Recently, video systems have been used for the recording and kinematic analysis of human movement. Whittle (1982) developed a 3-D method for kinematic analysis using a television system connected to a digital computer and the measurement error ranged from 0.7 mm to 5 mm. This was determined as the error in reconstructing a distance of 150 mm formed by two reflective markers. Shapiro *et al.* (1987) presented a system for the manual digitization of video images. In this study the measurement error was 0.79% of the actual distances between sets of points, which ranged from 25.5 cm to 210 cm, marginally higher than those observed in cinematographic analyses. Similar results were reported in studies that compared digitization accuracy between video and cine systems (Kennedy *et al.*, 1989; Angulo and Dapena, 1992). Angulo and Dapena (1992) specifically examined the measurement error in a wide field of view. These studies indicate that film systems are more accurate than video, but this difference is not significant when considering the measurement error as a percentage of the field of view (especially in large filming areas). The advisability of the use of video systems depends on the requirements of each study. Although the relatively low sampling rate (compared to cinematography systems) and the limited resolution (Dainty *et al.*, 1987) remain a disadvantage for the use of video systems, the ability to review the movement at once and the low running costs, are significant advantages, which resulted in their widespread use in movement analysis (Atha, 1984). In addition, the technology in this field is progressing, with new types of video systems being developed having higher sample rates and resolution (Paisley, 1981; Henning, 1988; Furnee, 1990; Kerwin and Maybery, 1993).

A number of different 3-D coordinate reconstruction algorithms have been reported, but the most frequently used is the Direct Linear Transformation (DLT) technique. However, the problem with the construction of an appropriate 3-D calibration object (Challis and Kerwin, 1992; Chen *et al.*, 1994; Yeadon and Challis, 1994) for the DLT method has resulted in the development of a number of DLT modifications (Miller *et al.*, 1980; Dapena *et al.*, 1982; Hatze, 1988) and polynomial methods (Andriacchi *et al.*, 1979; Woltring, 1980; Fioretti *et al.*, 1985; Woltring and Huiskes, 1990), in order to facilitate the calibration and recording procedure and improve coordinate reconstruction accuracy.

Furthermore, in order to overcome the significant limitation of the complicated calibration procedure (construction of a large 3-D calibration object) and minimize the measurement error produced using the DLT method for large filming areas (Shapiro, 1978; Wood and Marshall, 1986), alternative approaches that can be implemented in a large field of view have been developed (Dapena *et al.*, 1982; Hatze, 1988; Yeadon, 1989). The measurement error produced by video systems using the DLT technique for large fields of view is relatively higher than cinematography systems (Angulo and Dapena, 1992).

The accuracy in 3-D reconstruction is also significantly affected by the different amount of optical distortion produced by video lenses (Woltring, 1975; Shapiro, 1978; Whitlle, 1982; Atha, 1984; Phillips *et al.*, 1984; Fioretti *et al.*, 1985), which must be compensated by incorporating appropriate correction algorithms (Andriacchi *et al.*, 1979; Miller *et al.*, 1980; Woltring, 1980; Wood and Marshall, 1986; Hatze, 1988; Hatze, 1990; Woltring, 1990; Woltring and Huiskes, 1990).

The purpose of this study is to evaluate a polynomial method for 3-D coordinate reconstruction using video systems. This method allows extrapolation for coordinate reconstruction outside the calibrated area and therefore is particularly useful in applications requiring large filming areas.

METHOD

Three-dimensional coordinate reconstruction through the application of this method is achieved using a calibration plane and at least two cameras. The 3-D coordinates of any point are determined as the intersection of the lines formed by the positions of (at least) two cameras and the projections of the point on the calibration plane from the two camera views (Fig. 3.1). The projection of any point on the calibration plane viewed from a camera, can be calculated using different degree polynomial models. The formulation of a first degree polynomial model consists of the following equations:

$X_p = a_1+a_2x+a_3y$ (1)

$Y_p = b_1+b_2x+b_3y$ (2)

A second degree polynomial model has the following form:

$X_p = a_1+a_2x+a_3y+a_4xy+a_5x^2+a_6y^2$ (3)

$Y_p = b_1+b_2x+b_3y+b_4xy+b_5x^2+b_6y^2$ (4)

where X_p, Y_p are the coordinates of the projection of any digitized point on the calibration plane mapped from the 2-D x, y camera image coordinates. Consequently, three or more calibration points with known X, Y coordinates are required, in order to evaluate the polynomial coefficients $a_1..a_3$ and $b_1..b_3$ using the first degree polynomial and six or more calibration points to evaluate $a_1..a_6$ and $b_1..b_6$ using the second degree polynomial (Andriacchi *et al.* 1979).

The 3-D camera position (coordinates relative to the calibration plane) is determined as the intersection point of (at least) two lines formed by two points (camera determination points) with known 3-D coordinates ($_{cd}X_j$, $_{cd}Y_j$, $_{cd}Z_j$, j=1,2) and their projections on the calibration plane ($^P{}_{cd}X_j$, $^P{}_{cd}Y_j$, j=1,2) (Fig. 3.2). The projected coordinates ($^P{}_{cd}X_j$, $^P{}_{cd}Y_j$, j=1,2) of the two camera determination points are estimated by equations (1) and (2) or (3) and (4) depending on the polynomial model. The $^P{}_{cd}Z_j$ coordinate of the projected image is the same with the ^{Gl}Z of the origin.

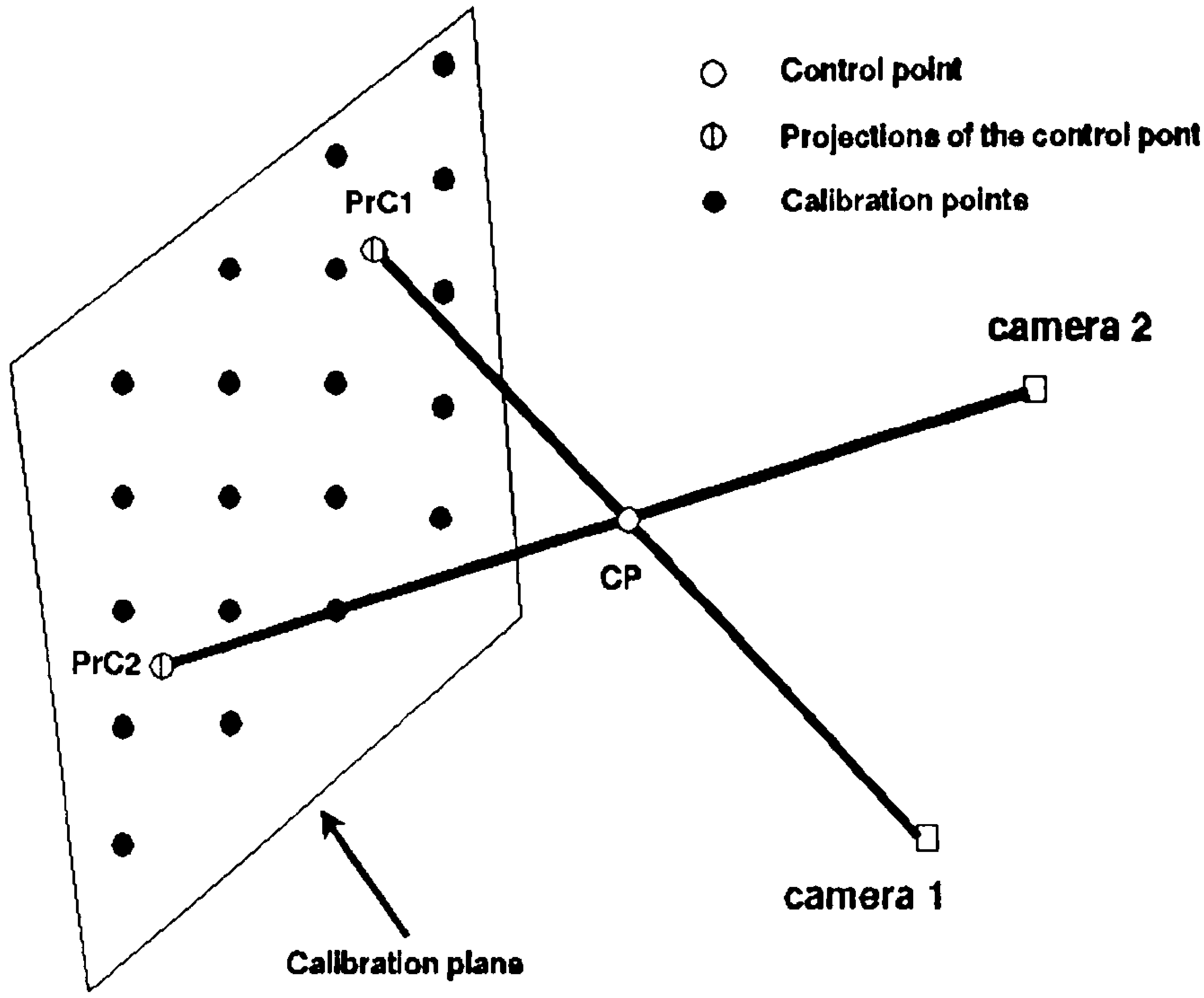

Figure 3.1. The 3-D reconstruction of a control point (CP) as the intersection point of two lines formed by the positions of two cameras and the projections of the point on the calibration plane from the two camera views.

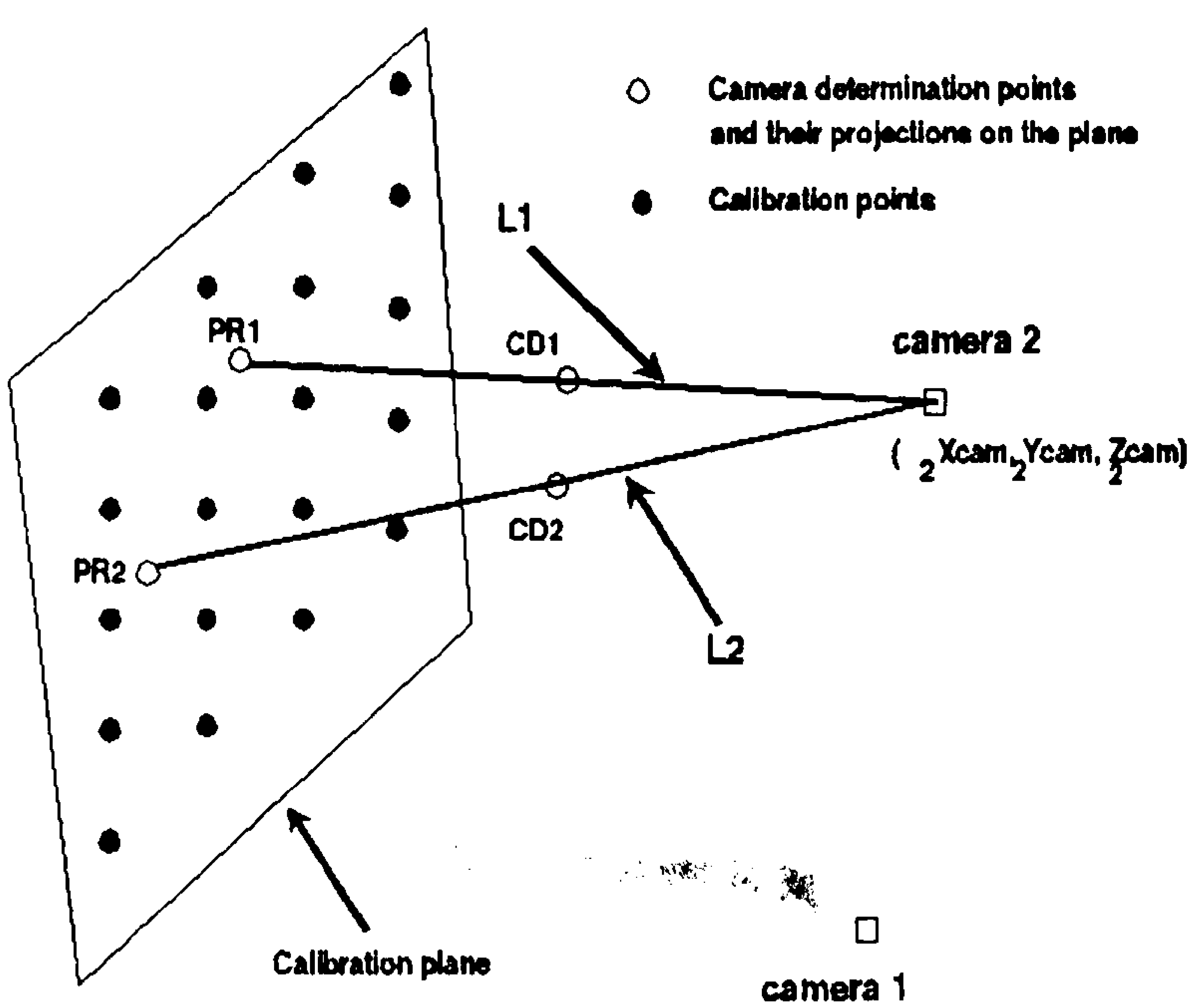

Figure 3.2. The determination of the camera position as the intersection point of two lines formed by two points (camera determination points) with known 3-D coordinates and their projections on the calibration plane.

The general expression of any point on line L_1 (the line passing through the first camera determination point and its projection on the calibration plane) has the form (see Fig. 3.2):

$$({}^{P}_{cd}X_1, {}^{P}_{cd}Y_1, {}^{P}_{cd}Z_1) + t\,(({}_{cd}X_1 - {}^{P}_{cd}X_1), ({}_{cd}Y_1 - {}^{P}_{cd}Y_1), ({}_{cd}Z_1 - {}^{P}_{cd}Z_1)) \quad \textbf{(5)}$$

Similarly the general expression of any point on L_2 is :

$$({}^{P}_{cd}X_2, {}^{P}_{cd}Y_2, {}^{P}_{cd}Z_2) + s\,(({}_{cd}X_2 - {}^{P}_{cd}X_2), ({}_{cd}Y_2 - {}^{P}_{cd}Y_2), ({}_{cd}Z_2 - {}^{P}_{cd}Z_2)) \quad \textbf{(6)}$$

where

t,s : scalar factors

${}^{P}_{cd}X_1$, ${}^{P}_{cd}Y_1$, ${}^{P}_{cd}Z_1$, ${}^{P}_{cd}X_2$, ${}^{P}_{cd}Y_2$, ${}^{P}_{cd}Z_2$: the projections of the two camera determination points on the calibration plane.

${}_{cd}X_1$, ${}_{cd}Y_1$, ${}_{cd}Z_1$, ${}_{cd}X_2$, ${}_{cd}Y_2$, ${}_{cd}Z_2$: the known 3-D coordinates of the two camera determination points

The camera position is the intersection point of these two lines and therefore can be described by the following equations:

$$_{cam}X = {}^{P}_{cd}X_1 + t\,({}_{cd}X_1 - {}^{P}_{cd}X_1) = {}^{P}_{cd}X_2 + s\,({}_{cd}X_2 - {}^{P}_{cd}X_2) \quad \textbf{(7)}$$

$$_{cam}Y = {}^{P}_{cd}Y_1 + t\,({}_{cd}Y_1 - {}^{P}_{cd}Y_1) = {}^{P}_{cd}Y_2 + s\,({}_{cd}Y_2 - {}^{P}_{cd}Y_2) \quad \textbf{(8)}$$

$$_{cam}Z = {}^{P}_{cd}Z_1 + t\,({}_{cd}Z_1 - {}^{P}_{cd}Z_1) = {}^{P}_{cd}Z_2 + s\,({}_{cd}Z_2 - {}^{P}_{cd}Z_2) \quad \textbf{(9)}$$

The scalar factors t and s can be evaluated from the overdetermined system of linear equations (7) - (9). Subsequently the 3-D camera position $({}_{cam}X, {}_{cam}Y, {}_{cam}Z)$ can be determined by replacing the scalar factors t and s in equations (7) - (9). This procedure is repeated for the total number of cameras (usually two).

The 3-D coordinates of any point, are defined as the intersection of the lines formed by the positions of the two cameras and the projections of the point on the calibration plane viewed from the two cameras (Fig. 3.1). The projections (${}^{P}_{cp}X_j$, ${}^{P}_{cp}Y_j$) are determined as described above using equations (1) and (2) or (3) and (4). The intersection of the two lines (3-D coordinates of the digitized point) can be determined by solving the overdetermined system of equations with respect to t_j and s_j:

$$^{R}_{cp}X_j = {}_{cam}X_1 + t_j\,({}^{P}_{cp}X_j - {}_{cam}X_1) = {}_{cam}X_2 + s_j\,({}^{P}_{cp}X_j - {}_{cam}X_2) \quad \textbf{(10)}$$

$$^{R}_{cp}Y_j = {}_{cam}Y_1 + t_j\,({}^{P}_{cp}Y_j - {}_{cam}Y_1) = {}_{cam}Y_2 + s_j\,({}^{P}_{cp}Y_j - {}_{cam}Y_2) \quad \textbf{(11)}$$

$$^{R}_{cp}Z_j = {}_{cam}Z_1 + t_j\,({}^{P}_{cp}Z_j - {}_{cam}Z_1) = {}_{cam}Z_2 + s_j\,({}^{P}_{cp}Z_j - {}_{cam}Z_2) \quad \textbf{(12)}$$

where

$^{R}_{cp}X_j$, $^{R}_{cp}Y_j$, $^{R}_{cp}Z_j$: the 3-D coordinates of any digitized j=1...N point.

${}_{cam}X_1$, ${}_{cam}Y_1$, ${}_{cam}Z_1$, ${}_{cam}X_2$, ${}_{cam}Y_2$, ${}_{cam}Z_2$: the 3-D coordinates of the two cameras

The calculation of the 3-D coordinates is achieved using least square techniques, because the formed lines do not intersect (Huntington et al., 1979; Büchi et al., 1990), due to the systematic (errors in the polynomial mapping of the camera image coordinates onto the calibration plane, signal "noise" and asymmetrical lens distortion) (Woltring, 1975; Andriacchi *et al.*, 1979; Miller *et al.*, 1980; Woltring, 1980; Hatze, 1981; Hatze, 1990; Woltring and Huiskes, 1990) and random errors (operator digitization error) (Hatze, 1990; D'Amico and Ferringo, 1992).

POLYNOMIAL MODEL COMPARISON

The measurement error, in determining the projected coordinates on the calibration plane, by applying the different polynomial models was examined using a calibration plane (3 m wide and 2.5 m high), formed by four (black colour) surveying poles with five white markers (22 mm X 15 mm) on each, a total of 20 planar calibration points (Fig. 3.3).

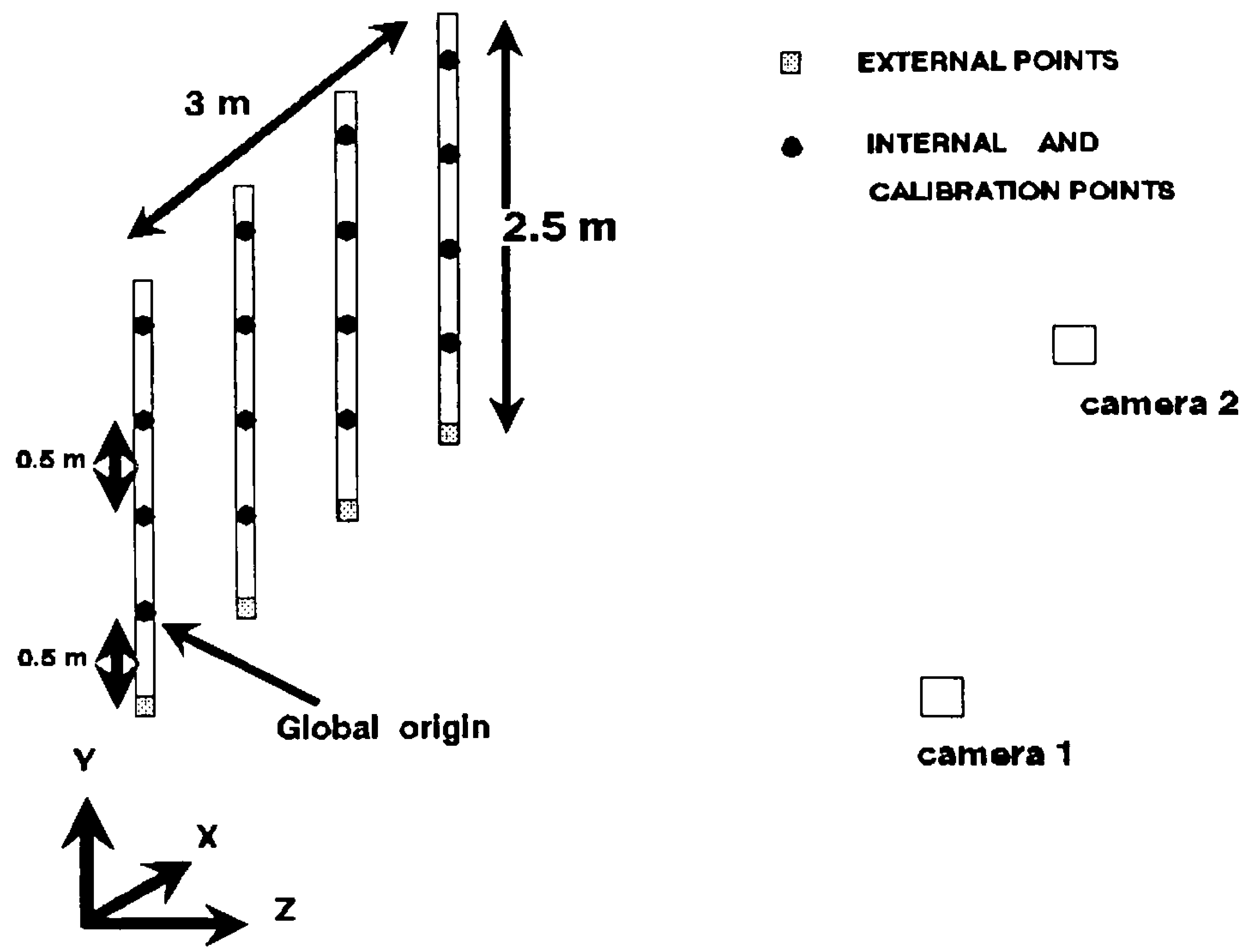

Figure 3.3. The formed calibration plane and the two camera positions.

The distances between the calibration points on every pole and the surveying poles were 0.5 m and 1 m respectively (measurement error ≤0.5 mm). In the digitization procedure the calibration plane was assumed to be the plane formed by only the top four markers on every pole. The other four points were outside the volume formed by the camera's position and the calibration plane. These four external points were used in the assessment of the accuracy of the method outside the calibrated area, and they will be referred to as 'external control points'. Control points on the calibration plane will be referred to as 'internal control points'. For reasons of analytical convenience, the origin of the system was selected to coincide with the internal lower-left marker of the calibration plane. Horizontal and vertical linear alignment of calibration and camera determination points was achieved using a Wild N20 level instrument. The distances between the surveying poles and the points on every pole were measured accurately by a Rabone Chesterman Digi-Rod 4000, an electronic digital measuring device, with measurement error of the actual distance ≤0.5 mm. A S-VHS Panasonic F-15 camera, fitted with WV-LZ14/15E lense, was used to videotape the calibration plane and control points. Two different recording angles (the angles between the camera optical axis and the calibration plane) of approximately 90° and 60° were selected, in order to examine the effects of different recording angles on the determination of the X_p and Y_p coordinates, using first and second degree polynomials. In this procedure the camera position is not required. A S-VHS Panasonic AG-7330-B video recorder was interfaced to an Intel 82486 based computer using a PC-TV adaptor (II) provided by Vine Micros Ltd. The image was displayed on TV monitor (Sony PVM -2130QM). A coded Pascal version of the described algorithm was used to digitize and analyze the recorded data.

The criterion for the selection of the most appropriate mathematical model, was the difference between the known coordinates of the control points on the calibration plane and their coordinates determined by the polynomial models (equations (1) and (2) or (3) and (4)). Both internal and external control points, relative to the calibration plane-camera volume, were used for the evaluation of the polynomial methods. Some of the calibration points were also used as control points, (points whose spatial coordinates are to be reconstructed), a common practice in studies of 3-D kinematic method evaluation (Miller *et al.*, 1980; Wood and

Marshall, 1986; Hatze, 1988).

Initially, a first degree polynomial was implemented using different numbers of calibration points distributed throughout the calibration plane. The use of a linear algorithm was based on the assumption that a first degree polynomial can produce acceptable reconstruction accuracy for the internal, as well as, external markers.

The first degree model produced accurate overall results when the camera optical axis was approximately perpendicular to the calibration plane (angle 90°, using 6 calibration points). The measurement error (mean of absolute error values ± SD), using the total of 16 internal control points was 4.3 ± 1.6 mm and 2.5 ± 1.5 mm in the X and Y axis respectively. With the increase of the camera optical angle (60°, 6 calibration points) the measurement error was increased (55.7 ± 29.7 mm and 46.3 ± 42.8 mm in X and Y axis respectively). The measurement error using the total number of internal control points, was slightly reduced with the increase in the number of calibration points (55.7 ± 29.7 mm, 52.5 ± 16.3 mm and 50.6 ± 20.7 mm in X axis and 46.3 ± 42.8 mm, 35.9 ± 35.9 mm and 38.4 ± 32.6 mm in the Y axis for 6, 9 and 15 calibration points respectively). Inaccurate results (at the 60° angle, using 15 calibration points) were produced for the external points (81.1 ± 17.1 mm and 105.2 ± 66.4 mm in X and Y axis respectively). These results indicate that a first degree model fitted to all the calibration points is inadequate to represent the relationship between global and video coordinates due to perspective, image distortion and digitizing errors (Shapiro, 1978; Andriacchi *et al.*, 1979; Woltring, 1975; Miller *et al.*, 1980; Woltring, 1980; Whitlle, 1982; Atha, 1984; Phillips *et al.*, 1984; Fioretti *et al.*, 1985; Wood and Marshall, 1986; Hatze, 1988; Hatze, 1990; Woltring and Huiskes, 1990).

A second degree polynomial was also tested for the estimation of the projection coordinates on the calibration plane. The accuracy for the 90° recording angle was similar to the first degree polynomial model (measurement error 3.0 ± 1.3 mm and 2.1 ± 1.1 mm in X and Y axis respectively). The measurement error, using six calibration points and the total of 16 internal control points, at the 60° recording angle, was very large (maximum measurement error 155.9 ± 173.4 mm and 260.1 ± 215.1 mm in X and Y axis respectively), but by increasing the number of calibration points, the measurement error was decreased for every screen location (8.7 ± 4.9 mm and 8 ± 3.6 mm in X axis, and 8 ± 3.6 mm and 7.5 ± 4.1 mm in Y axis for 9 and 15 calibration points respectively). However, the measurement error (using 15 calibration points) for external points was very large (12.6 ± 5.6 mm and 73.3 ± 33.6 mm in X and Y axis respectively).

The comparison of the measurement error produced by the first and second degree polynomials indicates that the second degree polynomial is more accurate overall. The reason for this is that the image of calibration plane is represented as a curved surface rather as a plane because of the video lense distortion. Consequently, the second degree polynomial is more appropriate to fit through the image of calibration points. However, the measurement error produced using second degree polynomial is high and unacceptable for accurate 3-D reconstruction.

Coordinate reconstruction using local calibration points

In order to reduce this error, the polynomial models were used in combination with a sorting procedure for the calibration points. This sorting technique was used for selection of the three (for the first degree polynomial) or nine (for the second degree) closest calibration points (according to their distance from the projection of any digitized point) from a total number of calibration points

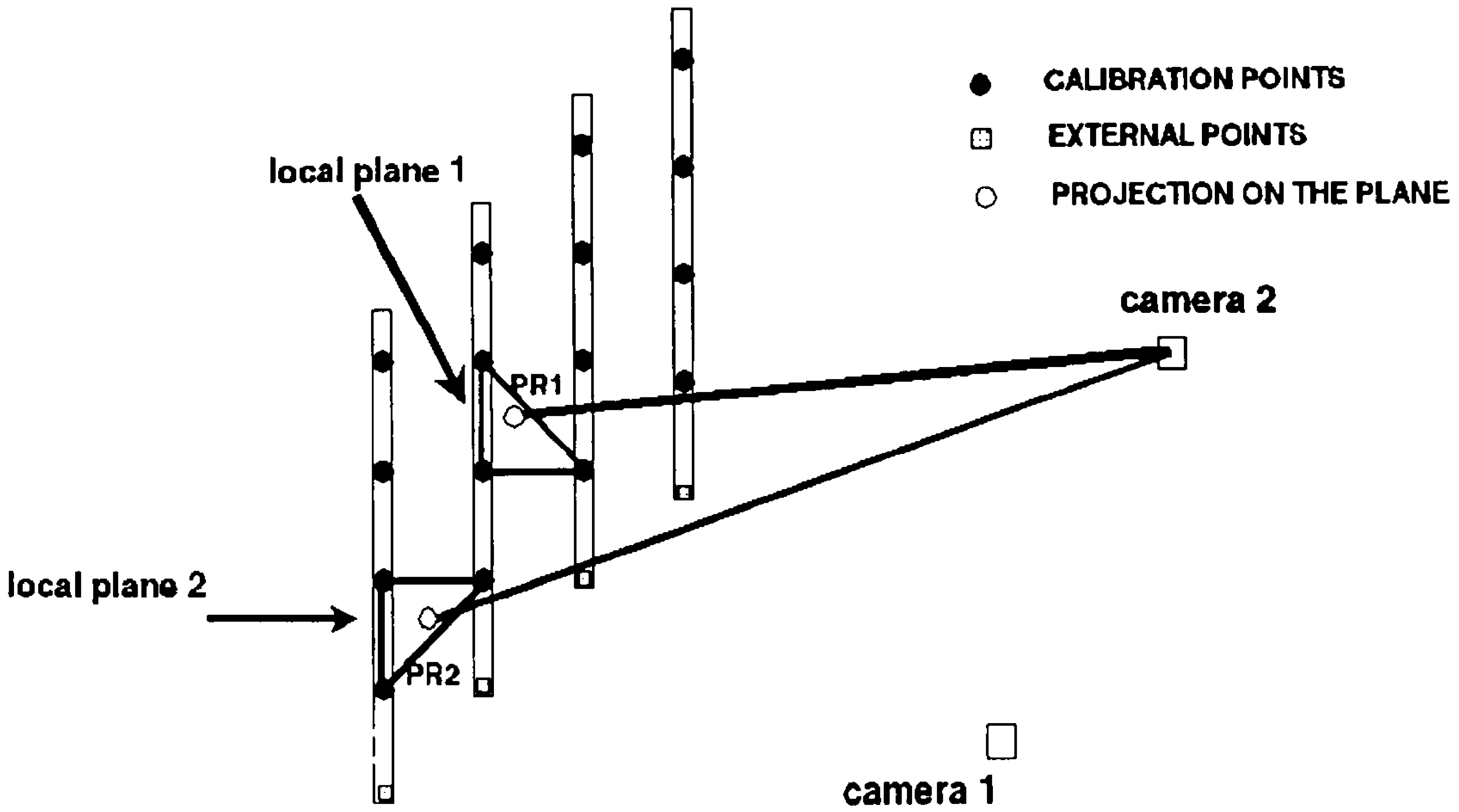

Figure 3.4. **The local calibration planes for the determination of the projection on the calibration plane of any digitized point using a first degree polynomial.**

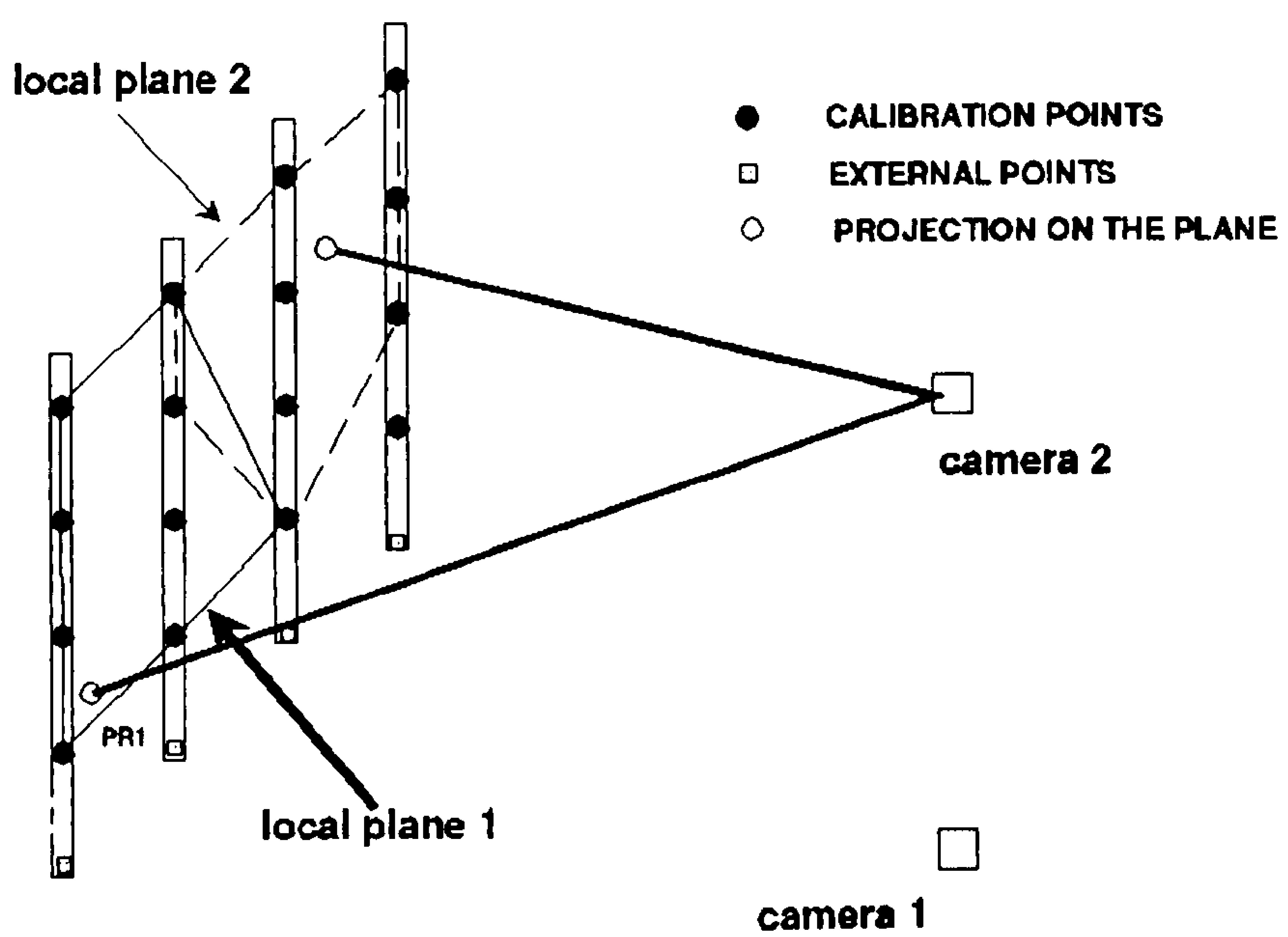

Figure 3.5. **The local calibration planes for the determination of the projection of any point on the calibration plane using a second degree polynomial.**

available. These calibration points formed a local plane which it is used for the determination of the polynomial coefficients (see figures 3.4 and 3.5). A control procedure is necessary to ensure that the selected calibration points (for the first degree model) are not collinear and form a local plane. Consequently, the projection of any digitized point on the calibration plane was calculated from a local plane (and not a global plane fitted to all calibration points). Thus accomplished the correction of the effects of perspective error associated with acute recording angles and of optical distortion produced by the video lenses at different screen locations.

Implementation of this modification reduced the measurement error significantly for both internal and external control points, using either first or second degree polynomials. Twelve calibration points in total (the three central markers from every surveying pole) and twenty control points (twelve internal and eight external) were used for the implementation of both polynomial procedures using a 60° recording angle (Fig. 3.6). The upper and lower marker of every pole was used as an external control point. The reason for this modification of the calibration procedure was to examine the reconstruction accuracy of external control points, using the two polynomial methods, when a small calibration plane is used, relative to a large field of view. The error was determined from 10 repetitions of a single frame in order to allow a better estimation of the overall measurement error using this method. The first degree polynomial produced less measurement error for both internal and external control points and the mean error from 10 repeated digitizations of a single frame is presented in Table 3.1.

Table 3.1. **The mean measurement error (± standard deviation) in mm, with first and second degree polynomial models and 60° camera angle using the sorting technique.**

	1st degree polynomial		2nd degree polynomial	
	Internal	External	Internal	External
X (mm)	1.4 ± 0.5	5.0 ± 2.6	2.1 ± 0.9	7.4± 2.6
Y (mm)	1.1 ± 0.7	4.1 ± 2.3	1.7 ± 1.0	7.1 ± 2.9

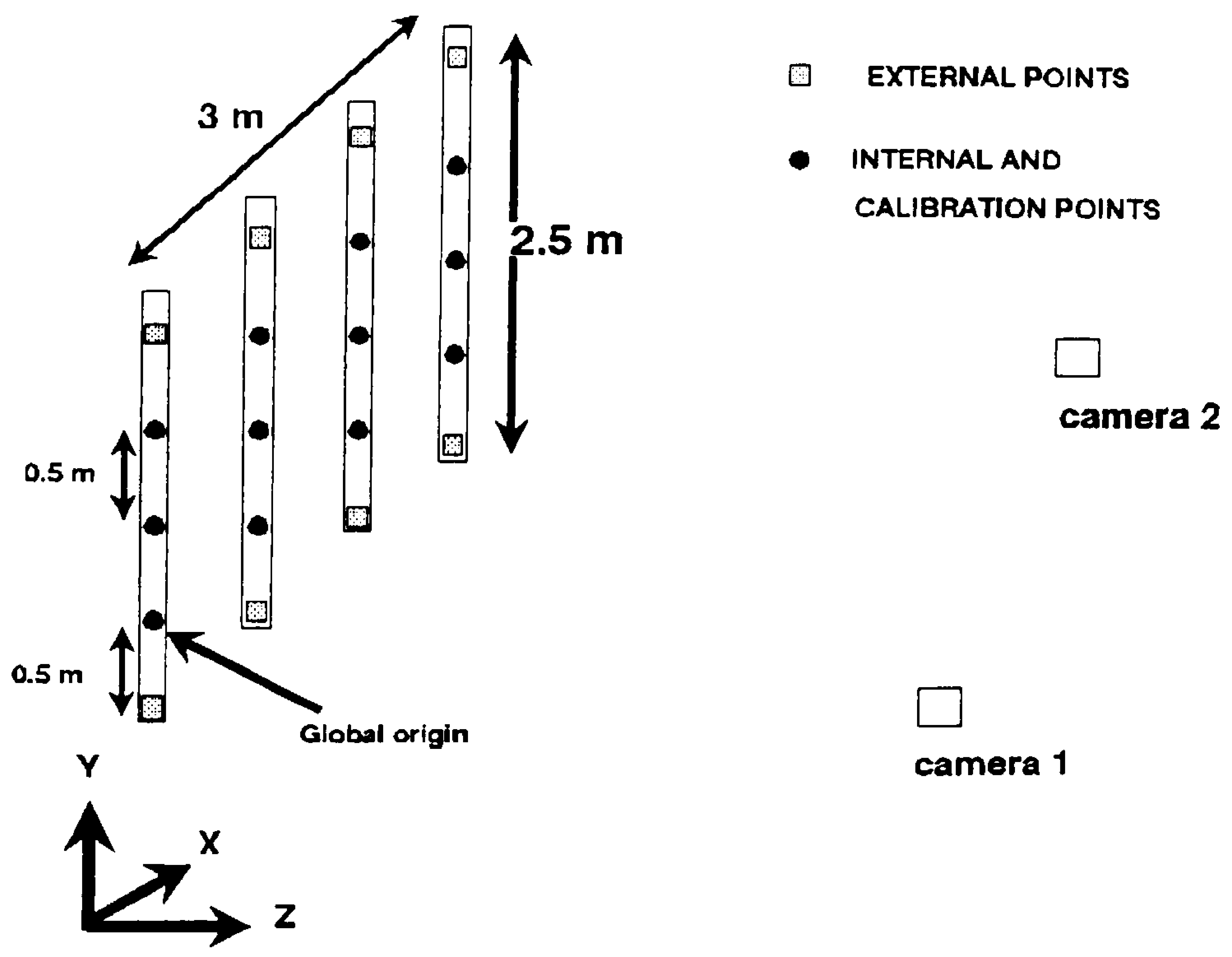

Figure 3.6. **The formed calibration plane for coordinate reconstruction error measurement using local calibration points.**

This polynomial model comparison examined the use of the 1st and 2nd degree polynomials fitted to all the calibration points for the estimation of the projection of any digitized point on the calibration plane. The results presented indicate that these models are not acceptable when fitted to all calibration points. The modification, using the sorting method in order to use only local calibration points, improved significantly the measurement error. Since the first degree model produced more accurate results for the estimation of the projection coordinates, it was subsequently used for 3-D coordinate reconstruction.

3-D EXPERIMENTAL PROCEDURE

For the assessment of measurement error in 3-D coordinate reconstruction, using this polynomial method, a simple 3-D calibration structure was used. This consisted of a calibration plane (with dimensions 2.1 m Wide (W) X 1.1 m High (H)) and two camera determination points in known positions relative to the calibration plane. A calibration plane with relatively small dimensions was used because the dimensions of a calibration plane placed between the camera and the movement, could be considerably reduced, compared to the calibrated volume (Fig 3.7). Thus, a planar calibration object with small dimensions is easier to implement and transport (as a prefabricated or an assembled product) than a large 3-D object.

The calibration plane was formed by a prefabricated structure using aluminium square tubes (Fig. 3.8). Forty seven black markers (22 mm X 15 mm) were mounted on the square tubes throughout the calibration plane. The position of every marker was precisely measured from the lower left marker (origin) of the calibration plane (measurement error ≤0.5 mm). Two additional square tubes (0.5 m length) were positioned perpendicularly on the calibration plane. The edge points of these square tubes were used to determine (equations 7 - 9) the 3-D camera position (camera determination points).

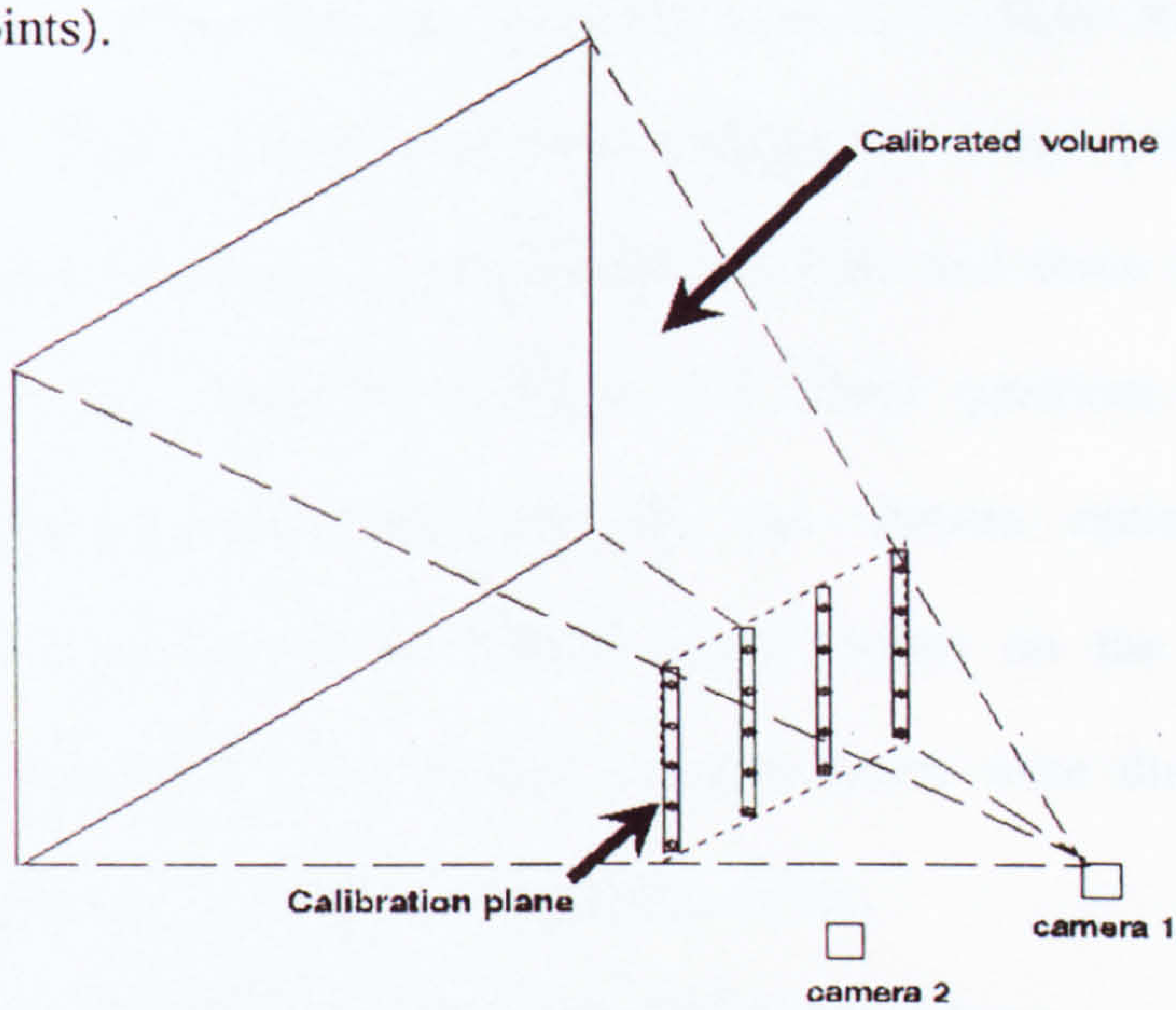

Figure 3.7. The dimensions of a calibration plane positioned between the camera and the movement could be considerably reduced compared to the dimensions of the field of view.

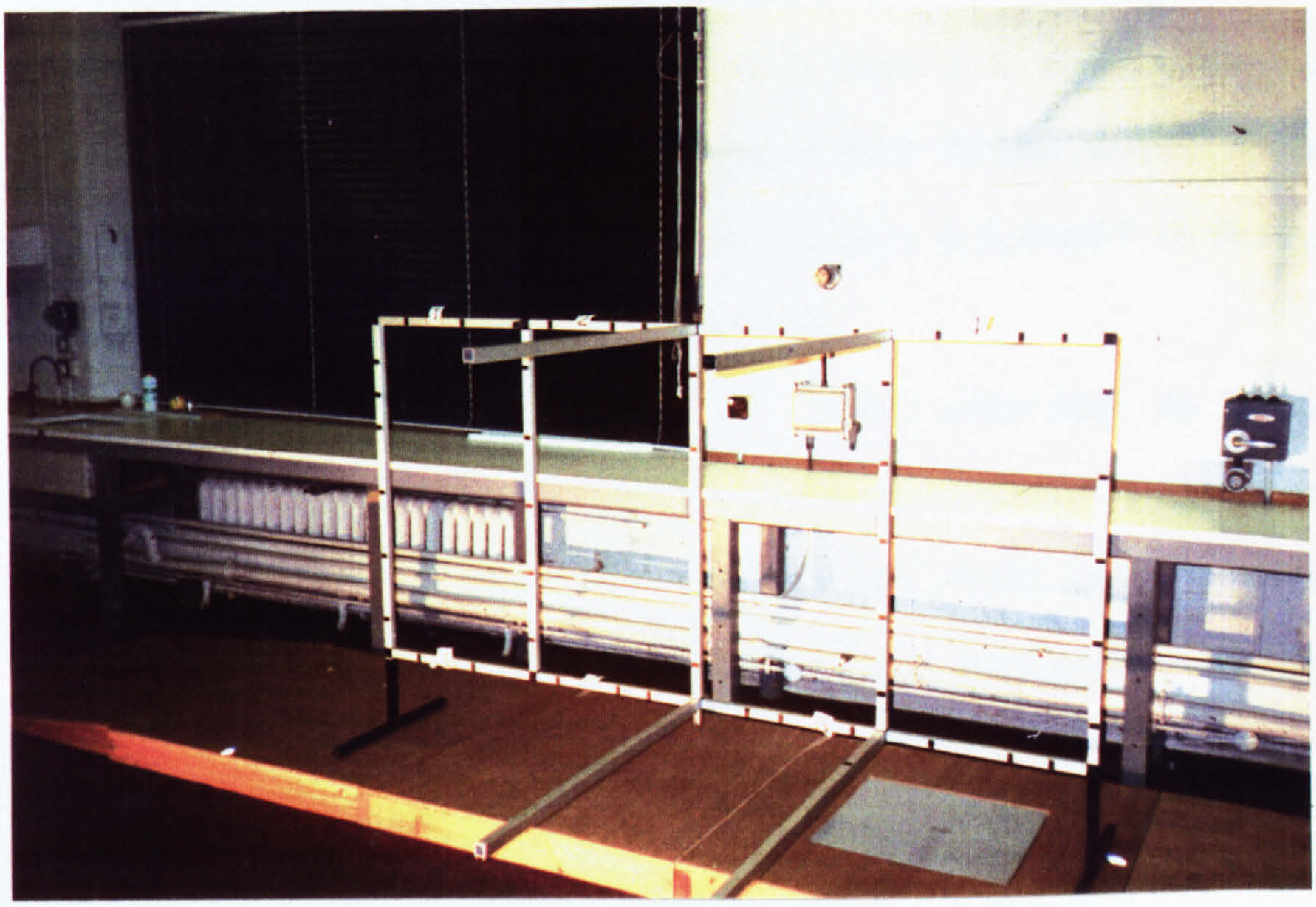

Figure 3.8. The calibration structure used in the 3-D experimental procedure.

3-D reconstruction procedure inside the calibrated volume

A pole with 4 markers (control points) was fixed in two random (non-parallel) positions in front and two random positions behind the calibration plane. Furthermore, six survey poles, with two markers on every pole, were placed in three known positions (relative to the origin) in front and three positions behind the calibration structure as illustrated in figure 3.9. These positions of the poles were inside the volume (internal) formed by the two camera optical views and the calibration plane. Furthermore, 10 internal control points on the plane, with known 3-D coordinates were used. These internal control points were distributed in different locations throughout the calibration plane (Fig. 3.10).

3-D reconstruction procedure outside the calibrated volume

Ten survey poles with two control points on each (20 in total) were fixed in different surveyed positions in front, behind, and on the level of the calibration plane outside the calibrated volume as illustrated in figure 3.11. The projections of these control points on the calibration plane were outside the area covered by the calibration points viewed from both cameras for positions 4, 5, 6 and 7 or from at least one of the cameras for all the other positions.

The distances of the surveyed external control points from the closest calibration point ranged from approximately 2.1 m to 2.5 m for the control points behind, from 1.6 to 2 m for the control points in front of the calibration plane, and from 0.8 m to 0.4 m for the control points on the level of the calibration plane.

The internal and external control points were used to determine the reconstruction error for movement occurring in front and behind the calibration plane.

Horizontal and vertical linear alignment of calibration and control points (internal - external) was achieved using a Wild N20 level instrument. The distances between the surveying poles and the points on every pole were measured accurately by a Rabone Chesterman Digi-Rod 4000, electronic digital measuring device. Two S-VHS Panasonic F-15 cameras, fitted with WV-LZ14/15E lense, were used to videotape the calibration plane and control points. The recording angles (the angles between the camera optical axis and the calibration plane) were approximately 50° for both cameras. The focal length and therefore the field of view, was sufficient to identify markers of 22 mm X 15 mm, at a distance of approximately 15 m from the camera.

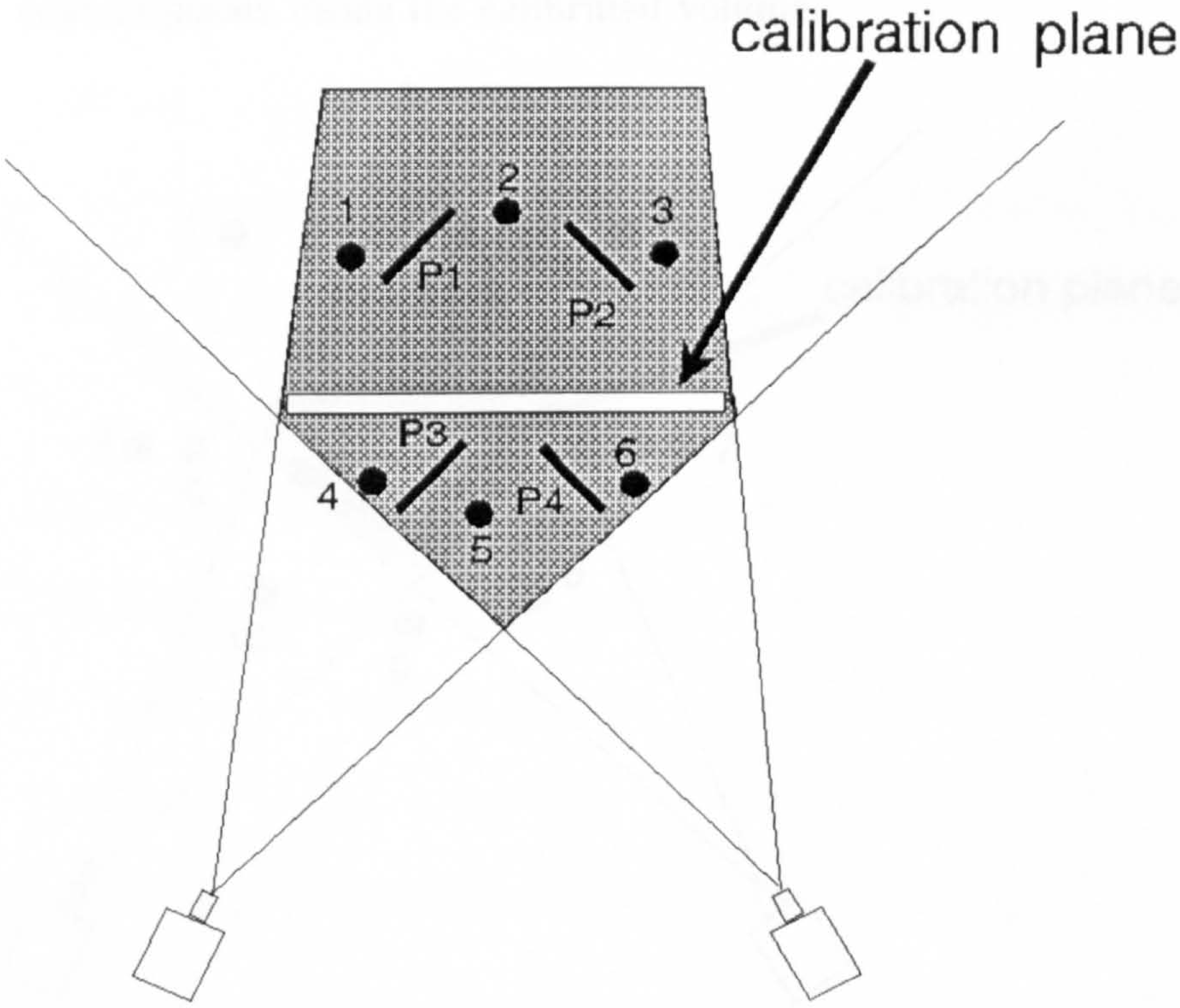

Figure 3.9. Top view of experimental set-up for the determination of measurement error inside the calibration volume. Lines P1-P4 represent the approximate positions of the control distances and points 1-6 the vertical positions of the poles with surveyed control points.

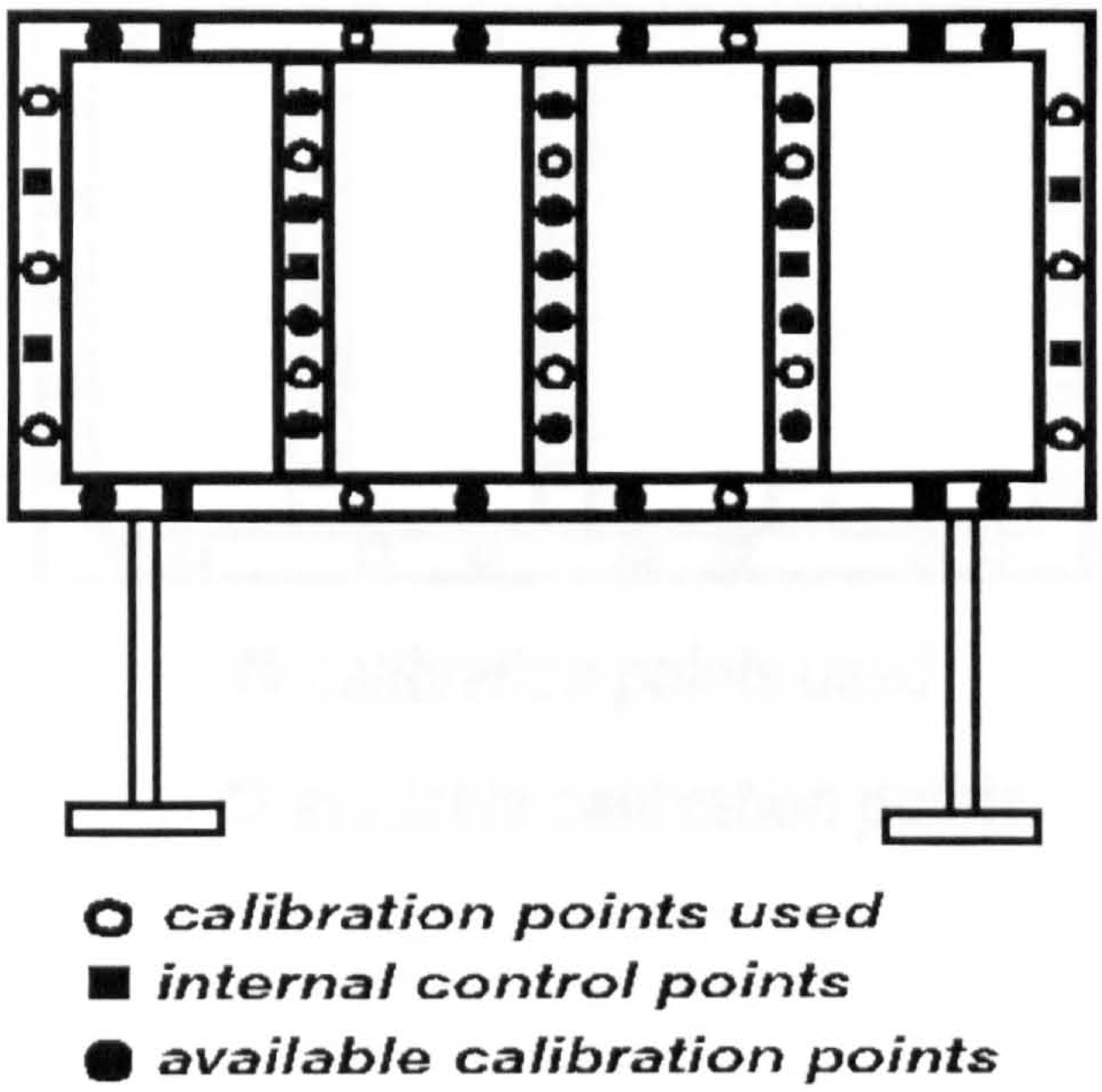

Figure 3.10. The distribution of the calibration and the internal control points on the calibration plane, used for the determination of measurement error of control points inside the calibrated volume.

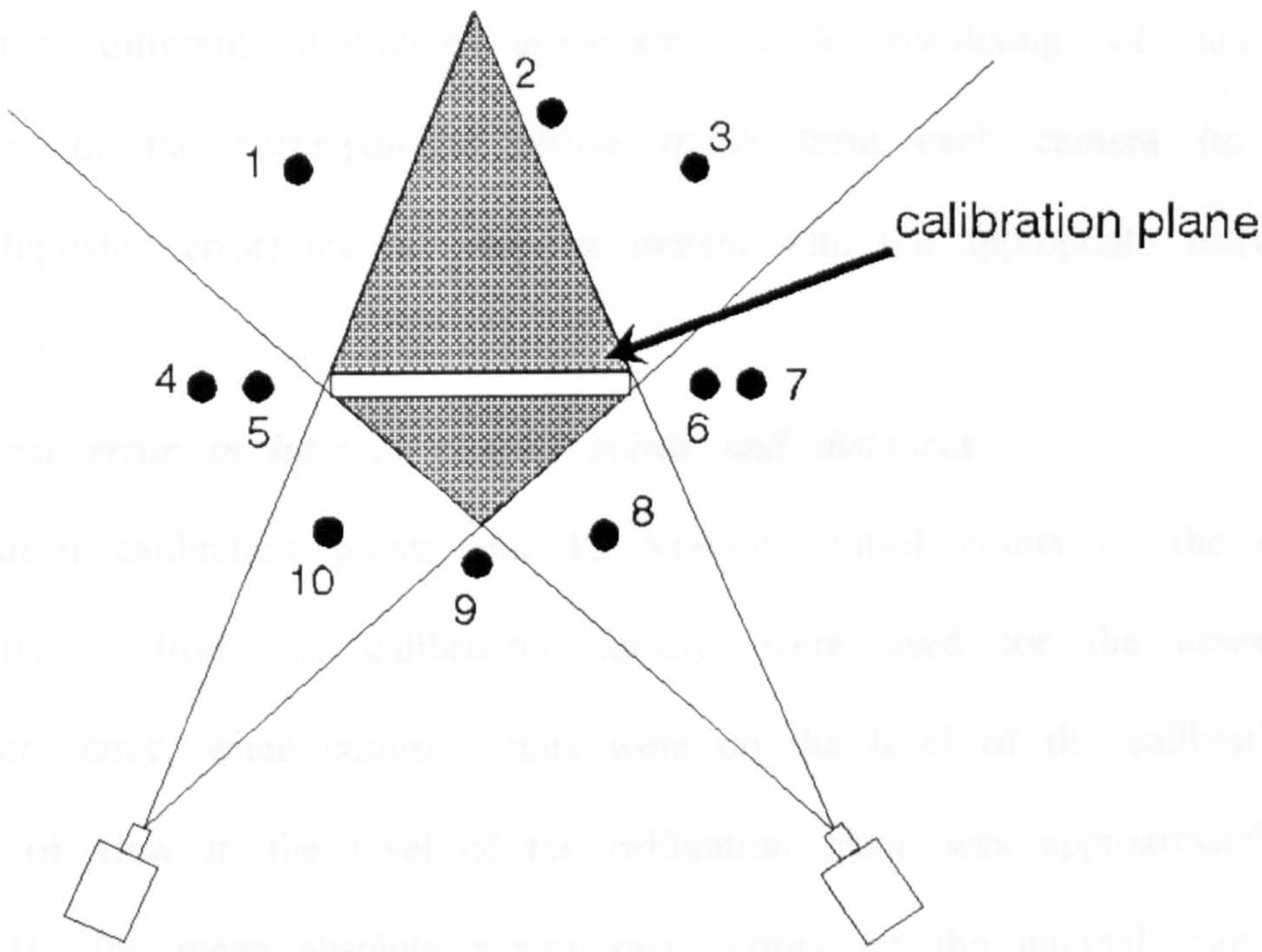

Figure 3.11. Top view of the experimental set-up for the determination of measurement error outside the calibration volume (extrapolation). Points 1-10 represent the vertical position of the poles with surveyed control points.

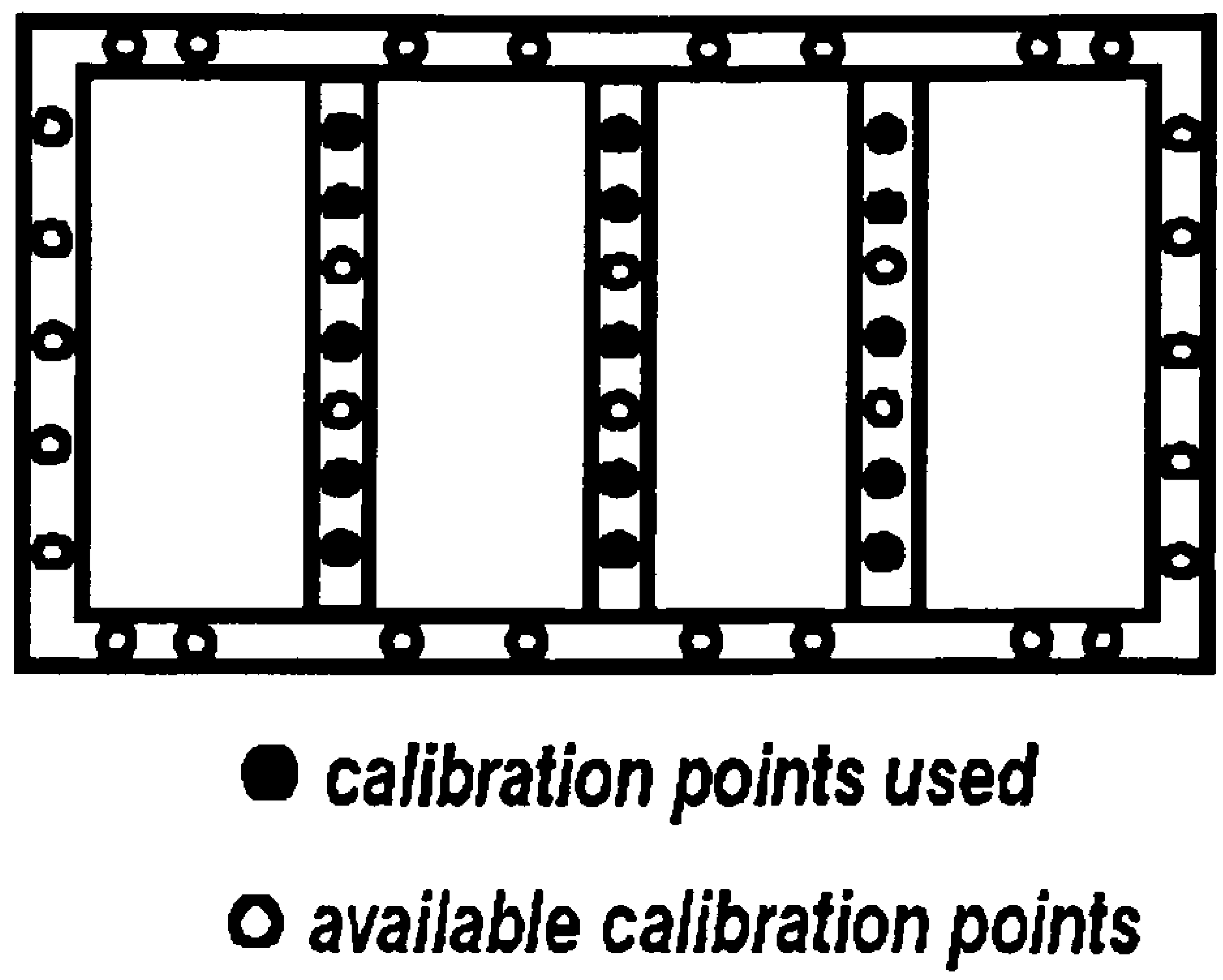

Figure 3.12. The distribution of the calibration points on the calibration plane, used for the determination of measurement error of control points outside the calibrated volume.

RESULTS

Three different digitizing procedures, each consisting of ten repeated digitizations of the corresponding single frame from each camera (to minimise operator digitising error) and a computer system with the appropriate software were implemented.

Measurement error in internal control points and distances.

Sixteen calibration points and 10 internal control points on the calibration plane (different from the calibration points) were used for the assessment of measurement error, when control points were on the level of the calibration plane. The field of view in the level of the calibration plane was approximately 3 m W by 2.5 m H. The mean absolute measurement errors for the internal control points, ranged from 0.7 mm to 2.7 mm in the X axis, from 0.6 mm to 2.6 mm in Y, and from 0.6 mm to 3.7 mm in Z (Table 3.2).

Table 3.2. The mean measurement error (± standard deviation) in mm, and relative to the horizontal lenght of the field of view for internal control points on the calibration plane (see figure 3.10).

POINTS	X (mm) ±SD	Y (mm) ±SD	Z (mm) ±SD
P1	1.8 ± 0.6	2.4 ± 1.1	2.2 ± 1.3
P2	2.7 ± 0.9	1.9 ± 1.2	1.7 ± 1.2
P3	0.7 ± 0.8	1.8 ± 0.9	0.9 ± 1.2
P4	2.1 ± 0.6	2.6 ± 1.4	3.8 ± 0.4
P5	1.7 ± 1.0	2.5 ± 1.2	2.4 ± 1.6
P6	1.3 ± 0.6	0.6 ± 0.3	2.5 ± 1.3
P7	1.5 ± 1.3	2.6 ± 0.9	1.4 ± 1.2
P8	1.0 ± 0.5	2.0 ± 0.9	0.6 ± 0.9
P9	1.6 ± 1.2	1.9 ± 1.3	1.7 ± 0.3
P10	1.8 ± 0.5	1.8 ± 1.1	1.9 ± 1.2
MEAN (%FOV)	1.5 (0.04%)	1.8 (0.05%)	1.9 (0.05%)

For the determination of error in the volume in front and behind the calibration plane, the same number of calibration points and 28 in total internal control points were used. These consisted of the twelve control points mounted on the six surveying poles (two points on every pole) and the 4 points on the pole placed in two random positions in front and two behind the calibration plane (sixteen in total), forming two distances of 0.5 m. Control distances have been extensively used for the estimation of the 3-D reconstruction accuracy in previous studies (Andriacchi *et al.*, 1979; Angulo and Dapena, 1992). The average field of view was approximately 2.5 m W by 2 m H in the level of the surveying poles in front and 4.5 m W by 3 m H behind the calibration plane. The mean absolute measurement errors for the surveyed control points ranged from 3.2 mm to 1.3 mm

Table 3.3. The mean measurement error (± standard deviation) in mm, and relative to the horizontal lenght (width) of the field of view for internal control points infront and behind the calibration plane at different positions (see figure 3.9).

	X ± SD	Y ± SD	Z ± SD
BEHIND			
POLE 1	3.2 ± 1.4	2.1 ± 1.5	2.1 ± 1.7
POLE 2	3.0 ± 1.3	2.4 ± 1.3	3.0 ± 1.0
POLE 3	2.9 ± 1.2	2.3 ± 1.6	2.7 ± 1.5
MEAN (FoV)	3.0 (0.07%)	2.3 (0.05%)	2.6 (0.06%)
INFRONT			
POLE 4	1.5 ± 1.2	1.6 ± 0.8	1.8 ± 1.1
POLE 5	1.3 ± 0.9	1.4 ± 0.9	1.7 ± 0.8
POLE 6	1.9 ± 1.1	1.7 ± 0.8	1.5 ± 0.9
MEAN (FoV)	1.6 (0.06%)	1.6 (0.06%)	1.7 (0.07%)

in the X axis, from 2.4 mm to 1.4 mm in Y and from 3.0 mm to 1.5 mm in Z (Table 3.3). The mean absolute measurement errors for the distances ranged from 1.4 mm to 2.3 mm, when the survey pole was positioned in front and from 2.3 mm to 3.1 mm when it was behind the calibration plane (Table 3.4).

Measurement error in external control points.

Fifteen calibration points forming a calibration plane 1.0 m W X 0.55 m H (Fig. 3.12) and 20 external control points (Fig. 3.11), were used for the determination of measurement error outside the calibrated volume (extrapolation). The average field of view was approximately 3.3 m W by 2.5 m H in the level of the calibration plane, 5 m W by 4 m H in the level of the surveying poles behind the calibration

Table 3.4. **The mean measurement error (± standard deviation) in mm, and relative to the horizontal lenght (width) of the field of view for control distances infront and behind the calibration structure at different positions (see figure 3.9).**

	IN FRONT		BEHIND	
	DISTANCE 1	DISTANCE 2	DISTANCE 1	DISTANCE 2
POSITION 1	2.3 ± 1.4	2.1 ± 1.0	3.1 ± 1.0	2.5 ± 1.0
POSITION 2	1.4 ± 1.3	1.7 ± 0.8	3.0 ± 1.0	2.3 ± 0.8
MEAN (%FOV)	2.2 (0.09%)	1.6 (0.06%)	3.1 (0.07%)	2.4 (0.05%)

Table 3.5. **The mean measurement error (± standard deviation) in mm, and relative to the horizontal lenght (width) of the field of view, for two external control points on surveying poles in different positions (see figure 3.11)**

POLE No	X (FoV)	Y (FoV)	Z (FoV)
1	9.4 ± 2.6 (0.19%)	10.8 ± 2.6 (0.22%)	8.2 ±8.2 (0.16%)
2	8.5 ± 2.9 (0.17%)	12.0 ± 4.1 (0.24%)	9.1 ± 1.9 (0.18%)
3	14.5 ± 2.2 (0.29%)	16.0 ± 2.6 (0.32%)	13.3 ± 4.4 (0.26%)
4	16.7 ± 1.7 (0.51%)	14.0 ± 3.4 (0.42%)	16.3 ± 2.5 (0.49%)
5	5.7 ± 1.6 (0.17%)	5.8 ± 2.0 (0.17%)	6.0 ± 1.7 (0.18%)
6	5.2 ± 1.9 (0.16%)	6.0 ± 2.7 (0.18%)	5.1 ± 1.9 (0.15%)
7	14.7 ± 3.0 (0.42%)	13.5 ± 3.7 (0.38%)	15.1 ± 1.9 (0.43%)
8	12.7 ± 3.1 (0.51%)	7.9 ± 3.8 (0.31%)	10.3 ± 1.6 (0.41%)
9	3.8 ± 2.2 (0.15%)	4.8 ± 1.5 (0.19%)	5.2 ± 3.0 (0.21%)
10	11.8 ± 1.8 (0.47%)	6.1 ± 1.4 (0.24%)	7.5 ± 2.1 (0.30%)

plane, and 2.5 m W by 1.5 m H in the level of the surveying poles in front of the calibration plane. The mean absolute measurement errors for the external points ranged from 3.8 mm to 16.7 mm in the X axis, from 4.8 mm to 16.0 mm in Y, and from 5.1 mm to 16.3 mm in Z (Table 3.5).

DISCUSSION

This paper presents a modified polynomial method for 3-D coordinate reconstruction. The polynomial model comparison examined two different polynomial models and the final choice of the first degree model was based on the accuracy of the projection coordinates of any digitized point on the calibration plane. The main 3-D experimental procedure examined the measurement error in three-dimensional reconstruction using a first degree polynomial and a sorting technique for selection of the nearest calibration points for the determination of the projection coordinates. The measurement error using this method is significantly reduced, compared to any other video (Whittle, 1982; Shapiro *et al.*, 1987; Kennedy *et al.*, 1989; Angulo and Dapena, 1992), and the majority of film or optoelectronic kinematic systems (Andriacchi *et al.*, 1979; Miller *et al.*, 1980; Woltring, 1980; Dapena *et al.*, 1982; Fioretti *et al.*, 1985; Hatze, 1988; Woltring and Huiskes, 1990). This method requires at least two cameras. Previous studies for 3-D reconstruction have also used a single camera, but only under restricted conditions. Plagenhoef (1968) used a single-camera procedure, with trigonometric and scaling functions, in order to estimate the 3-D coordinates of the subject. The scale applied for the correction of measurement error varied for each camera-plane angle and was consequently inaccurate for 3-D reconstruction. Bourgeois (1983) implemented the DLT algorithm using only one camera for the estimation of the 3-D object orientation. This method is valid only if the 3-D orientation of at least one landmark is known. Miller *et al.* (1980) determined the 3-D parameters using only one camera, but at least three points of known location must be available on each body. The accuracy in this particular study was improved with the use of two or more cameras. Consequently, the accurate 3-D reconstruction requires the use of two or more recording instruments.

The DLT method presents significant limitations, because the calibration structure must be as large as the calibrated movement area. This can be very time consuming and inaccurate for large fields of view and furthermore 3-D reconstruction outside the calibration area (extrapolation) is not accurate (Shapiro, 1978; Woltring, 1980; Wood and Marshall, 1986; Angulo and Dapena, 1992). Another significant limitation with the typical portable 3-D calibration structures, used for DLT reconstruction, is that the calibration points are not distributed evenly throughout the calibration volume. Consequently, if there is high density of calibration points in a particular region of the calibrated volume (usually the centre), the accuracy in this specific region will be high, in contrast to low reconstruction accuracy elsewhere in the field of view (Chen, *et al.*, 1994; Yeadon and Challis, 1994). The method presented in this study overcomes these significant limitations.

Andriacchi *et al.* (1979), Woltring (1980), Fioretti *et al.* (1985) and Woltring and Huiskes (1990) have reported methods where the calibration structure used is a plane. This simplified the structural requirements (the large three-dimensional DLT calibration objects) and increased reconstructive accuracy. However, these algorithms are not sufficient for the estimation of points outside the area formed by the camera and the calibration plane. The mathematical models used for coordinate reconstruction were second degree polynomial (Andriacchi *et al.*, 1979), Taylor series (Fioretti *et al.*, 1975), and fractional linear transformation polynomial (Woltring, 1980; Woltring and Huiskes, 1990). In addition, Woltring's method is not adequate for motions covering very large areas, because of the requirement to film the calibration plane in a very large number of overlapping positions, or the use of an inordinately large calibration plane. The polynomial method presented by Fioretti *et al.* (1985) is accurate (better than 0.1% of the observation distance), but it is more suitable if the measurement field is small (equal or smaller than 0.5 m x 0.5 m x 0.5 m), and adequate only in the analysis of small segment movements. Woltring *et al.* (1989) presented a "self" calibration procedure without the need for a separate calibration object, using landmark clusters each with four points of known distance apart mounted on the subject. However this approach allows only the reliable assessment of relative (to the landmark clusters) movements.

The calibration technique used in the present study not only simplifies the calibration object, but is also adequate and easily implemented for large filming areas. Routine implementation of this method requires a prefabricated or assembled simple 3-D calibration structure, consisting of a plane and two points out of the plane. More importantly the calibration structure is not required to cover the filming volume (as applied to reconstruction using DLT) and therefore the dimensions of the calibration plane can be considerably reduced relative to the calibrated volume. The calibrated volume is not restricted to the volume formed by the calibration plane-camera, but expands beyond the calibration plane (Fig. 3.7). Therefore any movement occurring between the camera-calibration plane, as well as beyond the calibration plane (assuming no refocusing is required), can be analyzed accurately. This is indicated by the results presented in Table 3.3. The accuracy in 3-D reconstruction for both internal and external control points was high. The small difference in the reconstruction accuracy between the control points infront and behind the calibration plane, is due mainly to difference in resolution. A small image size, due to the long distance of the recorded object from the camera, is represented by a smaller number of pixels, compared with a larger image size of the same object in front of the calibration plane. Therefore, the reconstruction error increases when a small size image is digitized, because of the lack of sufficient number of pixels. However, if the reconstruction error is expressed relative to the field of view, then the measurement error produced using either large or small image sizes is similar and independent from the object-camera distance (Table 3.3). In this study the measurement error was expressed in terms of horizontal dimension of the field of view to facilitate comparison with other published data (Kennedy *et al.*, 1989; Harrisson and Littler, 1991; Kerwin and Maybery, 1993).

Dapena *et al.* (1982) reported a method which allowed the reconstruction of coordinates in a large filming area, but requires the distance of the camera (relative to the calibration structure) using manual measurement. The mean measurement error of this study was 0.6%. In addition, the corrected version of this procedure produced a measurement error of 1.1% (Dapena, 1985). Two modified DLT methods were presented by Hatze (1988). The non-linear modified technique, although is very accurate for the reconstruction of internal points, produces large error for points outside the calibrated space, in contrast to the linear, which produces accurate results for both internal and external points. In one of the first applications of the extrapolation technique, Shapiro (1978) reported that the measurement error for points outside the calibration object ranged from 2% to 4% (or from 20mm to 40mm, for 1 m calibration object). Improved results were reported by Wood and Marshall (1986), but the RMS error for the reconstruction of the external points remained significant and ranged from 7.1 mm to 17.8 mm (for 3.5 x 2.5 x 1.5 calibration volume). In this study, the distances of the external points from the calibration structure were not reported. It was concluded that procedures based on other methods rather than DLT may be more appropriate. A similar measurement error was presented by Angulo and Dapena (1992). The mean error was 29mm and 39mm (or 0.4% and 0.5% relative to 8 m field of view) for the cinematography and video system respectively. Chen *et al.* (1994), reported measurement error ranged from 1.2 mm to 17.3 mm for points ranged from 0.3 m to 0.9 m outside the calibrated volume. It is evident that the use of relatively small calibration structures in large filming areas, for extrapolation purposes, increases the measurement error significantly.

Using the procedure presented in this study with a first degree polynomial, the accuracy of the external points depends primary on the distance in screen coordinates of the projected point, on the level of the calibration plane, from the closest calibration point and the image size. Thus, the measurement error for the points on the surveying poles in positions 4 and 7 (Fig 3.11), on the level of the plane, is higher overall compared with the error in the other positions, although these poles were not the most distal from the calibration plane. The measurement error of the points mounted on the poles in positions 4 and 7 was higher because these points were viewed as external points by both cameras. It is important to note that the reconstruction accuracy for extrapolation depends on whether the projection of the reconstructed point on the calibration plane (viewed from at least one camera) is within the area covered by the calibration points. This means that the distance of external points from the calibration plane does not significantly affect the reconstruction error, if the projection of these points viewed from one camera, is on the calibration plane. The measurement error in the external points overall is relatively low, compared with the reported error of previous studies (Shapiro, 1978; Wood and Marshall, 1986; Angulo and Dapena, 1992; Chen *et al.*, 1994), especially when the distance of the projections of the external control point and the closest calibration point is less than 40% of the calibration plane length (Table 3.5, poles 5 and 6). Consequently, this method is suitable for applications requiring extrapolation for coordinate reconstruction in large filming areas.

It is important to note that, in this method, there is no need to survey the camera locations and no assumptions are required for the internal camera parameters.

Higher degree local (piecewise) polynomial models can be used for different degrees of optical distortion, although first degree models are more suitable for extrapolation purposes. It is evident from previous studies (Shapiro, 1978; Andriacchi *et al.*, 1979; Miller *et al.*, 1980; Woltring, 1980; Fioretti *et al.*, 1985; Hatze, 1988; Hatze, 1990; Woltring, 1990; Woltring and Huiskes, 1990) that different amount of distortion is produced by the video lenses, in different screen locations. Woltring (1975), Atha (1984), Phillips *et al.* (1984) and Wood and Marshall (1986) have reported that the different amount of distortion results in lower accuracy in the periphery than in the centre of the screen. On the contrary, Whittle (1982) has reported no distinct accuracy differences in different locations. Another reason for image deformation is the perspective error due to the acute recording angle. Gervais *et al.* (1989) and

Chow (1993) reported that the measurement error was related to the recording angle. In the present study, it was not possible to isolate the different components of measurement error (errors in the polynomial mapping of the camera image coordinates onto the calibration plane, signal noise, asymmetrical lens distortion). However, the sorting method implemented produced accurate results in coordinate reconstruction, because any digitized point is estimated from local calibration points and therefore is not affected by different amount of error present in different areas of the image. The measurement error depends on the area of the local calibration plane. Although the accuracy reported using 16 calibration points is adequate for kinematic studies, an increase in the number of calibration points will reduce measurement error (Karara, 1980; Chen *et al.*, 1994).

In addition, a limiting factor is the resolution of the video adaptor. There were limitations on the number of pixels in the horizontal and vertical direction, which decreased the reconstruction accuracy. Thus, in many cases the accurate digitization of the control points was not possible. The use of higher resolution video adaptors will be a significant factor for the improvement of digitization and reconstruction accuracy.

In conclusion, the method presented for 3-D coordinate reconstruction using video systems is easily implemented, reduces measurement error significantly and is suitable for large filming areas.

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CHAPTER 4

A METHOD FOR 3-D KINEMATIC ANALYSIS USING PANNING VIDEO SYSTEMS

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ABSTRACT

The panning method is the most advantageous technique, when a wide field of view is required, due to its simple implementation, and has widespread applications in the analysis of human movement. The panning technique described in this study uses video systems and a polynomial method for optical distortion correction and coordinate reconstruction. A calibration plane (10 m wide x 2.5 m high) was formed by eleven poles with five markers on each. The two S-VHS Panasonic cameras used to videotape the calibration and control points were free to rotate in vertical axis, in order to record the control points simultaneously in different positions. The measurement error was found to be considerably reduced compared with previous film or video studies, ranging from 0.053% to 0.095% of the field of view. The recording angle did not affect the 3-D reconstruction accuracy.

INTRODUCTION

The accurate measurement of kinematic parameters is of fundamental importance in the evaluation of human movement performance. The data collection process in biomechanics is highly dependent on rapid advances in technology. According to recent studies (Shapiro *et al.*, 1987; Kennedy *et al.*, 1989; Angulo and Dapena, 1992; Pigos and Baltzopoulos, 1993) video systems offer an accurate and less expensive alternative to cine-photographic systems. Although the relatively low sampling rate (compared to cinematography systems) and limited resolution (Dainty *et al.*, 1987) affect measurement accuracy, coordinate reconstruction error can be improved using appropriate correction algorithms (Pigos and Baltzopoulos, 1993). Higher sample rates and resolution video systems (Paisley, 1981; Henning, 1988; Furnee, 1990; Kerwin and Maybery, 1993) can further improve kinematic measurements accuracy.

A number of different 3-D coordinate reconstruction algorithms have been reported, but the most frequently used is the Direct Linear Transformation (DLT) technique. However, the problem with the construction of an appropriate 3-D calibration object (Challis and Kerwin, 1992) for the DLT method has resulted in the development a number of DLT modifications (Miller *et al.*, 1980; Hatze, 1988) and polynomial methods (Andriacchi *et al.*, 1979; Woltring, 1980; Fioretti *et al.*, 1985; Woltring and Huiskes, 1990), and alternative approaches that can be implemented in large fields of view (Dapena *et al.*, 1982). This has facilitated the calibration and recording procedure and improved coordinate reconstruction accuracy.

The usual practice in 3-D filming is to set up two or more stationary cameras that simultaneously record the same filming area. This procedure is not appropriate for the reduction of measurement error when a large field of view is required, due to the small image size and limited resolution. In previous studies for two and three-dimensional analysis, different techniques have been developed in order to minimize this measurement error. This was accomplished using different camera placements (Fredricson *et al.*, 1970; Whittle, 1982; Wood and Marshall, 1986) or multiple cameras (Noble and Kelley, 1966; Huntington *et al.*, 1979; Williams and Cavanagh, 1983; Dillman *et al.*, 1985; Cappozzo and Gazzani, 1990). The limitations in kinematic analysis using cinematography, optoelectronic or video systems, when a wide field of view is required, can be overcome with camera panning. In this technique the camera is free to rotate about the vertical axis (Dapena, 1978; Chow, 1987; Gervais and Wronko, 1988; Hay and Koh, 1988; Gervais *et al.*, 1989; Yeadon, 1989; Chow, 1993; Yu *et al.*, 1993).

The accuracy of 3-D reconstruction is also affected by video lens distortion and perspective error (Woltring, 1975; Shapiro 1978; Whitlle, 1982; Phillips *et al.*, 1984; Fioretti *et al.*, 1985). A number of appropriate correction algorithms have been developed in order to minimize this type of error and optimize the accurate 3-D coordinate reconstruction (Andriacchi *et al.*, 1979; Miller *et al.*, 1980; Woltring, 1980; Hatze, 1981; Wood and Marshall, 1986; Hatze, 1988; Hatze, 1990; Woltring, 1990; Woltring and Huiskes, 1990). However, these techniques have not been implemented for panning video procedures where image distortion resulting from acute camera-plane of movement angles is increased.

The purpose of this study was to develop and evaluate a method for image distortion correction and coordinate reconstruction, in order to improve the 3-D reconstruction accuracy of spatial coordinates, using panning video techniques.

METHOD

Coordinate reconstruction model

The three dimensional coordinates of any point are determined as the intersection of two lines formed by the position of the cameras and the projection of the point on a calibration plane, viewed from the two cameras respectively. These projections are determined using first degree polynomial model:

$$X_p = a_1+a_2x+a_3y \qquad (1)$$

$$Y_p = b_1+b_2x+b_3y \qquad (2)$$

where X_p, Y_p are the coordinates of the projection of any 3-D digitized point on a calibration plane mapped from the 2-dimensional x, y camera image coordinates. The polynomial coefficients $a_1..a_3$ and $b_1..b_3$ are determined from the three calibration points that are closest to the digitized point and thus forming a local calibration plane (Fig. 4.1).

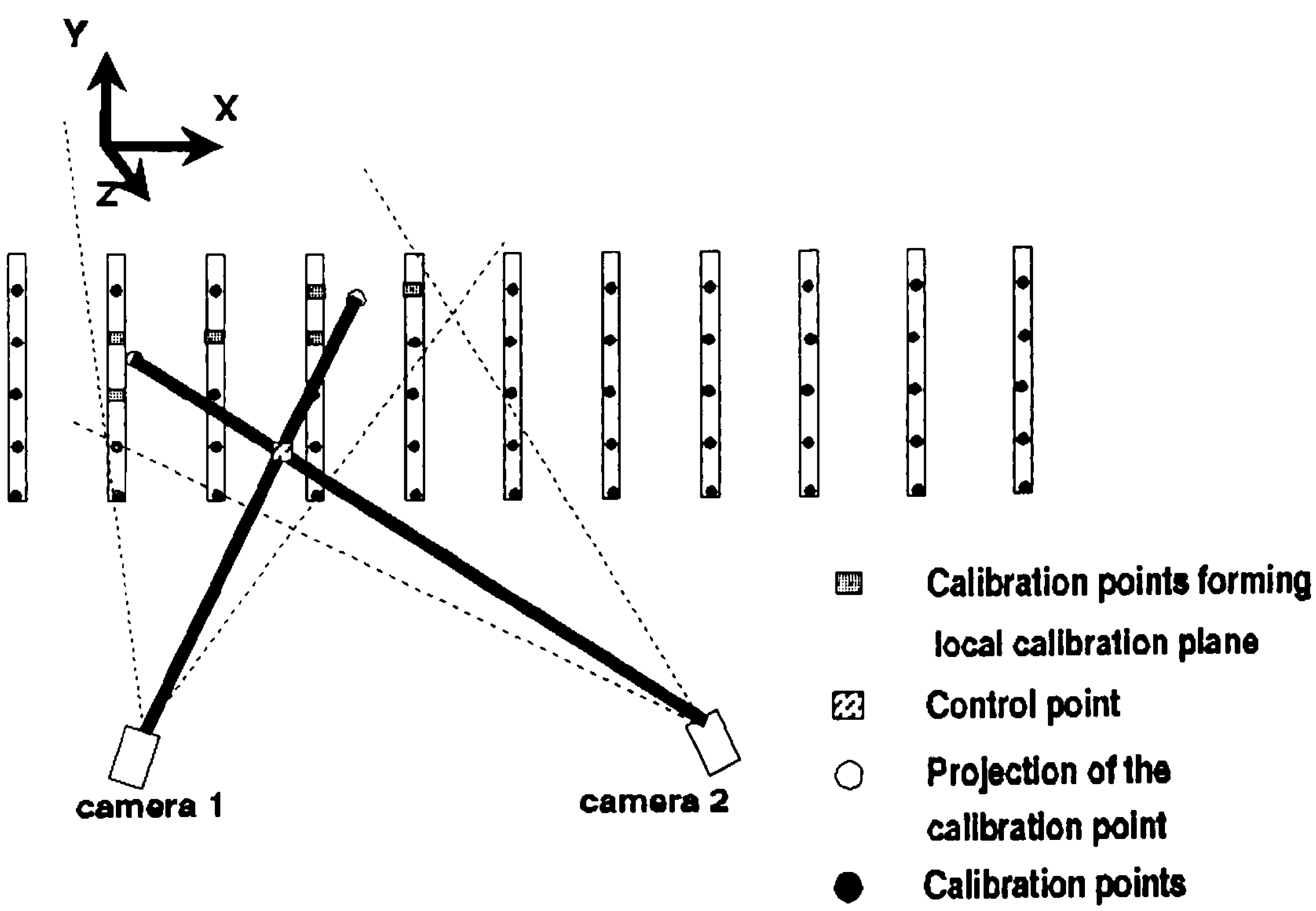

Figure 4.1. The projection of any digitizing point and the formed local calibration plane.

Image distortion and coordinate reconstruction is therefore based on calibration points from a confined area with reduced distortion. This is important as image distortion is not uniform at different screen locations, especially when the camera is at an acute angle to the calibration plane during panning. In this method the 3-dimensional position of the camera must be determined in every different field of view as the camera panned to record the moving subject. Consequently, whenever the field of view between the frames is remain the same, no additional orientation of the cameras is required. The method is presented in detail in Chapter 3.

Calibration procedure

A calibration plane (10 m wide x 2.5 m high) was formed using eleven survey poles, with five markers on each. The distances between the points in each pole and between the survey poles were 0.5 m and 1 m respectively (measurement error ≤0.5 mm). For reasons of analytical convenience, the origin of the system was selected to coincide with the first lower-left marker of the first calibration plane. A survey pole was fixed in a parallel and horizontal position, 1.90 m in front of the calibration plane, and 0.80 m from the ground, with its markers (camera determination points) in known 3-D coordinates relative to the fixed calibration origin. The points on this external pole were used for the determination of the position of the 3-D cameras. A second pole with markers (control points) was fixed in five random and non parallel (relative to the calibration plane) positions between the camera's optical view and the calibration plane. Four control points on the pole were used to determine the reconstruction error, forming two distances of 0.5 m in random positions in the field of view. Horizontal and vertical linear alignment of survey poles was achieved using a Wild N20 level instrument. The distances between the points on every pole (0.5 m) were measured using a Rabone Chesterman Digi-Rod 4000, electronic digital measuring rod (measurement error ≤0.5 mm). The two S-VHS Panasonic F-15 cameras (fitted with WV-LZ14/15E lense) that were used to videotape the calibration and control points, were positioned 1.20 m and 1.50 m (left and right camera respectively) from the ground and 5 m from the calibration plane and were free to rotate about the vertical axis, in order to record the control points simultaneously in different (panning) positions. A S-VHS Panasonic AG-7330-B video recorder was interfaced to an Intel 82486 based computer using a PC-TV adaptor (II) provided by Vine Micros Ltd. The image was displayed on TV monitor (Sony PVM -2130QM). A coded Pascal version of the described algorithm was used to digitize and analyze the recorded data. The calibration plane of the test and the camera positions are illustrated in figure 4.2.

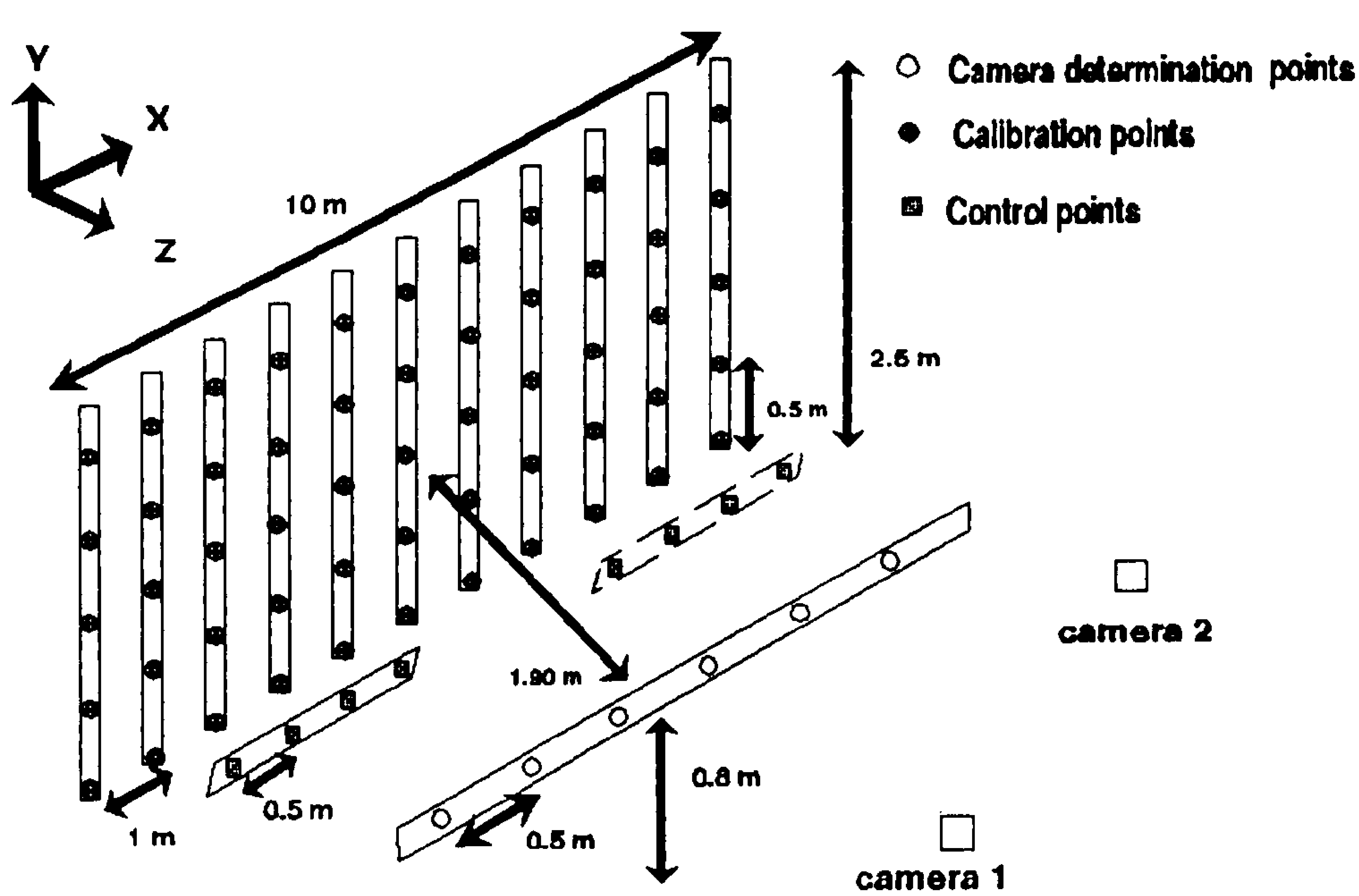

Figure 4.2. The calibration plane and the camera positions.

RESULTS

Sixteen calibration and four control points were digitized in each of 2 reference frames from both cameras. This procedure was repeated in five different camera positions during panning with the angles between camera optical axes and the normal to the calibration plane ranging from approximately -30^0 to 60^0. The values of the calibration points were expressed relative to the first lower marker of the first marker. Thus, in every different panning angle (field), only the distance in horizontal axis of the first lower calibration point of the field from the origin, was required. The calibration points were redigitized and orientation of the cameras was determined in every panning angle (field). The average field of view for every frame was approximately 3.5 m wide x 3 m high. The measurement error (comparing the reconstructed with the actual 3-D distances between the control points) at the five different panning positions was analyzed using a Friedman's test. The statistical results indicate that the measurement error at the different panning positions of the camera optical axis are not significant ($p>0.05$). Mean error and the standard error of the mean ranged from 1.856 ± 0.640 mm (0.053% of field of view) to 3.334 ± 0.210 mm (0.095%) for the five different panning positions (Table 4.1).

Table 4.1. Mean 3-D reconstruction error and standard error of the mean (mm) for two distances in five different panning angles.

	ANGLE 1	ANGLE 2	ANGLE 3	ANGLE 4	ANGLE 5
Distance 1	3.128 ±0.557	1.856±0.905	2.552 ±0.847	2.136 ±0.308	2.521 ±1.062
Distance 2	2.539 ±1.317	2.040±0.163	2.060 ±1.694	2.043 ±1.715	3.334 ±0.297

DISCUSSION

A 3-D panning technique was developed using video systems in order to overcome the limitations of a small image size and a limited field of view when fixed cameras are used.

Different techniques have been implemented in order to record a large film of view. Noble and Kelley (1969) used three cameras to determine the three dimensional coordinates of a moving ball, describing the path of a right circular helix. Fredricson *et al.* (1970) used a parallel (relative to subject motion) moving camera in order to conserve a large image size throughout the athlete's movement. In the study of Dillman *et al.* (1985), an increase of the phases of the movement and the conservation of a relatively (to the field of view) large image size during the long horse vaulting, was achieved using three high-speed cine cameras. Williams and Cavanagh (1983) used four Locam cameras around the 3-D calibrated area, in order to calculate the mechanical power during distance running. Similarly, Huntington *et al.* (1979) used three cameras, with the recording axis of the first (central) camera facing down onto the line of movement and two side cameras set at 45^0 to either side of the movement. Cappozzo and Gazzani (1990), in a study for joint kinematic assessment during physical exercise, have used a COSTEL system equipped with three cameras which were mounted on a pole at three different positions. Whittle (1982) used two television cameras at four different position around the calibration area, in order to provide better observation and, consequently, reconstruction accuracy of the markers. Similarly, Wood and Marshall (1986) used four camera positions to estimate the digitizing accuracy of 3-D coordinates outside of the calibration structure (extrapolation) using the DLT method. The implementation of the above techniques can not be generalized for all human movement analysis, because the use of more than two cameras is not easily implemented. Furthermore, it is time-consuming, expensive and usually only appropriate under specific conditions.

The panning method is the most effective technique because it can be implemented easily and thus has widespread applications in the analysis of human movement when a large field of view is required. The panning method has been applied for two (Chow, 1987; Gervais and Wronko, 1988; Hay and Koh, 1988; Gervais *et al.*, 1989; Chow, 1993) and three-dimensional analysis (Dapena, 1978; Yeadon, 1989; Yu *et al.*, 1993). In order to film an object line of length 102 m Gervais *et al.* (1989) used a 2-D panning procedure with a single camera (field of view for every different panning angle was approximately 2 m). The same technique was used by Chow (1987), Hay and Koh (1988) and Chow (1993), for the estimation of different kinematic parameters in athletic events. Chow (1993) specifically used a panning video technique in order to analyze the strides in sprint hurdling. In this study, there was no image distortion correction to compensate for the effects of the acute recording angle during the panning procedure. In order to minimize this error, the author suggested that the camera should be placed as far away from the plane of action and a telephoto lens be used in order to increase the image size. This method however, is not an appropriate correction for perspective error and image distortion, because the error depends on the distance from camera to object and furthermore the camera can not always be fixed a long distance from the plane of action. Dapena (1978) used two cinematography cameras for the 3-D analysis of high jump, which were free to rotate about the vertical axes. Yeadon (1989) presented a method for the 3-D analysis of ski jumping using two pan and tilt metric cine cameras. However, in both the above studies the metric cameras must be in known positions (relative to the global origin) and furthermore, a large number of accurately measured control points placed in the field of view of each camera are required. Yu *et al.* (1993) develop a method for panning technique based upon the DLT method. Small 3-D calibration structures were combined to form a large calibration volume. Although this method is applied for large areas, the major shortcomings are the large number of calibration points which must be digitized in each frame (time-consuming and error prone digitization), and the large measurement error.

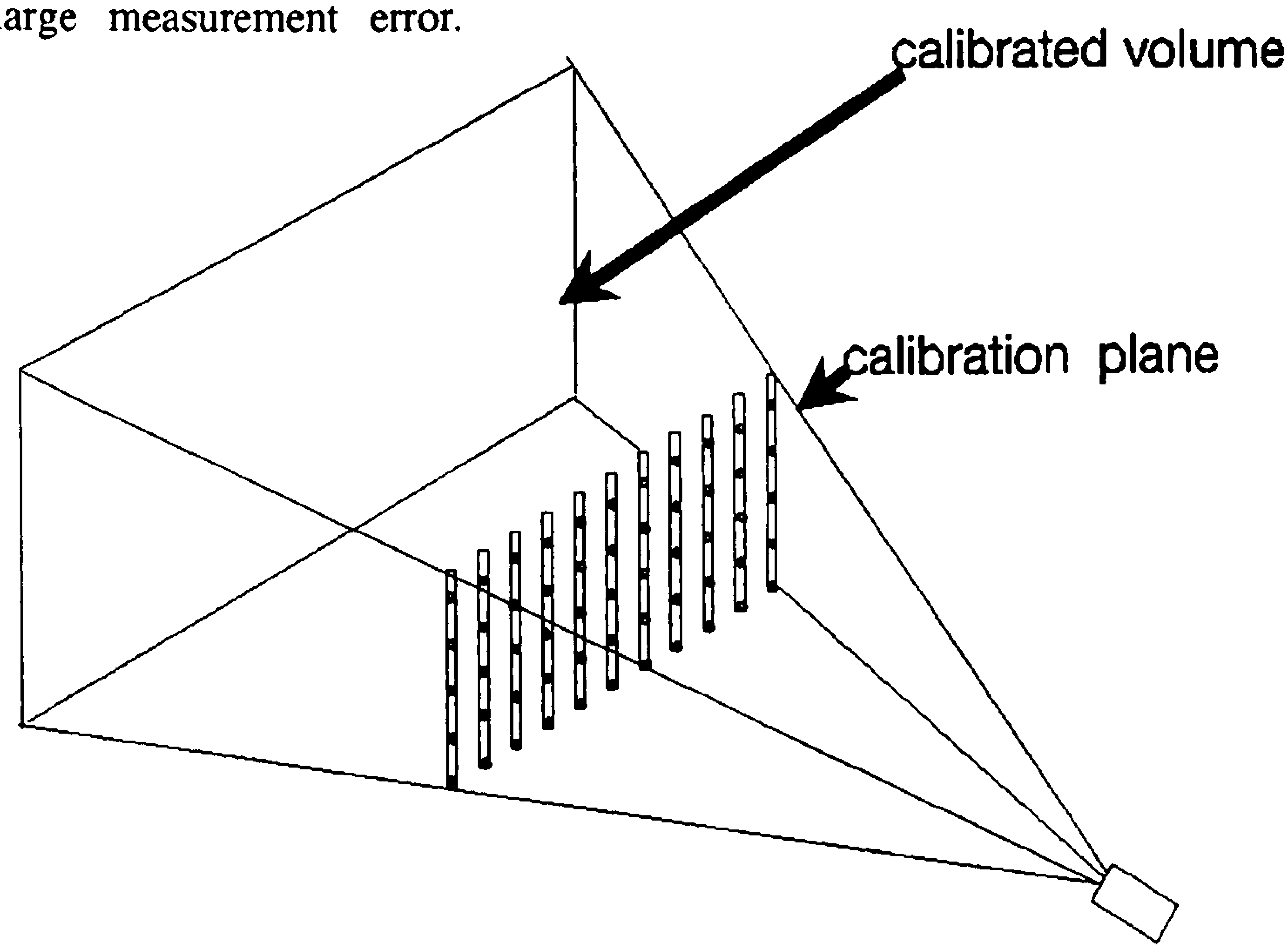

Figure 4.3. The dimensions of a calibration plane positioned between the camera and the movement could be considerably reduced compared to the dimensions of the field of view.

The planar calibration procedure (and not 3-D structure) used in the present study, not only simplifies the calibration structure, but is also adequate and easily implemented for large calibration areas. Although the presented method requires the redigitazation of the calibration points in every different field of view, it is less time-consuming than the method reported by Yu *et al.* (1993). Furthermore, the dimensions of the calibration plane can be considerably reduced relative to the calibrated volume. This volume is not restricted in the area formed by the calibration plane-camera but expands beyond the calibration plane (Fig.4.3). Therefore, any movement occurring between the camera-calibration plane, as well as beyond the calibration plane (assuming no refocusing is required), can be analyzed accurately.

In this panning method a first degree polynomial model is used to determine the 2-D projection of any digitized point on the calibration plane. The measurement error in the 3-D reconstruction was lower than previous 2-D (Gervais and Wronko, 1988; Gervais *et al.*, 1989; Chow, 1993) and 3-D (Dapena, 1978; Yeadon, 1989; Yu *et al.*, 1993) studies, using panning film or video systems.

More specifically, Gervais *et al.* (1989) (using cinematography systems) reported mean measurement error ranging from ± 2.5 mm (approximately 0.13% of field of view) to ± 2.7 mm (approximately 0.38%). Chow (1993) using a similar technique, but with video systems for the recording and analysis process, defined a measurement error to be 10 mm, 20 mm, 30 mm and 40 mm (or ranged from approximately 0.14% to 0.57% of the field of view) for length measures of 0.5 m, 1 m, 1.5 m, and 2 m, respectively. These errors were determined using a stationary camera with 90^0 recording angle in a approximately 7 m wide field of view. The mean measurement error for the panning procedure (determined as the absolute error between the 2-D coordinates calculated from a stationary and the panning camera) was 70 mm in a stride length. The random measurement error reported by Dapena (1978) (using cinematography systems) was ± 5 mm in the X, Y and Z coordinates. The systematic measurement error in the same study, varied from - 20 mm to + 20 mm for the X and Y and -2 mm to +2 mm for the Z coordinates (horizontal field of view was approximately 10 m). The measurement error reported by Yeadon (1989) (using cinematography systems) was 0.05 m and 1^0 for the centre of mass location and orientation angles respectively. Yu *et al.* (1993) (using video systems) reported a measurement error ranging from 14.4 mm to 44.7 mm.

Gervais *et al.* (1989) reported that the measurement error was related to the recording angle (the angle formed by the camera optical axis and the calibration structure). The mean error was ± 7.5 mm for a calibration width of 102 m or panning angle of 120^0, and ± 2.5 mm for a calibration width of 46 m and 22 m or panning angles of 75^0 and 40^0 respectively. Similarly, an increase of the measurement error with increasing angle between the optical axis of the panning camera and the calibration structure was reported by Chow (1993). In addition, Phillips *et al.* (1984) reported that the measurement error was increased from less than 2% before the camera was tilted upwards, to 2% for 10 mm elevation at a 6 m distance between camera-calibration plane and 2.09% for 6 mm elevation at 10 m. In the present study, although the measurement error in the first and fifth panning angles (the extreme left and right panning angles shown in figure 4.4) is slightly higher (Fig. 4.5) than the others, there is no significant difference in the accuracy between the panning angles.

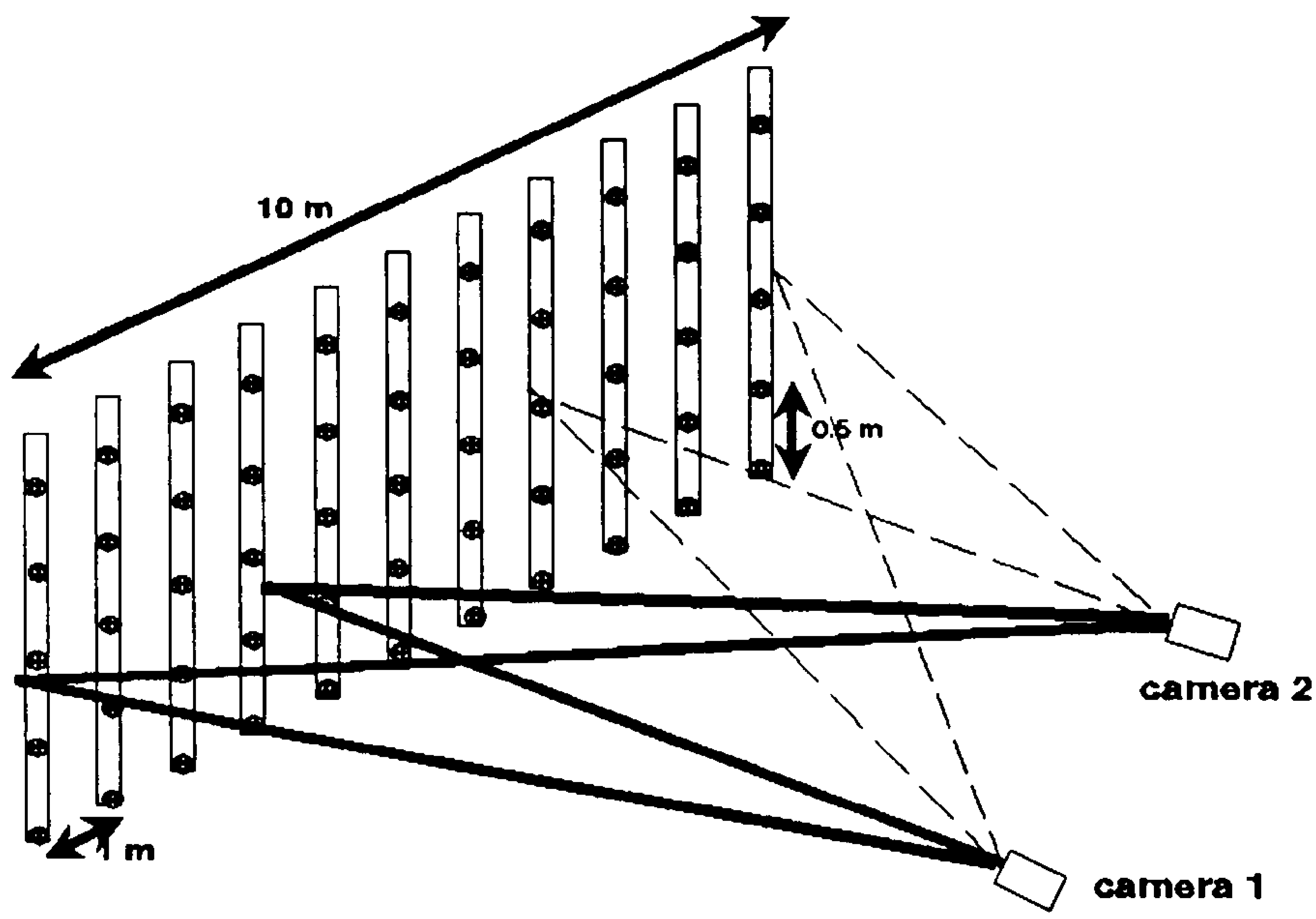

Figure 4.4. The extreme left (angle 1) and right (angle 5) panning angles.

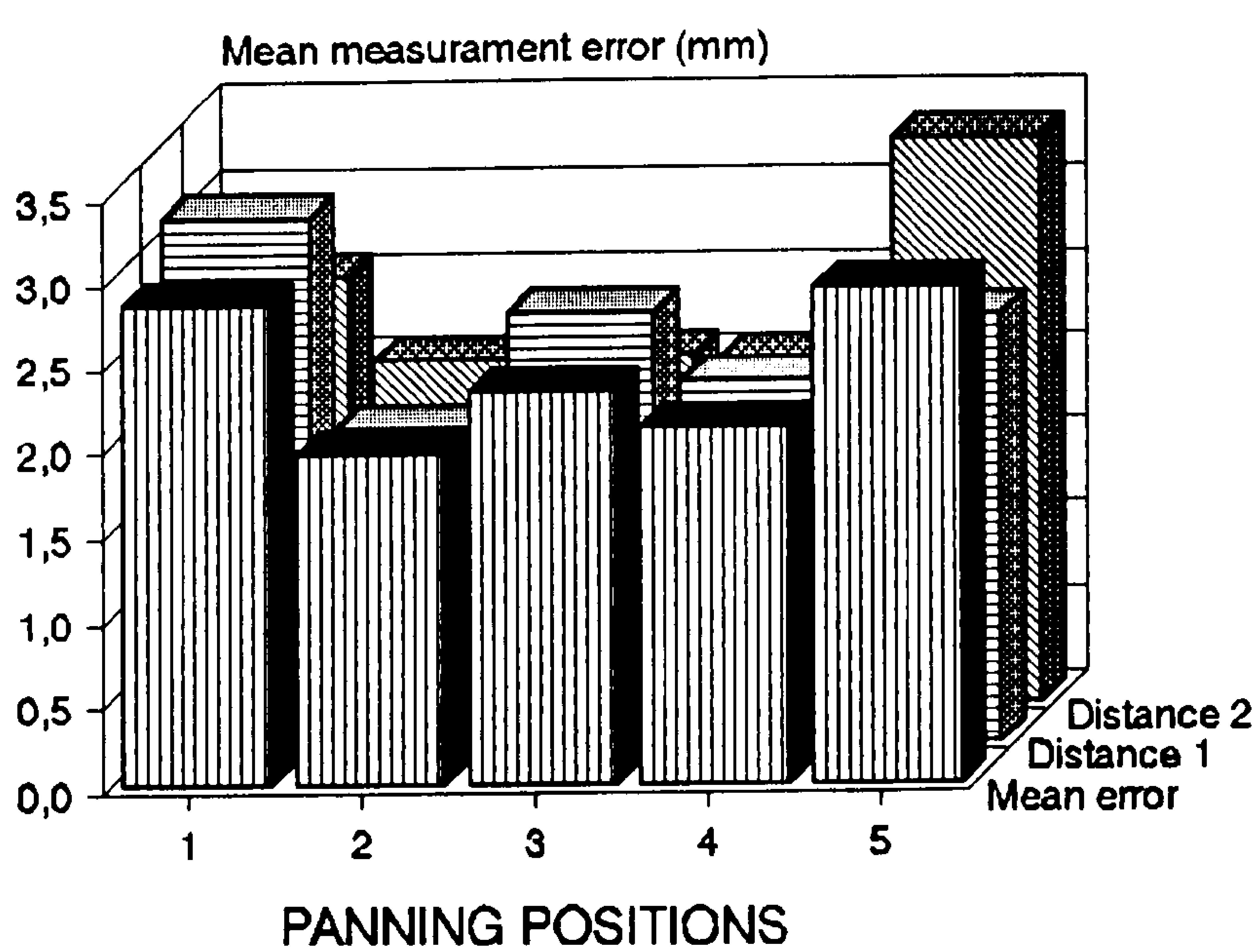

Figure 4.5. The mean measurement error in five camera positions for the left (distance 1) and right (distance 2) distances.

It is evident from previous studies (Shapiro, 1978; Andriacchi *et al.*, 1979; Woltring, 1975, Miller *et al.*, 1980; Woltring, 1980; Whitlle, 1982; Atha, 1984; Phillips *et al.*, 1984; Hatze, 1988; Hatze, 1990; Woltring, 1990; Woltring and Huiskes, 1990) that different amounts of distortion are produced by video lenses in different screen locations. In the study by Gervais *et al.* (1989), the control points were approximately in the centre of the screen (during the recording procedure) and there is no information indicating the error produced in the periphery of the screen. However, in outdoor recording procedures, the image of the subject can not be maintained in the centre of the screen throughout the recording movement. The sorting method used in the present study corrects the image deformation and produces accurate results in every screen location. The measurement error depends upon the area of the local calibration plane and therefore the density of the calibration points. Although the accuracy reported using 16 calibration points (for 3.5 m W X 3 m H field of view) is adequate for kinematic studies, an increase in the number of calibration points will further reduce measurement error.

A limiting factor is the resolution of the video adaptor. There were limitations on the number of pixels in the horizontal and vertical direction, which decreased the reconstruction accuracy. The approximate digitizing resolution was about 5.5 mm (3500 mm / 640 pixels) in the horizontal direction and 6.3 mm (3000 mm / 480 pixels) in the vertical direction, for a 3.5 m high by 3 m wide field of view respectively. Consequently, the maximum measurement error due to video resolution is equal to one half of the video resolution, assuming the image of a marker is represented by two consecutive pixels. Therefore, maximum measurement error due to video resolution limitation is 2.3 mm in the horizontal and 3.2 mm in the vertical direction.

CONCLUSION

Static 3-D filming procedures can not be applied effectively for the recording of movements requiring large filming areas.

The advantage of the panning method presented in this study is that a planar calibration structure is required. The dimensions of the calibration plane can be considerably reduced relative to the calibrated area. The effects of an acute recording angle and lens distortion are corrected using a sorting technique, reducing significantly the measurement error compared to any other film or video method used. In addition, the use of higher resolution video adaptors will be a significant factor for the improvement of digitization and reconstruction accuracy.

In conclusion, the developed three dimensional polynomial method for panning video systems, is an accurate and easily implemented technique that is suitable for large filming areas.

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CHAPTER 5

ASSESSMENT OF ANGULAR MEASUREMENT ACCURACY USING VIDEO ANALYSIS

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ABSTRACT

In this study video systems were tested for assessment of angular measurement using the Biomechanics Workstation (BmWs) system and a first degree polynomial method. The accuracy of BmWs, when the zoom facility is implemented, was also examined. A calibration plane with 19 markers was recorded in an underwater and an indoors environment. Five 90° angles formed by three non linear calibration points were used in the accuracy estimation of the above methods. The mean angular measurements for both environments ranged from 89.983° to 90.000° using the polynomial method, from 90.761 to 89.842 using the BmWs without zooming and from 90.700° to 90.090° using the BmWs with zoom facility. It was concluded that the polynomial method was superior to BmWs and produced accurate angular measurements in every screen location. Furthermore, there was no difference in the accuracy between the angular measurements in different environments.

INTRODUCTION

The field of kinematic measurement is constantly being enriched by new technological advances in the analysis process. In recent years, video systems have been developed for the recording and kinematic analysis of human movement (Shapiro *et al.*, 1987; Kennedy *et al.*, 1989; Angulo and Dapena, 1992; Pigos and Baltzopoulos, 1992; Chow 1993; Kerwin and Maybery, 1993; Pigos and Baltzopoulos, 1993; Yu *et al.*, 1993). Kerwin and Templeton (1991) compared digitisation accuracy of the Biomechanics Workstation Video system (BmWs), which enables two dimensional (2-D) analysis, with a film system. Operator performance was determined from 100 digitisations of a standard length for both systems. The root mean square difference between the video and cinematography systems was 0.024 m. The field of view in this study was 4.11 m x 3.15 m for the video and 4.65 m x 3.12 m for the cinematography. It is evident, from the majority of previous studies that cinematography systems are more accurate than video systems, due to the relatively low sampling rate and the limited resolution (Dainty *et al.*, 1987) of video systems. However, the possibility of instant feedback by reviewing the movement at once and furthermore the low running cost, are significant advantages of the video systems, which enable their widespread use for movement analysis. Moreover, the low video resolution can be effectively compensated using appropriate mathematical methods (Pigos and Baltzopoulos 1993) (see Chapter 3).

It is evident, considering previous studies (Whiting *et al.*, 1985 ; Gregor *et al.*, 1985; de Boer *et al.*, 1987; Elliott *et al.*, 1988; Sanders and Wilson, 1988; Whiting *et al.*, 1988; Elliott and White, 1989; Elliott and Marsh, 1989; Koh *et al.*, 1992; Sakurai, *et al.*, 1993), that the precise assessment of angular measurements is a significant parameter in the evaluation of human movement. In the research applications of Biomechanics in swimming, especially, the implication of accurate angular assessment is fundamental to improve the athlete's performance (Mason *et al.*, 1985; Schleihauf *et al.*, 1988; Sanders and Stewart, 1992). Angular measurements are applied to determine the appropriate angle a) at entrance into the water (i.e. the angle of incline formed by the body, relative to the surface of the water) in order to minimize the drag produced during swimmer entrance (Counsilman *et al.*, 1988), and b) during the race, to specify the angle of the swimmer's body relative to the movement axis, in order to maintain a hydrodynamic position (Mason *et al.*, 1985; Hay, 1988; Sanders and Stewart, 1992b), and the optimum hand angle throughout the stroke, (Mason *et al.*, 1985; Hay, 1988; Sanders and Stewart, 1992a; Sanders and Stewart, 1993) producing effective propulsive and lifting forces. In the underwater filming environment, the refraction due to water, is an additional limitation in the accurate determination of angular measurements, and therefore researchers have devised appropriate structures (e.g. custom-build underwater housings, underwater windows) in order to record the movement below the water level and to minimize this type of error (Vertommen *et al.*, 1983; Mason *et al.*, 1985; Schleihauf *et al.*, 1988; Hay and Thayer, 1989; Hay and Gerot, 1991).

All the previous studies (Shapiro *et al.*, 1987; Kennedy *et al.*, 1989; Kerwin and Templeton, 1991; Angulo and Dapena, 1992), compared the differences between the actual 2 or 3 dimensional coordinates of points or the distances between a series of control points, with the respective image coordinates, or distances, which were digitized and analyzed by the video systems. Although angular measurement depends on the accurate reconstruction of control points, forming the angle, it is also affected by the measurement error of total points (usually three), in every axis. Hence, the difference in directions (the reconstructive value is less or more than the actual value) in every axis and the magnification of reconstructed error, due to the different amount of image (points) deformation in every screen location and the digitizing error, is affected in the accurate estimation of the formed angle. Consequently, although the absolute mean error in the coordinate reconstruction of the points forming the angle could be low, the error in the determination of the angle could be high. This is because the magnitude of the measurement error of every point is present in different directions and axes.

The purpose of this study was to examine and compare the accuracy of angular measurements indoors and underwater, for swimming applications, using the two-dimensional (2-D) Biomechanics Workstation system (BmWs) (Harrison and Littler, 1991) and a 2-D method using a first degree polynomial.

METHOD

Mathematical method

The BmWs system was based on an Acorn Archimedes computer. A simple mathematical expression, consisting of a scaling method, was implemented for the reconstruction of 2-D coordinates of the image. The scaling method was used to convert the screen coordinates to the actual 2-D coordinates using the actual length of one known distance.

In the polynomial method (modified from the 3-D method presented in Chapter 3 for 2-D analysis), the 2-D coordinates of any digitized point were determined as the projections of this point on a calibration plane mapped by the

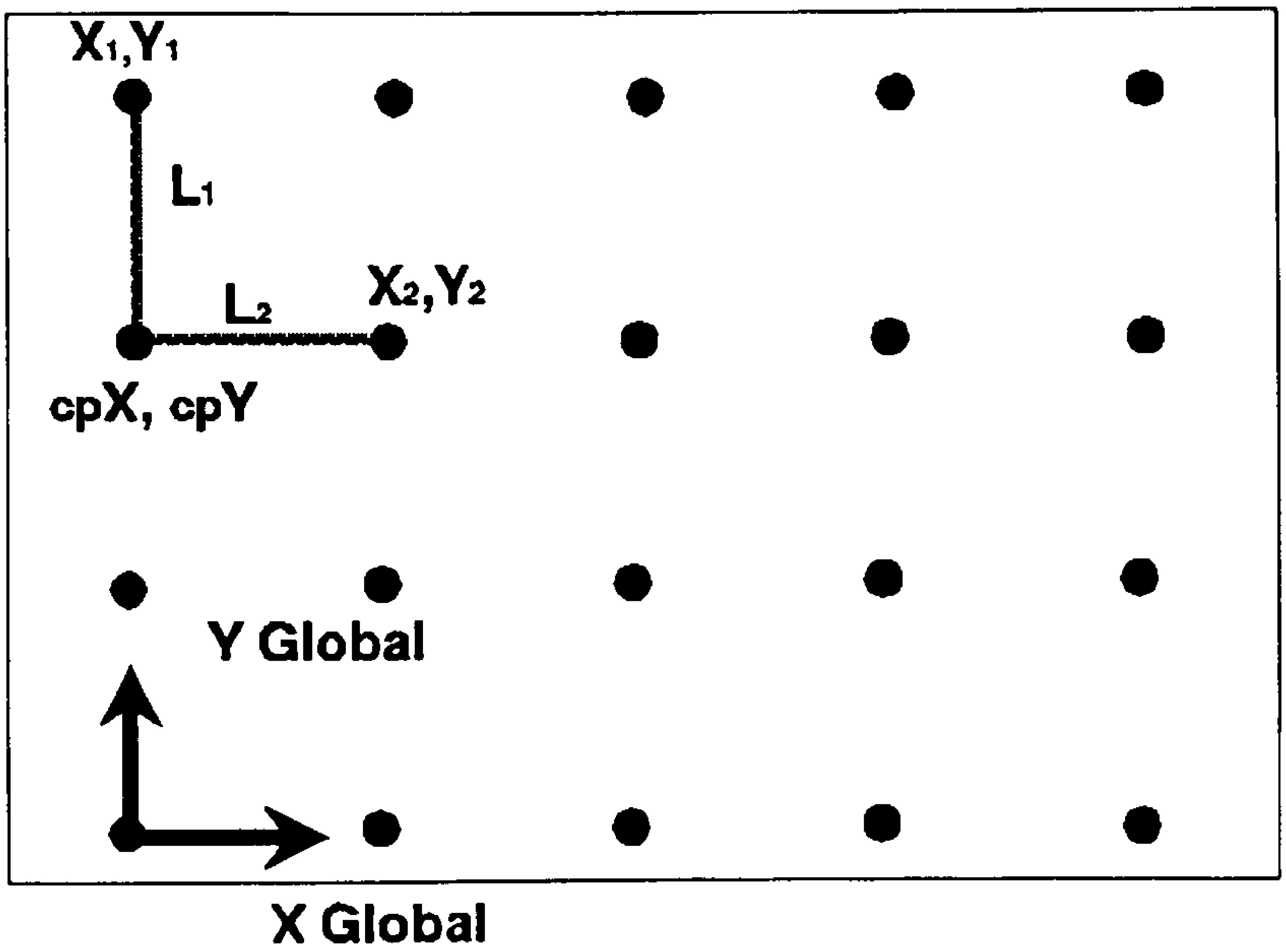

Figure 5.1. The three points forming a 90 degree angle. The point with coordinates cpX, cpY is the intersection point of the two lines L_1 and L_2 and is determined by the general expression of the two lines (see Method Section).

2-D x, y camera image coordinates. A first degree polynomial was used for the determination of the projection coordinates of any digitized point on the calibration plane:

$$X_p = a_1+a_2x+a_3y \qquad (1)$$

$$Y_p = b_1+b_2x+b_3y \qquad (2)$$

where X_p, Y_p : the coordinates of the projection of any digitized point on the calibration plane.

The polynomial coefficients $a_1..a_3$ and $b_1..b_3$ were determined using (a minimum of) three calibration points.

The angular measurements were calculated by estimating the angle between two intersected lines, formed by three non linear points on the calibration plane, using the expressions for non parametric and normalized lines (Fig. 5.1). Any point (${}_{cp}X_j$, ${}_{cp}Y_j$, j=1...N points) of the first line L_1 is determined using the following equations:

$${}_{cp}X_j = X_1 + f_1 * t_1$$

$${}_{cp}Y_j = Y_1 + g_1 * s_1$$

Similarly, for the second line L_2 the corresponding equations are:

$${}_{cp}X_j = X_2 + f_2 * t_2$$

$${}_{cp}Y_j = Y_2 + g_2 * s_2$$

where $t_{1,2}$, $s_{1,2}$: scalar factors

X_1, X_2, Y_1, Y_2: the known coordinates of points on the calibration plane.

f_1, f_2, g_1, g_2: the direction of the lines.

Consequently, the value of the angle between these two lines is calculated using the following equation:

$$\theta = \cos^{-1} \frac{(f_1 * f_2 + g_1 * g_2)}{\sqrt{(f_1^2 + g_1^2) * (f_2^2 + g_2^2)}} \qquad (3)$$

In order to reduce the measurement error, caused by the different degrees of image distortion at different screen locations, the polynomial model was used in combination with a sorting procedure for the points on the calibration plane (calibration points). This sorting technique was used for the selection of the three closest calibration points, according to their distance from the projection of any digitized point, from the total number of available calibration points, in order to form a local plane and determine the polynomial coefficients. Consequently, the projection of any digitized point on the calibration plane was calculated from a local plane and not a global plane fitted to all calibration points, in order to accomplish the correction of the different degrees of image distortion. A control procedure was necessary to ensure that the selected calibration points were not collinear and that they formed a local plane (for further details see Chapter 3).

Instrumentation

A calibration plane 76 cm High (H) X 180 cm Wide (W) was used, with 19 black adhesive markers (24 mm round labels which were placed in the horizontal and vertical axes on the plane) mounted on to a white background (Fig. 5.2). The alignment of the markers into the respective axes was performed using a Wild Heerbrugg N20 level instrument. The distance between the markers was accurately measured in the horizontal and vertical axes using a Rabone Chesterman Digi-Rod 4000, electronic digital measuring rod. The measurement error of the actual distance was $\leq$0.5 mm. Five angles of 90 degrees were formed, one in every corner and one in the centre of the plane, using three non collinear points on the calibration plane (Fig. 5.1 and 5.2).

A S-VHS Panasonic F-15 camera fitted with WV-LZ14/15E lenses was used to film the calibration plane. A S-VHS Panasonic AG-7330-B video recorder was also used to review and analyze the recorded data. The video recorder was interfaced to an Acorn Archimedes computer, when the BmWs was used and to an Intel 82386 based-computer, when the polynomial method was implemented to review and analyze the recorded data. In addition in the polynomial method, a coded Pascal version of the described algorithm was implemented to analyze the recorded data.

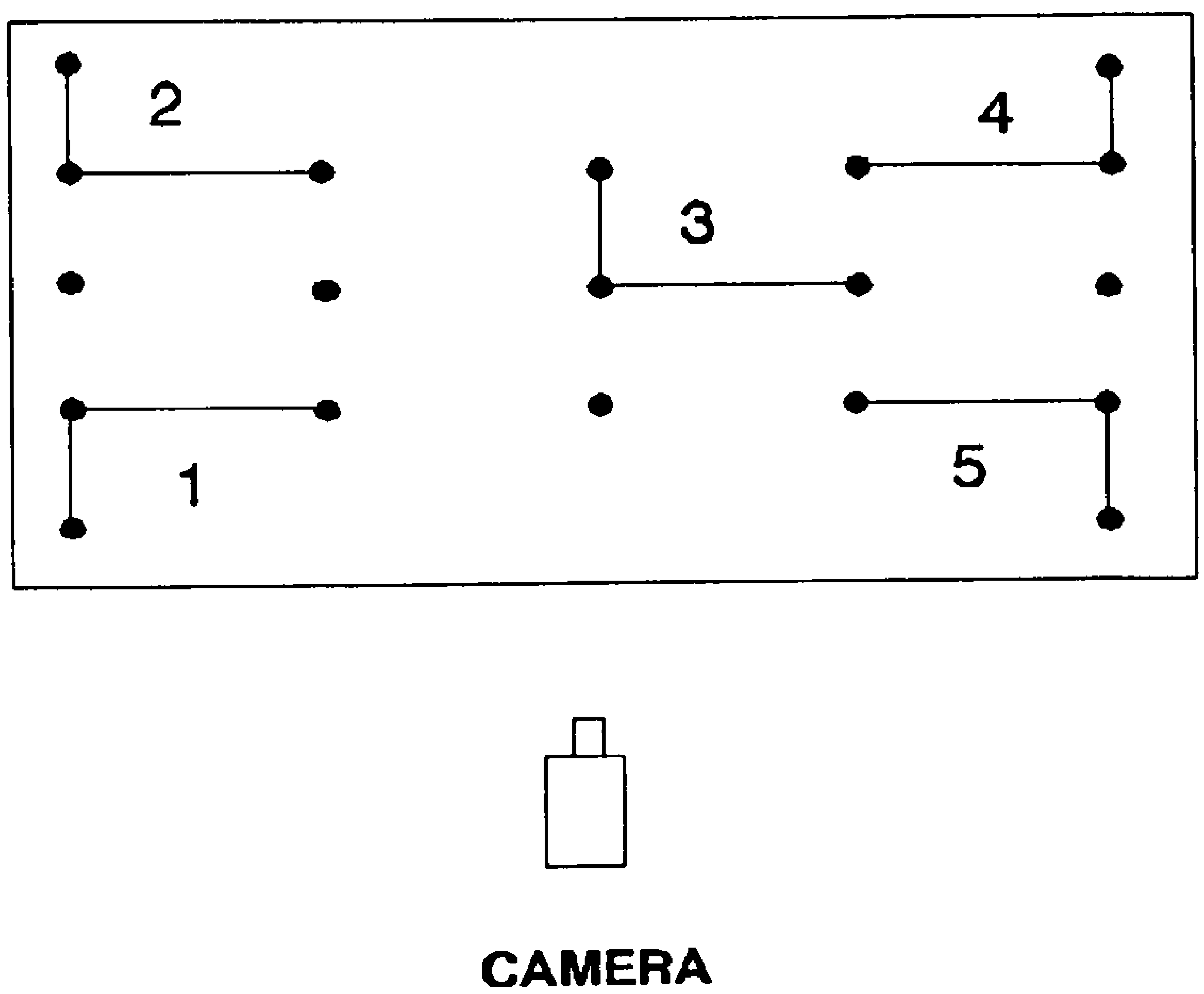

Figure 5.2. The calibration plane with the markers and the five 90 degree angles.

The calibration plane was filmed by the camera in two environments : a) underwater in a swimming pool and b) indoors in a biomechanics laboratory. The field of view in both recording procedures was approximately 1.5 m H X 2 m W.

Recording procedure

A pilot test was performed, in order to select the most adequate background (for underwater recording) as well as clear and visible markers for the main test. A small calibration plane with different background colours, and markers with various colours and sizes was used. White and black colours for the background and the markers respectively, and 24 mm round labels for the markers were selected (see Instrumentation section).

In the main test the calibration plane was submerged in a swimming pool, in a stationary position, parallel to (and in front of) the underwater glass window of the swimming pool (Figure 5.3). The markers (and consequently the formed angles) were recorded by the video camera behind the window. The distances between the camera-window and window-calibration plane were 0.5 m and 5 m respectively (Figure 5.3). A similar technique was followed to record the calibration plane indoors. The camera was positioned 1.45 m from the floor and 4.0 m from the calibration plane.

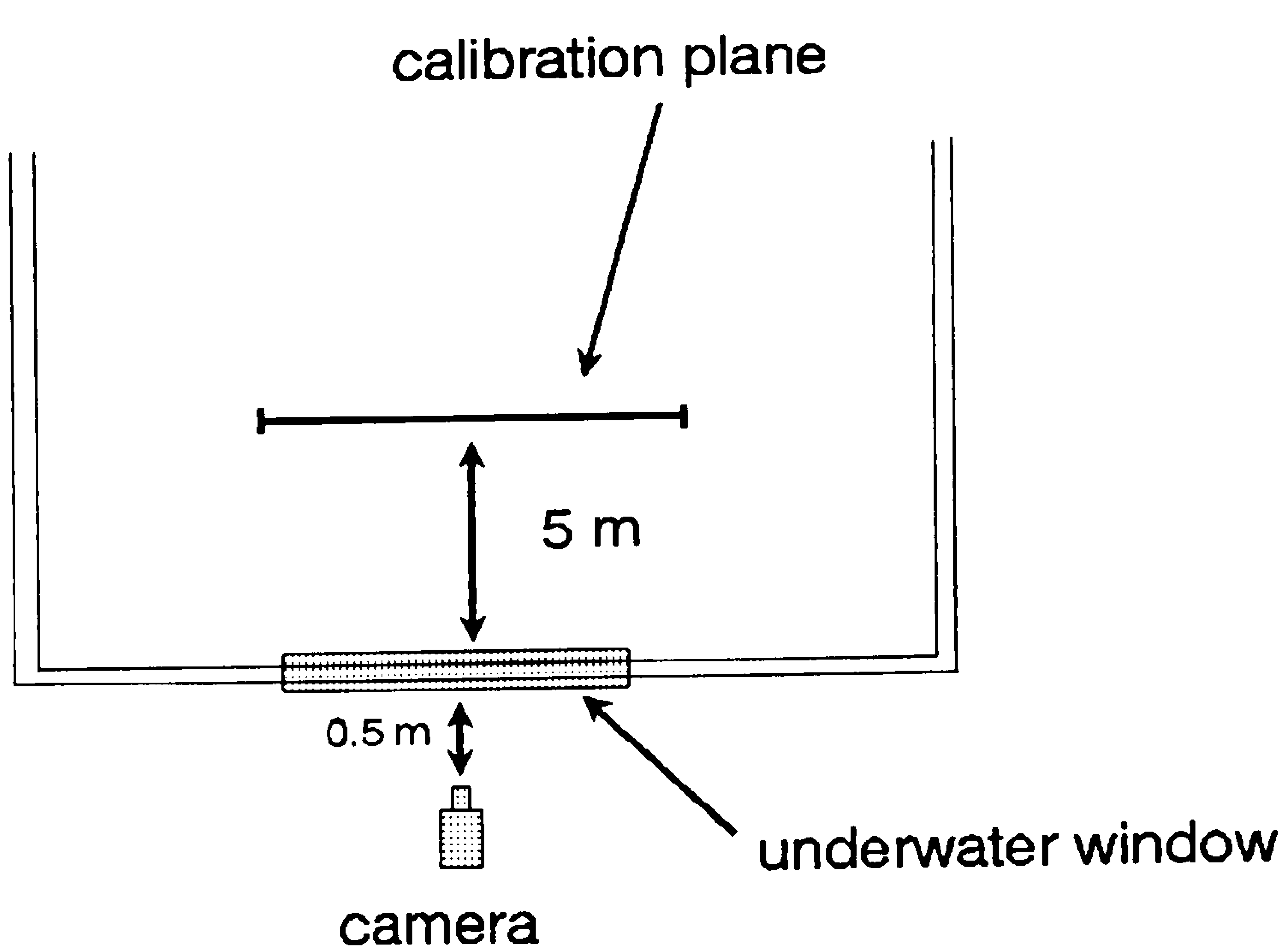

Figure 5.3. Top view of experimental set up for underwater recording

Digitizing procedure

Ten repeated digitizations of a single frame from each recording, underwater and indoors, were digitized using the Biomechanics Workstation system (BmWs) and compatible IBM PC microcomputer (386) using the polynomial method.

The ability of the BmWs to digitize using the zoom facility has been reported in previous studies to improve the reconstruction accuracy (Kerwin and Templeton, 1991). In order to examine if there was any significant difference in the accuracy of angular measurements using the zoom facility, the five different areas of the screen containing the formed angles (upper right, bottom right, central, upper left and bottom left screen locations), were digitized with and without the zoom facility. A new digitizing model in BmWs was created to digitize the markers and consequently the formed angles, as described in the BmWs manual in the "Constructing Models" section. The angular measurements using the polynomial 2-D method were calculated from the unsmoothed two-dimensional marker coordinates, as described in the method section of this study.

RESULTS

The mean angular measurements using the BmWs, ranged (Mean ± SD) from 90.152° ± 0.49° to 90.761° ± 0.48° in the underwater environment and from 89.842° ± 0.33° to 90.605° ± 0.83° in the indoor environment. The respective mean angular measurements using the first degree polynomial method, ranged (Mean ± SD) from 90.000° ± 0.00° to 89.983° ± 0.01° for the underwater environment and 90.001° ± 0.00° for the indoor environment (Table 5.1).

The mean angular measurements using the BmWs with the zoom facility ranged from 90.090° ± 0.63° to 90.700° ± 0.39° and from 89.982° ± 0.45° to 90.542° ± 0.46° for underwater and indoor environment respectively (Table 5.2).

STATISTICAL ANALYSIS

Differences in angular measurements between the five angle positions on the calibration plane, underwater and indoors using the three different procedures (BmWs without zoom facility, BmWs with zoom facility and polynomial method) were examined using a two factor (5 X 3) repeated measures Analysis of Variance. Significance was accepted of the 99% level of probability in both statistical analyses.

The statistical results indicate that there was an overall difference between the procedures using the BmWs and the first degree polynomial method ($F=26.67$, $p<0.01$). Subsequently Tukey tests ($T = 0.160$) revealed that the significant differences were between the first degree polynomial and the two procedures using the BmWs, whereas there was no significant difference between the procedures using the BmWs. In addition, there was an overall difference between underwater and indoor environments ($F=20.77$, $p<0.01$), but there was no overall difference between angle positions ($F=3.26$, $p>0.01$).

Table 5.1. Mean and Standard Deviation of the underwater and indoor angular measurements using the BmWs without zoom facility and the 1st degree polynomial method.

	BmWs (without zoom)		Polynomial method	
	WATER ± SD	INDOOR ± SD	WATER ± SD	INDOOR ± SD
ANGLE. 1.	90.761 ±0.48	89.842 ±0.33	89.996 ±0.04	90.007 ±0.02
ANGLE. 2.	90.657 ±1.07	90.455 ±0.39	89.983 ±0.01	90.001 ±0.01
ANGLE. 3.	90.478 ±0.50	89.912 ±0.50	90.000 ±0.00	89.998 ±0.01
ANGLE. 4.	90.152 ±0.49	89.808 ±0.75	90.003 ±0.03	89.995 ±0.00
ANGLE. 5.	90.694 ±0.68	90.605 ±0.83	89.987 ±0.01	89.999 ±0.01
MEAN	90.548	90.124	89.994	90.000

Table 5.2. Mean and Standard Deviation of the underwater and the indoor angular measurements using the BmWs with zoom facility.

BmWs (with zoom)		
	WATER ± SD	INDOOR ± SD
ANGLE. 1.	90.684 ± 0.50	90.225 ± 0.43
ANGLE. 2.	90.325 ± 0.60	90.215 ± 0.40
ANGLE. 3.	90.228 ± 0.27	89.982 ± 0.45
ANGLE. 4.	90.090 ± 0.63	90.186 ± 0.41
ANGLE. 5.	90.700 ± 0.39	90.542 ± 0.46

DISCUSSION

The examination of the optimum angles during athletic movements is a significant component of successful performance. Moreover, the angular measurements are generally significant for the precise determination of joint range (Chaffin and Anderson 1991; Koh *et al.*, 1992) in order to prevent injuries. In the field of swimming the importance of accurate assessment in angular measurements has been extensively documented by previous studies (Mason *et al.*, 1985; Counsilman *et al.*, 1988; Hay, 1988; Sanders and Stewart, 1992a,b; Sanders and Stewart, 1993).

For the accurate determination of the appropriate joint angle during the swimmer's movement, underwater recording is required. Special structures called 'underwater housings' fixed to the sides or bottom of the pool, have been frequently used (Vertommen *et al.*, 1983; Schleihauf *et al.*, 1988). However, these structures are inconvenient, because of the substantial time required to set up the camera(s) in the appropriate position for the recording. A periscopy system for recording the underwater motions of a swimmer, was presented by Hay and Gerot (1991). The basic design of this system consists of a camera and a mirror fixed in the side of the pool. However, this method is limited by the image deformation due to the mirror and the refraction. The use of underwater windows appears to have increased in popularity in recent years. Most new pools are equipped with one or more underwater windows designed to enable teachers, coaches and researchers to view or record the motions of swimmers. Therefore, in the present study underwater windows were used.

The majority of previous studies estimated the reconstruction accuracy of video systems (Shapiro *et al.* 1987; Kennedy *et al.* 1989; Kerwin and Templeton 1991;

Angulo and Dapena 1992), using coordinate or distance reconstruction. Although angular measurement depends on the accurate reconstruction of individual control points, it is also affected by the measurement error of the points (in every axis and in every direction) forming the specific angle. Consequently, a separate estimation of the angular accuracy using video systems is required.

The present study examined the validity of video systems for angular measurements in both underwater and indoor environments, using two different methods and software: the Biomechanics Workstation system and a first degree polynomial method, based on a compatible IBM PC microcomputer (386). It was found that the mean angular measurement errors were low in both methods, for the underwater and indoor environments. However, using the first degree polynomial method, the angular measurement error produced was considerably reduced, compared to the error using the BmWs for both environments (Figure 5.4). Moreover, the significant difference in accuracy between the two methods is indicated by the higher values of standard deviation (SD) using the BmWs relative to the respective SD of the polynomial method (Table 5.1). The maximum SD were ± 1.07 and ± 0.04 using the BmWs and the polynomial method respectively.

BmWs video system

By comparing the angular measurements of the underwater and indoor filming using the BmWs, it is evident that the digitization procedure of the indoor data was generally more accurate. The probable reason for the differences between these filming procedures, is the influence of the optical distortion caused from the swimming pool window and the water refraction, during underwater filming.

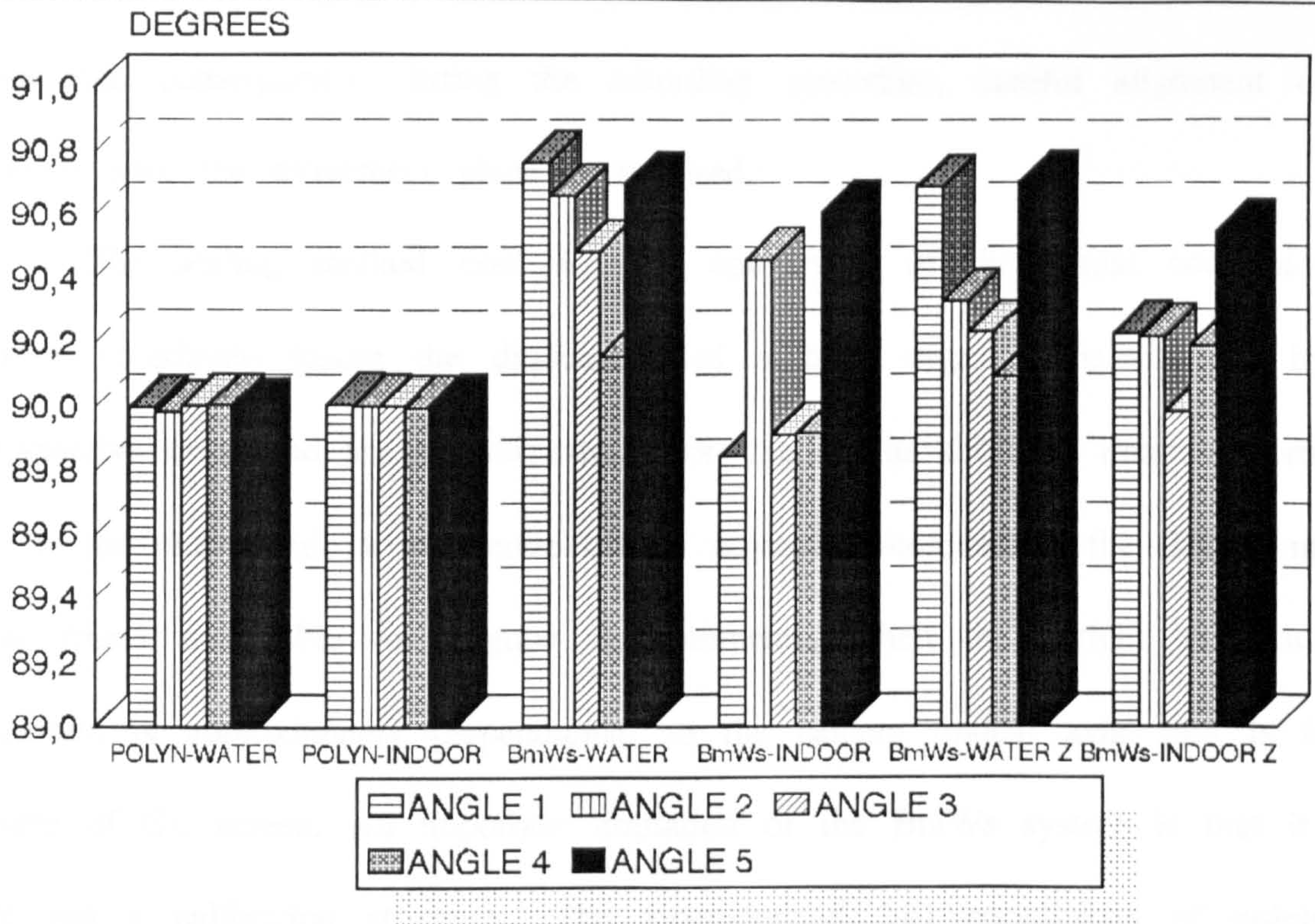

Figure 5.4. The mean of the underwater and indoor angular measurements using the BmWs and the 1st degree polynomial method.

The differences in the position of the most accurate angle between underwater and indoors using the BmWs, was probably caused by the misalignment between the camera and the calibration plane. The most accurate angle for the indoor procedure was the central, whereas for the underwater it was the upper right angle. In the underwater recording, the camera's position was not precisely in the centre of the calibration plane, because of the difficulty in aligning the submerged plane and the camera with the swimming pool window. Considering overall the accuracy of angular measurements using the BmWs, the digitizing accuracy is reduced in the periphery of the screen. This was probably due to the different amount of distortion produced by the video lenses, in the periphery and in the centre. Therefore, angular measurements are more accurate in the centre of the field of view and consequently, during the recording procedure, careful alignment of the camera with the movement plane is required.

The scaling method used for the conversion of the actual coordinates to screen coordinates (using the dimensions of a body segment) is limited by the perspective error and the measurement error due to the different image deformation in the periphery and in the centre of the screen. Consequently, the BmWs method was found acceptable for angular measurements, when the pattern of movement analyzed is approximately perpendicular to the camera optical axis and is in the centre of the screen. An important limitation of the BmWs system is that it does not use a calibration structure. The reconstructed 2-D coordinates of points are determined using a scaling factor and are relative not to a global origin, but to a screen origin. Therefore, if the camera is moved from the initial position (the field of view is different) during the recording, the origin of the system will change. Consequently, the BmWs can be implemented using only still cameras and is inadequate when the camera is panned or tilted.

Comparing the accuracy produced using the BmWs with and without the use of zoom facility, it is evident that although the accuracy of angular measurements is relatively higher without use of the zoom facility, reliability increased. This can be seen in the reduction of the Standard Deviation values (Tables 5.1 and 5.2). Consequently, the use of the zoom facility increases the reliability of the BmWs, because it minimizes the digitizing errors caused by the operator by increasing the video resolution, but can not significantly increase the accuracy in 2-D reconstruction. Furthermore, the procedure using the zoom facility is time consuming and consequently the advisability of the use of zooming depends on the requirements of each study.

First degree polynomial method

The first degree polynomial method produced similar accuracy between the angular measurements in different environments and positions (locations where the angles appeared in the video screen). The sorting method implemented, produced accurate results in the coordinate reconstruction, because any digitized point is estimated from local calibration points. For this reason, the reconstructed coordinates are not affected by the different amount of image deformation, due to the perspective error associated with the misalignment between the camera and the calibration plane, and the optical distortion produced by the video lenses at different screen locations. Furthermore, the uses of a global origin, in the polynomial method (which coincides with the lower left marker of the calibration plane) renders the method adequate for panning (see Chapter 4).

The superiority of the first degree polynomial method is indicated by the comparison of the coefficient of variation (CV) values. The coefficient of variation (CV), using the first degree polynomial method, ranged from 0.00% to 0.04% for underwater and from 0.00% to 0.02% for indoor filming. The coefficient of variation (CV), in underwater environment using the BmWs, ranged from 0.52% to 1.18% without zoom and from 0.30% to 0.70% with zoom facility. For the indoor filming the CV ranged from 0.36% to 0.91% and from 0.51% to 0.45% without and with zoom respectively. These results indicate that the polynomial method is adequate for accurate estimation of angular measurement in contrast to the BmWs which is not a highly reliable video system.

A serious problem is the resolution of the video adaptor. There are limitations on the number of pixels in the horizontal and vertical direction, using either the Acorn Archimedes computer or the Intel 82386 based-computer (resolution of the graphical adaptor for both computers is 640 x 480 pixels). Thus, in many cases the accurate digitization of the markers was impossible. This decreased the accuracy of the angular measurements. The use of higher resolution Video adaptors would be a significant factor for the improvement of digitization and angular measurement accuracy.

CONCLUSION

Two different 2-dimensional methods, the BmWs and a first degree polynomial method, were examined for the assessment of angular measurement. The first degree polynomial method is superior to the BmWs, achieving high accuracy in the determination of angular measurements. Furthermore, the polynomial method can effectively accomplish the correction of the refraction and the different amount of image deformation produced in different screen locations, due to video lens distortion and perspective errors, using a sorting technique.

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CHAPTER 6

A POLYNOMIAL METHOD FOR IMAGE DEFORMATION CORRECTION USING VIDEOFLUOROSCOPY

G. PIGOS

ABSTRACT

The analysis of dynamic images for the determination of skeletal deformation and joint kinematics using videofluoroscopy has been frequently implemented. However, image deformation is introduced in different stages of videofluoroscopy, reflected in the accurate reconstruction and consequently in kinematic analysis of dynamic images. A first degree polynomial incorporating an image deformation correction method was examined for the reconstruction of spatial points using videofluoroscopy. Different angles between image intensifier and calibration plane and different sets of calibration points were used. The results indicate that the absolute mean error was considerably reduced compared with previous studies. The different amount of image deformation produced in every screen location, has been effectively corrected. The number of calibration points affects the accuracy of the reconstruction. Thirty calibration points is the minimum number of calibration points required using this polynomial method, when the angle between object and X-ray ranges from 90° to 60°.

INTRODUCTION

Radiographic techniques remain the most widely used methods for the assessment of skeletal deformation, mechanical disorders (joint stability, prosthetic implant fixation-loosening) (Lippert *et al.*, 1982; Huiskes *et al.*, 1985; Meijer *et al.*, 1989; Briggs and Smith, 1993; Jonsson *et al.*, 1993; Wandtke, 1994), medical diagnosis and prognosis of the diseases (Bell, 1990; Lawrence *et al.*, 1993). The limitations of static X-rays for the analysis of movement have been reported in previous studies (i.e. Penning *et al.*, 1984). Roentgen stereophotographic analysis (RSA), using cinematography systems (based on conventional static X-rays), have been frequently used in previous studies, with low measurement error (Huiskes *et al.*, 1985; Selvik, 1989). However, the main limitation of this method is that the subjects are exposed to relatively large dosages of radiation, when conventional X-ray pictures are obtained. Furthermore expensive cameras and analysis equipment are required. Consequently, a very limited number of exposures can be obtained from the same subject (Wallace and Johnson, 1981; Breen *et al.*, 1988; Kärrholm, 1989).

The ability of videofluoroscopy, using image intensifier video systems interfaced to computers, to record in real-time skeletal segment movement and the instant review of the recorded data, render the method an advanced technique for radiology. The use of these systems eliminate the necessity for bulky and expensive camera set up film processing and projection systems (Breen *et al.*, 1988; Bell, 1990). The limitations of RSA can effectively be overcome using videofluoroscopy. The X-ray images using videofluoroscopy, can be accomplished with less X-ray dosage than that required for a single plain film (Breen *et al.*, 1989; Cholewicki *et al.*, 1991). This is a significant factor for the advisability of videofluoroscopy because, in pathological conditions, radiography analysis is usually applied more than once in the same patient and, moreover, there is inability to control the optical density of the resulting image, when there is slight underexposure (Wandtke, 1994).

However, using radiographic systems, image deformation is produced from various sources and affects the accurate reconstruction of skeletal images. Deformation commonly refers to the situation where the coordinates of a point in the object plane and the corresponding image point coordinates are not related by a linear transformation. In cine-radiography image deformation occurs basically as a result of perspective error and the dosage of X-ray exposure, however when the image intensifier (in videofluoroscopy) is used, deformation is introduced at a number of stages during the processing of the X-ray picture. The fundamental source of deformation is the perspective error, due to the curved intensifier fluoroscopy screen resulting in increased magnification of deformation at the periphery of the screen (Selvik, 1989) producing "pin-cushion" distortion as illustrated in figure 6.1 (Wallace and Johnson, 1981; Wood, 1982; Fioretti *et al.*, 1985). Furthermore, barrel, trapezoidal, non-linear distortions or a combination of these, are frequently present in videofluoroscopy (Wallace and Johnson, 1981; Chakraborty, 1987), due to the video lenses and television analysis system.

The accurate assessment of skeletal segment movement and mechanics is fundamental in the biomechanics, diagnosis and rehabilitation. The estimation of the skeletal deformations and dislocations, or the evaluation of the efficiency of the treatment, requires accuracy in the image reconstruction of skeletal segment, which must be examined.

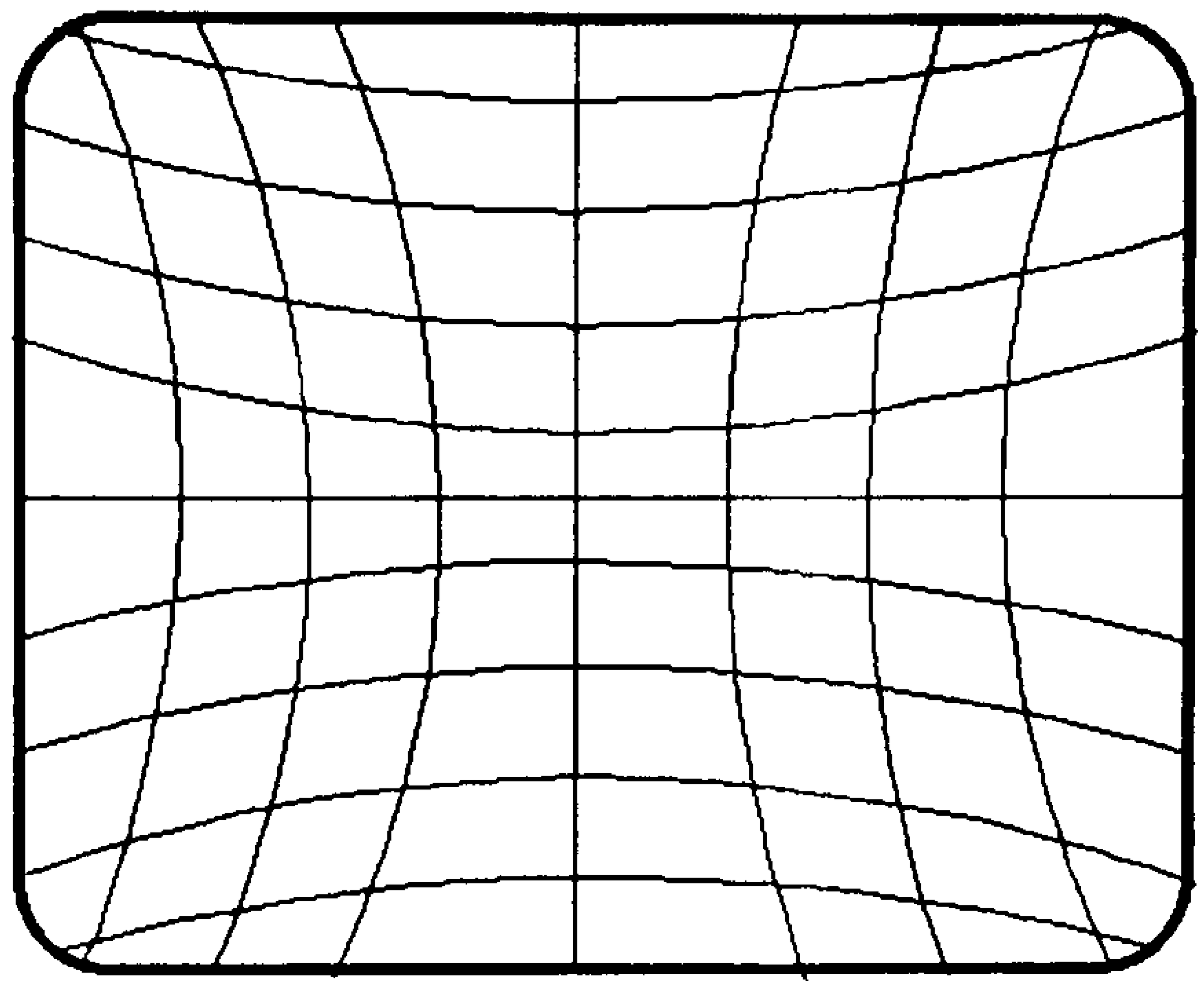

Figure 6.1. Pin-cushion distortion, presenting larger deformation in the periphery than in the centre

Consequently, all these errors must be compensated by appropriate mathematical models for image deformation correction, in order to minimize measurement error. The perspective error due to the distance between object and image intensifier screen, can be reduced by positioning the object close to the image intensifier screen (Cholewicki *et al.*, 1991). Adequate correction is accomplished with the implementation of simple geometrical methods, using the known distances (provided by the manufactures) from the focus of the X-ray beam to the object being X-rayed and from the focus to the film (Wallace and Johnson, 1981; Chakraborty, 1987; Büchi *et al.*, 1990). Cholewicki *et al.* (1991) proposed a geometrical method for the determination of the curvature of the image intensifier screen, when is not available from manufactures data. Baltzopoulos (1994) presented an accurate non-linear polynomial method for image deformation correction. However in this study a large number of calibration points (240) are required for accurate measurements.

The image deformation is significantly affected by the angulation between X-ray-image intensifier and object plane-image intensifier. The increase of the angle between X-ray and image intensifier or object plane and image intensifier increases the image deformation (Meredith and Massey, 1977; Chakraborty, 1987).

The purpose of the present study is to evaluate a first degree polynomial method used for the determination of 2-dimensional (2-D) reconstructed coordinates. Furthermore correction method implemented, for the reduction of measurement error caused by different types of image deformation. Two different angulations (0^0 and 30^0) between object and image intensifier plane was implemented using videofluoroscopy. Different number of calibration points were used to determine the minimum sufficient number of calibration points implemented relative to the field of view for accurate 2-dimensional (2-D) analysis, using videofluoroscopy.

METHOD

Polynomial model

The polynomial method implemented in the present study is presented in Chapter 5. The 2-D coordinates of any digitized point are determined as the projections of the point on a calibration plane mapped by the 2-D x, y camera image coordinates. A first degree polynomial was used for the determination of the projection coordinates of any digitized point on the calibration plane:

$$X_p = a_1+a_2x+a_3y \qquad \textbf{(1)}$$

$$Y_p = b_1+b_2x+b_3y \qquad (2)$$

where X_p, Y_p : the coordinates of the projection of any digitized point on the calibration plane.

In addition, in order to reduce the measurement error, due to the different degrees of image deformation at different screen locations, the polynomial model was used in combination with a sorting procedure (described in Chapter 5). The coordinates of each digitized point are reconstructed using a different set of coefficient a_j and b_j (j=1..3) and proximal calibration points. A control procedure is necessary to ensure that the selected calibration points, using the sorting procedure, are not collinear and form a local plane.

Instrumentation

A Philips Maximum CM 80 X-ray unit with a Philips television unit was used in the present study. The X-ray image was recorded on a Sony video cassette recorder (Fig. 6.2). Analysis of the video tapes was performed using a Sony U-matic system connected to an IBM compatible 386 computer. The resolution of the graphics adapter of this system is 640 x 480 picture elements (pixels). Video X-rays records were displayed on the computer monitor and were manually digitised using the computer's graphics cursor.

To quantify the image deformation, a phantom grid (Leeds M1 test object for image intensifier, Cowen *et al.* (1992)) was used. The grid (calibration structure) consisted of stainless steel wires (0.250 mm in diameter) mounted on perspex glass of 5 mm thickness and forming 20 mm squares (measurement error < 0.1 mm). The co-planar calibration points were located on the intersection of the wires in the corners of the squares (Fig. 6.3). The calibration structure was placed in two

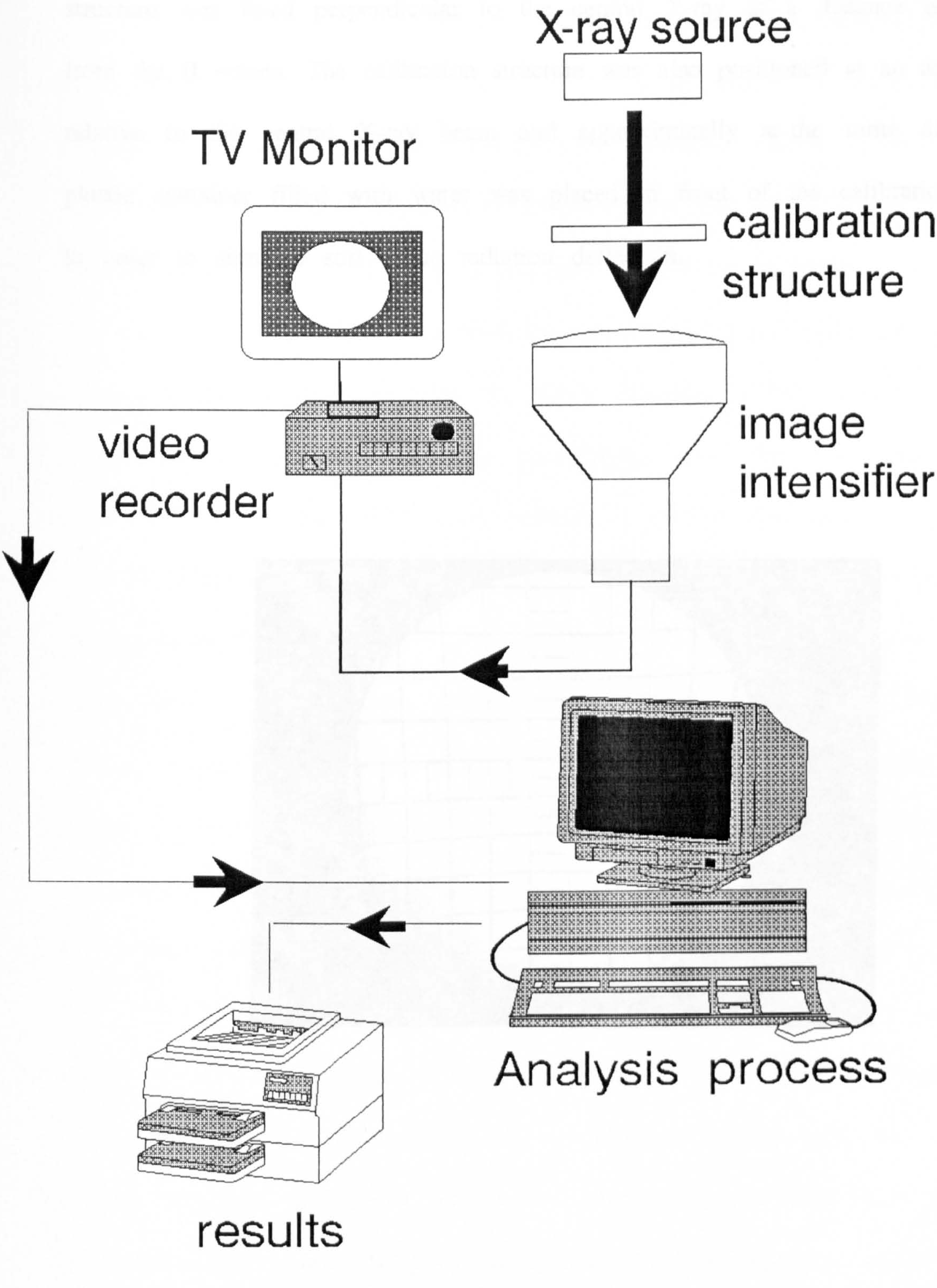

Figure 6.2. The components of an image intensifier-video system and a schematic representation of the analysis process.

different positions relative to the central X-ray beam. Initially the calibration structure was fixed perpendicular to the central X-ray at a distance of 100 mm from the II screen. The calibration structure was also positioned at an angle of 60^0 relative to the central X-ray beam and approximatelly at the same distance. A plastic container filled with water was placed in front of the calibration structure in order to simulate soft tissue radiation deflection.

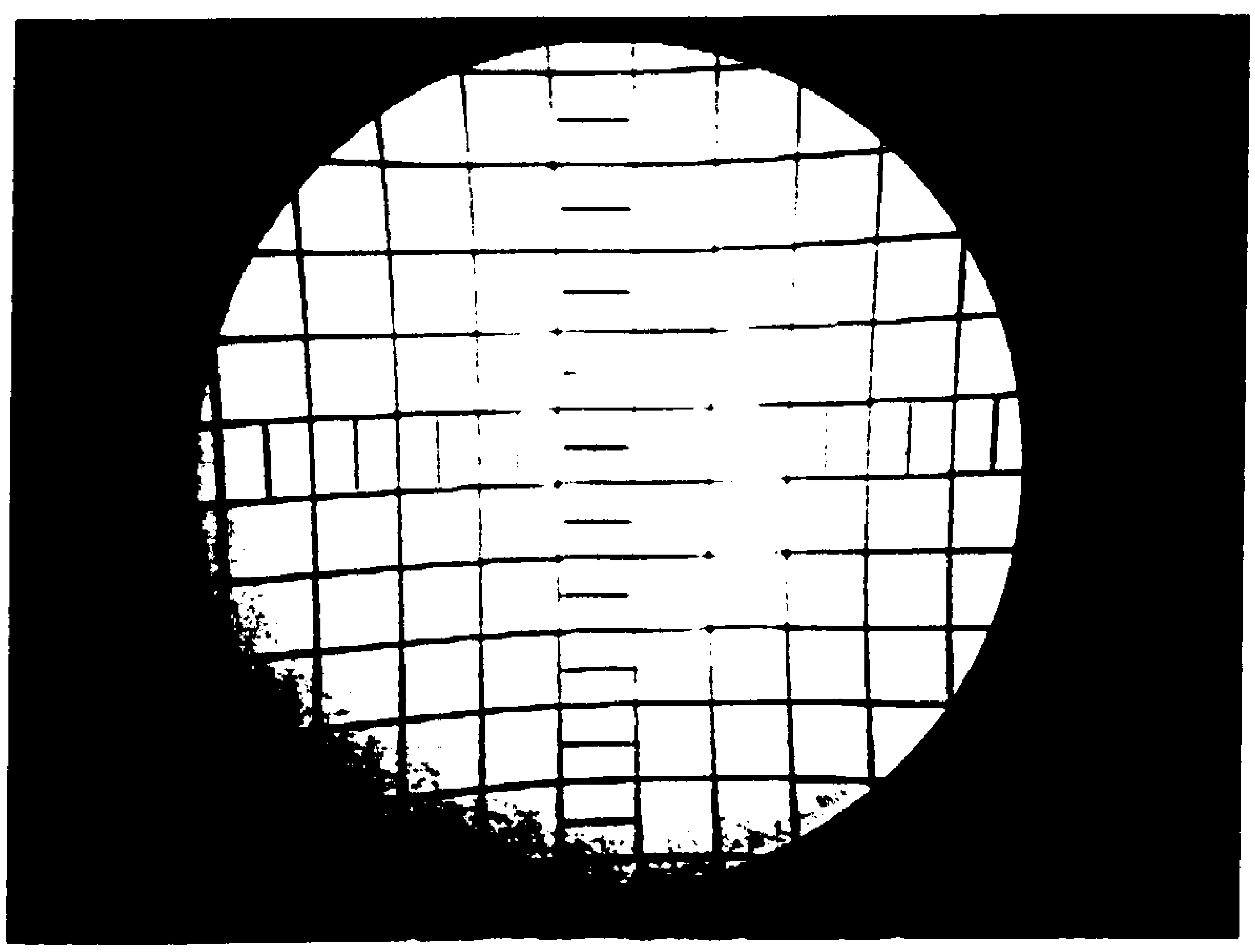

Figure 6.3. The calibration points, located in the intersection of the wires, displayed on the computer monitor. Distortion is minimal in the centre and maximal in the periphery of the screen.

Digitizing procedure

In the study by Baltzopoulos (1994), using videofluoroscopy, the accurate determination of the 2-D coordinates of any point was accomplished using 240 calibration points. This large number of calibration points required is time-consuming. Therefore, in the present study different sets of calibration points were used to determine the minimum appropriate number of calibration points that are required to calibrate the area covered by the calibration grid using the first degree polynomial method described. For this reason 70, 50, 30 and 15 calibration points were used (four separate digitizing procedures), when the calibration grid was positioned in 90^0 and 60^0 angle, relative to central X-ray beam. The different digitization procedures performed using these sets of calibration points will be referred to as '70CP', '50CP', '30CP' and '15CP'. The different calibration procedures using different angle of the calibration plane relative to X-ray beam, will be referred to as '90A' and '60A' calibration procedure. The density of the calibration points, in every digitizing procedure, was the same throughout the screen area. Furthermore, the calibrated area was the same, when different number of calibration points have used. The field of view (FOV) at the object plane was approximately 200 mm x 200 mm. The 2-D coordinates of the calibration points were digitised and stored for the determination of the polynomial coefficients in (1) and (2) and subsequently for the reconstruction of any digitized point, using the polynomial method described in Chapter 5. Twenty points, different from those points used to calibrate the area, were used to estimate the reconstruction accuracy of this method. These 20 points will be referred to as 'control points'. From these control points, 10 were located in the centre and 10 in the periphery of the screen. The reason for the selection of different screen locations was to examine if there is any significant difference in the reconstruction accuracy in the periphery, where the image deformation is significantly increased, and in the centre, where the deformation is minimal, using the correction algorithm (sorting technique). Ten repeated digitizations of a single frame, performed by two experienced operators, in order to minimize the error produced by the operator during the digitizing (Cholewicki *et al.*, 1991) were used.

RESULTS

For the 90A calibration procedure the absolute mean measurement error was 0.181 mm for the central and 0.184 mm for the peripheral control points in the 70CP digitizing procedure, 0.187 mm and 0.193 mm for the central and peripheral control points respectively in 50CP, 0.194 mm and 0.222 mm for the central and peripheral control points respectively in 30CP, and 0.680 and 0.819 mm for the central and peripheral control points in 15CP (Table 6.1).

For the 60A calibration procedure the absolute mean measurement error was 0.188 mm for the central and 0.208 mm for the peripheral control points in the 70CP digitizing procedure, 0.215 mm and 0.235 mm for the central and peripheral control points respectively in 50CP, 0.315 mm and 0.367 mm, for the central and peripheral control points respectively in 30CP, and 0.970 mm and 1.001 mm for the central and peripheral control points in 15CP (Table 6.2).

Measurement error differences using different angles (90A and 60A), screen locations (periphery and centre) and calibration points (70CP, 50CP, 30CP, 15CP) in the two axes (X, Y) were examined using 4 factor (2X2X4X2) repeated measures

Table 6.1. The measurement error and the standard deviation for the control points, when different sets of calibration points used, at 90° angle between the X-ray beam and the calibration plane.

90 degrees angle				
Calibration point	Centre (mm)		Periphery (mm)	
	X Axis ±SD	Y Axis ±SD	X Axis ±SD	Y Axis ±SD
70	0.165 ± 0.022	0.196 ± 0.032	0.188 ± 0.027	0.179 ± 0.027
50	0.191 ± 0.026	0.184 ± 0.036	0.193 ± 0.047	0.193 ± 0.023
30	0.195 ± 0.035	0.194 ± 0.026	0.221 ± 0.053	0.222 ± 0.026
15	0.648 ± 0.356	0.713 ± 0.247	0.861 ± 0.476	0.776 ± 0.428

Table 6.2. The measurement error and the standard deviation for the control points, when different sets of calibration points are used at 60° angle between X-ray beam and the calibration plane.

60 degrees angle				
Calibration point	Centre (mm)		Periphery (mm)	
	X Axis ±SD	Y Axis ±SD	X Axis ±SD	Y Axis ±SD
70	0.187 ± 0.099	0.189 ± 0.085	0.201 ± 0.072	0.190 ± 0.062
50	0.211 ± 0.119	0.219 ± 0.106	0.233 ± 0.053	0.234 ± 0.057
30	0.321 ± 0.117	0.312 ± 0.121	0.348 ± 0.164	0.385 ± 0.151
15	0.879 ± 0.422	1.062 ± 0.481	1.190 ± 0.385	1.012 ± 0.423

analysis of variance. Significance was accepted at the 99% level of probability. The statistical results indicate that there was an overall significant difference between the 90A and 60A calibration procedure ($F = 11.95$, $p<0.01$) and the number of calibration points ($F = 111.72$, $p<0.01$), but there was not an overall difference between the points in the periphery and centre ($F = 3.69$, $p>0.01$) and between the axes ($F = 0.00$, $p>0.01$). A Tukey test ($T = 0.113$) revealed that the significant difference between the number of calibration points was only between the 15CP and the other calibration sets.

DISCUSSION

Radiography techniques are frequently used for biomechanical reserch, diagnosis and prognosis of skeletal deformations (Lippert *et al.*, 1982; Huiskes *et al.*, 1985; Bell, 1990; Lawrence *et al.*, 1993). Furthermore, radiography techniques are fundamental in arthroplasty in order to determine the correct positioning of joint replacement components, because this is important for the function and stability of joints (i.e. DeLange *et al.*, 1990). The accurate reconstruction of the image and the reduction of the measurement error are the significant factors for the effectiveness of radiography techniques. This accuracy is generally attributed to the type and quality of the calibration equipment, image quality and digitizing accuracy (due to the digitizing equipment and the digitizing experience of the operator).

A plethora of studies have reported high reconstruction accuracy using RSA (i.e. Huiskes *et al.*, 1985; Kärrholm, 1989; Selvik, 1989). The basic principles of the RSA were presented by Selvic in 1974 and reprinted in 1989. The primary reason of the high accuracy produced using RSA is that the image can be digitized using high resolution digitizers (Huiskes *et al.*, 1985). However, the high level radiation exposure, the time-consuming process in the development of the film and the inability for instant feedback, have resulted in the investigation of alternative techniques such as videofluoroscopy.

In the conventional mode of continuous fluoroscopy (videofluoroscopy), the display monitor shows a continuously-updated (real-time) image. The introduction of digital technology has enable fluoroscopic images to be stored and then displayed later for appropriate manipulation, according to the requirements of the study or treatment (Cox *et al.*, 1990).

Accuracy limitations in videofluoroscopy

However, the image deformation in videofluoroscopy systems is significantly higher than the cine-radiography and this presents a significant limitation for accurate dynamic analysis. The image deformation is due to the operating sensitivity of the videofluoroscopy system and the perspective error. The operating sensitivity of videofluoroscopy systems is depended upon a large number of factors including X-ray dosage exposure (Wandke, 1994), X-ray generator calibration (Wandke, 1994), curvature of the intensifier input screen, the diameter of optical aperture (Chakraborty, 1987), the electronic gain of the camera channel and a possible contribution from television scan non-linearities. Image deformation is produced by the ambient magnetic field which introduce 'S-deformation' by its effect on the electron paths within the intensifier. Furthermore, the digitizing accuracy in videofluoroscopy is limited by the low resolution of the video analysis systems.

Image deformation correction

Recently, all the modern television fluoroscopy systems incorporated automatic control facilities that regulate the X-ray generator and TV camera. The recent videofluoroscopy devices derive their feedback reference using a photosensor, examining the light output of the intensifier. The information from the photosensor is used for the appropriate correction of the X-ray exposure (automatic brightness control). This is a significant advance of videofluoroscopy systems, which minimizes the error introduced when there is underexposure or overexposure (Wandke, 1994). In order to minimize the S-deformation manufacturers offer to fit a m-metal shield that cancels the ambient magnetic field causing this type of deformation.

However, the deformation caused by the internal construction of the image intensifier and the perspective error must be corrected by mathematical methods (Wallace and Johnson, 1981; Chakraborty, 1987; Breen *et al*, 1988; Breen *et al.*, 1989; Cholewicki *et al.*, 1991; Baltzopoulos, 1994).

A linear mathematical model for image deformation was proposed by Wallace and Johnson (1981). The correction in the coordinates of any point were achieved using the distortion in the position of four calibration points, forming a square. The measurement error produced using this method was not reported.

The image deformation caused by the image intensifier is separated by Chakraborty (1987) into two physically distinct components. A predominant component originating from the projection of any point onto the curved image intensifier (view depended distortion VDD) and the deformation resulting from the digital transformation of the image (view independent distortion VID). The correction of the VDD was achieved using a geometrical method (pairs of points with the same image coordinates viewed by two different angles, were used), and the VID using least square method. The deformation of the image was increased when the image viewed at 28^0 angle (the angle between the calibration plane and the X-ray beam was 62^0). The measurement error produced using this method was not reported.

The main limitation of the above methods, is that the linear correction models implemented, are not adequate for correction of non-linear deformation in image intensifiers.

Breen *et al.* (1988) and Breen *et al.* (1989) corrected the image deformation using a scaling method. In this study the image intensifier was interfaced to a computerized image processor in order to digitize and display selected images on a computer monitor. The scaling factor used, was constant for the entire screen. Consequently this method is not adequate for accurate reconstruction due to the different image deformation in the periphery and the centre of the screen. A method modified from Wallace and Johnson (1981) was presented by Cholewicki *et al.* (1991). The reported measurement error was 0.33 mm (in 1 X 1 cm calibration structure). Baltzopoulos (1994) developed a non-linear algorithm for image deformation correction. The measurement error was 0.246 mm, when 240 calibration points were used, in a 180 mm by 180 mm field of view. The angle of the calibration plane relative to the X-ray beam was 90^0 degrees.

The use of different number of calibration points in the present study (for the selection of the appropriate number of calibration points in 2-D reconstruction), was based on the assumption that the measurement error depends on the number of calibration points. Although there is only one previous study which report the number of calibration points used for coordinate reconstruction, in radiography (Baltzopoulos, 1994), there is a plethora of references using video and cinematography systems. Baltzopoulos (1994) reports a measurement error of 0.13% (relative to the field of view), using 240 calibration points. Angulo and Dapena (1992) reported a measurement error ranged from 0.025% to 0.05% using cinematography systems and 0.09% using video systems, when 68 calibration points were used. Hatze (1988) reported measurement error of 0.24% using 30 points, Wood and Marshall (1986) 0.23% using 30 points and Strokes (1984) 0.27% using 10 points. Andriacchi *et al.* (1979) highlighted that the average measurement error was decreased with the increase in number of the calibration points (4.5 mm for 29 point calibration points, 5.6 mm for 19 and 5.7 mm for 10). Similarly, Chen *et al.* (1994) demonstrated an increase reconstruction accuracy with the increase in number of calibration points used (14.6 mm for 8 calibration points, 8.6 mm for 12, 6.6 mm for 16, 7.0 mm for 20 and 7.1 mm for 24).

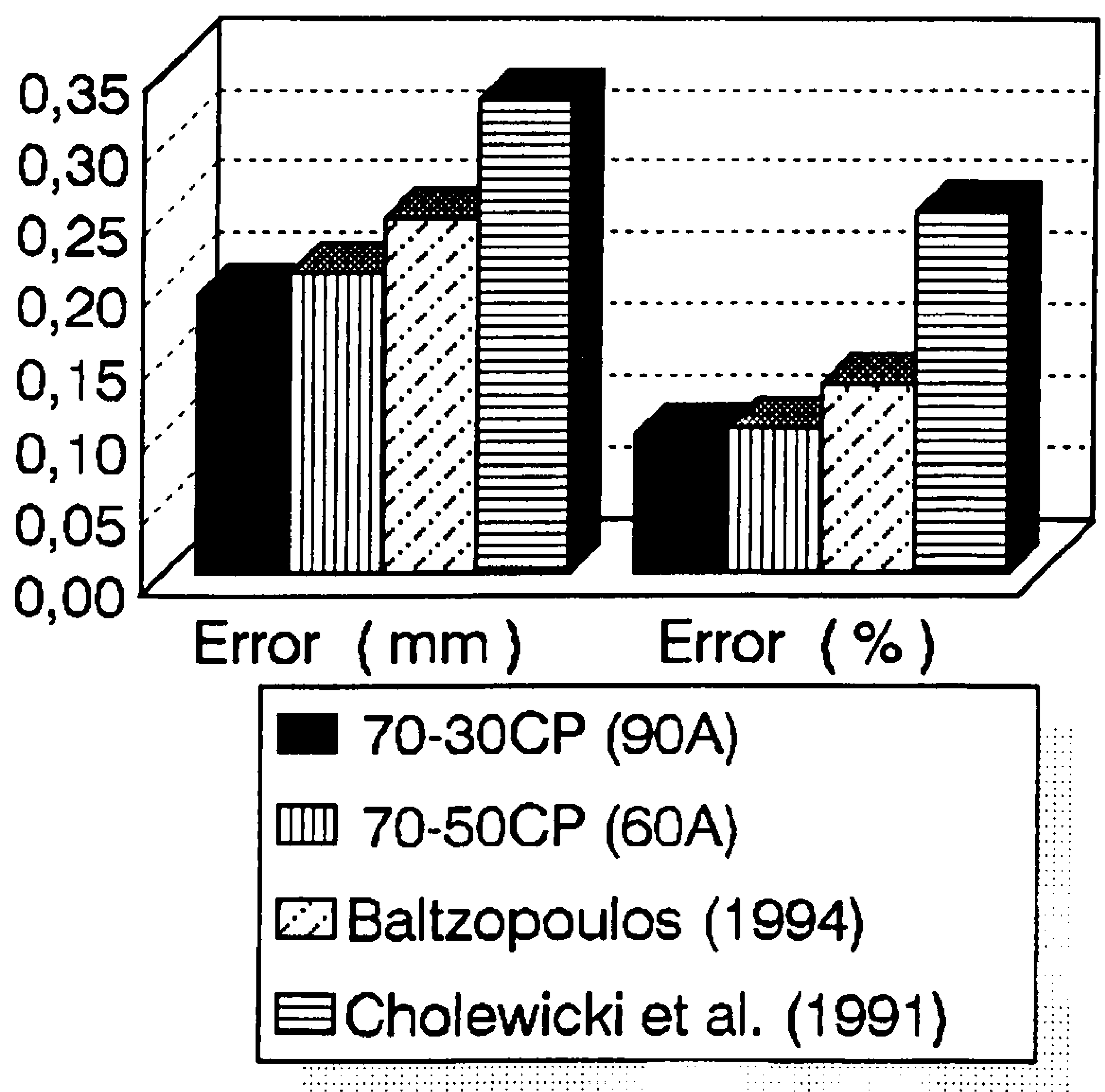

Figure 6.4. Comparison of the measurement error with previous studies.

The reconstruction accuracy achieved using the polynomial method for 2-D reconstruction combined with the correction of image deformation (sorting) technique, was considerably improved compared with the measurement error reported in any other study using videofluoroscopy systems (Cholewicki *et al.*, 1991; Baltzopoulos, 1994) (Fig 6.4).

More specifically, the reconstruction accuracy in 90A calibration procedure was similar for the 70CP, 50CP and 30CP digitizing procedures for the control points in the centre and in the periphery. The mean absolute measurement error from these digitizing procedures was 0.192 mm overall or 0.096% relative to the field of view, considerably reduced from the respective values of 0.25% reported by Cholewicki *et al.* (1991) and 0.13% reported by Baltzopoulos (1994). These results indicate that accurate reconstruction can be achieved using the polynomial procedure with less than 70 (and more than 15) calibration points, when the angle of the plane relative to the X-ray beam is 90^0. The accuracy produced in the periphery and in the centre of screen using 70CP, 50CP and 30CP respectively, is similar and consequently the deformation correction algorithm implemented, can effectively reduce the different amount of deformation produced in different screen locations. Although, the measurement error with 15CP is significantly higher than the other digitizing procedures, the use of 15 calibration points is not unacceptable (in videofluoroscopy) and depends on the requirements of the analysis.

In clinical and research X-ray applications, for the analysis of dynamic images, different angulation of the X-ray beam is required (Lippert *et al.*, 1982). However, the angulation of the X-ray relative to the image intensifier (Chakraborty, 1987) or the object plane relative to image intensifier, affect the image deformation (Meredith and Massey, 1977). The results of this study using 60^0 angle between the calibration plane and the X-ray beam, indicate that the deformation correction algorithm used, can effectively minimize the measurement error, when sufficient calibration points are used (70CP-30CP, see Table 6.2). More specifically, using the 60A calibration procedure the reconstruction accuracy was remained high for 70CP and 50CP. The mean absolute measurement error for 70CP and 50CP overall was 0.208 mm or 0.1% considerably reduced from previous videofluoroscopy studies with 90^0 angle between calibration structure and X-ray beam. The mean absolute measurement error in 30CP (0.341 mm overall or 0.17%) although was higher relative to the respective error in 70CP and 50CP, was significantly reduced compared with the error reported by Cholewicki *et al.* (1991) (0.33 mm or 0.25%).

In both calibration procedures (90A and 60A) there is no overall significant difference for the 70CP, 50CP and 30CP between the reconstruction error in the periphery and the centre of the screen, and between the X and Y axes.

Cholewicki *et al.*, (1991) and Baltzopoulos (1994) reported that the reconstruction error is affected by the distance between calibration plane and object plane. They concluded that the analysis of dynamic images is accurate when the movement occur on the level of calibration plane.

The video resolution is another significant factor which affects the quality of the image. A recent innovation which should improve image quality, is the introduction of high-resolution display monitors (based on high-resolution hardware), using twice the normal number of raster lines, thus increasing image sharpness. In the study reported by Frank *et al.* (1989) the image was displayed on a 2,560 X 2,048 pixel monitor. They concluded that the interactive display of images on high resolution displays offer an alternative to the viewing of computed radiographs in a hard-copy format.

Moreover, in this study, no additional information concerning the construction of the image intensifier and the distances between X-ray source, calibration plane and image intensifier, is required for the correction of image deformation.

CONCLUSION

A polynomial method with an incorporate deformation correction algorithm (sorting technique) was implemented in the present study, for 2-D image reconstruction in two different angulation of the calibration structure and the image intensifier. The sorting method effectively corrects the non-linear image deformation of the image intensifier and the different amount of deformation produced in the periphery and in the centre of the screen location in both angles. The minimum number of calibration points required for accurate reconstruction are 30, reducing considerably the number of calibration points required in previous studies and consequently analysis time for measurement of joint kinematics.

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CHAPTER 7

AN APPLICATION OF A POLYNOMIAL METHOD FOR THREE-DIMENSIONAL KINEMATIC ANALYSIS DURING LEVEL AND DOWNHILL TREADMILL RUNNING

G. PIGOS

ABSTRACT

Accurate kinematic analysis of human movement is a significant factor for the improvement of movement performance and for the reduction of injuries. A polynomial method for 3-D analysis was implemented to determine the knee kinematic parameters during level and 9% downhill grade running. The knee kinematic parameters for the level and downhill running were: 20.9° and 17° degrees for the flexion angle in footstrike, 36.2° and 43.1° for the peak flexion angle in stance phase, and 7.1 $rad.sec^{-1}$ and 7.4 $rad.sec^{-1}$ the peak flexion angular velocity respectively. The knee kinematic characteristics, determined using the developed polynomial method, were within the range of the respective values reported in previous studies, indicating that the developed method is adequate for accurate 3-D kinematic analysis.

INTRODUCTION

The biomechanical aspects of running are significant factors for the identification of optimal running mechanics in order to improve the athlete's performance and to identify the mechanical strategies that can be applied to reduce mechanical overloading of the locomotor system and thus prevent injuries (Nigg, 1985; Subotnick, 1985; Brown and Yavorsky, 1987; Armstrong, 1990; Gross and Napoli, 1993). The stance phase of gait (walking and running) is a closed chain lower extremity activity that requires coordinated movement between the proximal and distal joints. The lower limb performs many essential dynamic functions during the stance phase, that enable the body to be propelled forward during gait. In running, as the velocity increases (compared with waking), the stance phase decreases, there is a double unsupported phase or flight phase and the double support limb phase vanishes (Enoka, 1988). This reflects the higher proportion of eccentric and concentric muscle work performed in running (more so, during downhill running). The kinematics and kinetics of the ankle have been extensively documented in previous studies (Kaelin *et al.*, 1985; McKenzie *et al.*, 1985; Soutas-Little *et al.*, 1987; Nigg and Morlock, 1987; Engsberg and Andrews, 1987; Nigg *et al.*, 1988; Kepple *et al.*, 1990). Although the contribution of the knee angle in human locomotion is important and the knee is susceptible to injuries (over 25% of all running injuries reported by Hamill *et al.* (1992)), there are few previous studies in this field (i.e. Andriacchi, 1990). There are a few studies investigating the different kinematic characteristics of the knee angle, in order to identify the causes of muscle damage during level and downhill running (Hamill *et al.*, 1984; Buczek and Cavanagh, 1990). Kinematic adaptations during downhill, uphill and level running were measured by Hamill *et al.* (1984), using a high speed cine camera. In this study, the reported values for the knee flexion angles at heal strike were 15.27° and 20.06° degrees for 9% gradient downhill and level running respectively. Similar values for knee flexion angles were reported by Buczec and Cavanagh (1990), using a similar gradient (8.3%).

The purpose of this study was to apply the polynomial method presented in Chapter 3 for the measurement of knee joint kinematics during level and downhill running.

METHOD

Instrumentation

A motorized treadmill (Woodway), capable of operating at different speeds and gradients, was used. Treadmills have been frequently used for kinematic analysis in previous studies (Soutas-Little *et al.*, 1987; Nigg and Morlock, 1987; Hamill *et al.*, 1984; Buczek and Cavanagh, 1990; Hamill *et al.*, 1992; Iversen and McMahon, 1992) and there is no significant difference to overground running, when the speed is less than 5 $m.s^{-1}$ (Williams, 1985; Williams *et al.*, 1991). The speed of the treadmill belt (length 3.6 m) was approximately 3 $m.s^{-1}$ for both the level and downhill running. The selection of this speed was based on speeds used in previous studies (Hamill *et al.*, 1984; Buczek and Cavanagh, 1990; Iversen and McMahon, 1992; van Woensel and

Cavanagh, 1992) and was used to facilitate the comparison of the results. During downhill running, the treadmill was elevated up using an iron structure, in order to provide a gradient of 9% similar to those used by Hamill *et. al* (1984) and Buczek and Cavanagh (1990) (Fig. 7.1).

A calibration procedure was performed before both run protocols, using a calibration plane with dimensions 2.1 m wide X 1.1 m high formed by aluminium square tubes. Forty seven markers were mounted on the square tubes throughout the calibration plane. The position of every marker was precisely measured from the lower left marker (origin) of the calibration plane (measurement error $\leq$0.5 mm). Four additional square tubes (0.5 m length) were positioned perpendicularly on the calibration plane. The edge points of the square tubes were used to determine the 3-D camera position (camera determination points). The calibration procedure was explained in detail in Chapter 3. The calibration plane was placed between the camera positions and the athlete, so that the athlete was within the calibrated volume throughout the level and downhill running (Fig. 7.2). The calibration plane and subsequently the athlete's movements, were recorded using two S-VHS Panasonic F-15 cameras fitted with WV-LZ14/15E lenses. Once the calibration plane was recorded it was then removed and no additional calibration procedure was performed between the level and downhill running. The cameras were mounted on tripods with no panning possibility and were positioned as illustrated in figure 7.2. The angle between the two camera optical axes was approximately 90^0. The synchronization of the shutter in both cameras was achieved using a gen-lock system (WV-AD 36E Panasonic gen-lock adaptor). The speed of the shutters was fixed at 1/500 sec in order to eliminate any blurring and improve image quality.

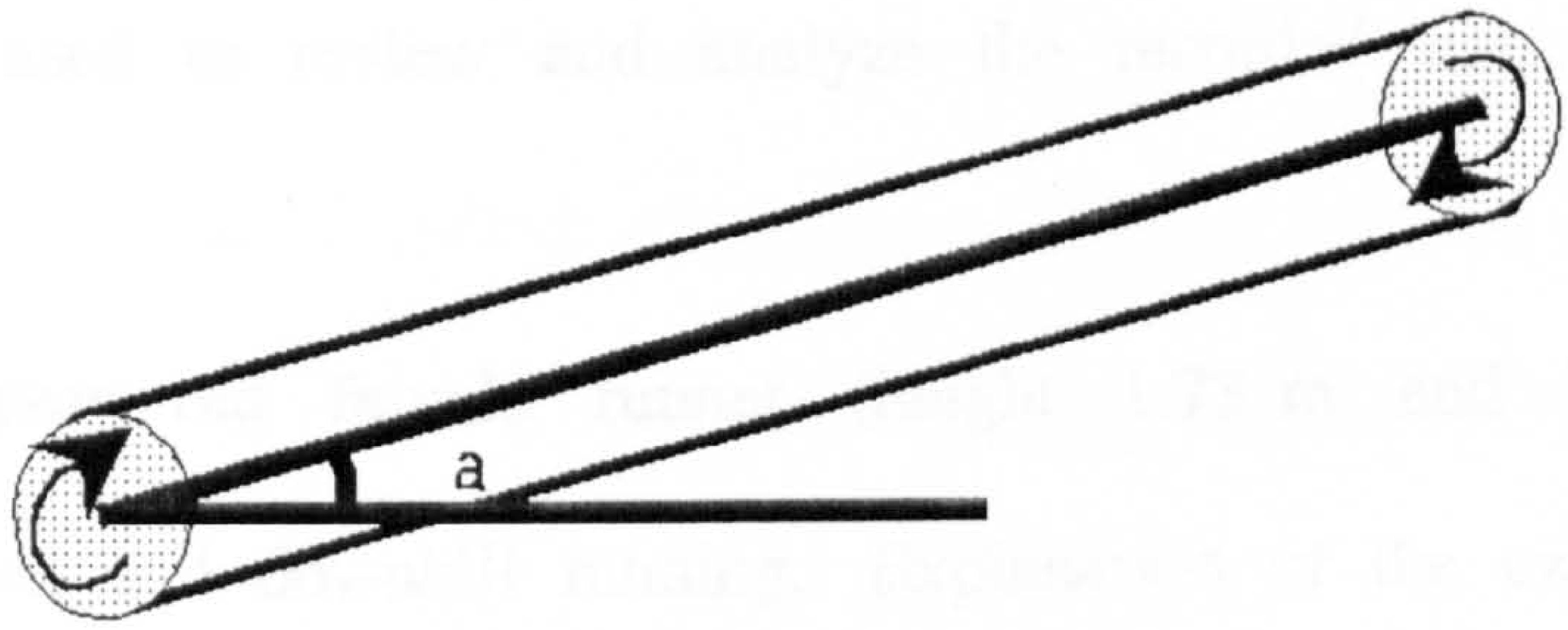

Figure 7.1. The propped up treadmill to provide a gradient of 9% during downhill running.

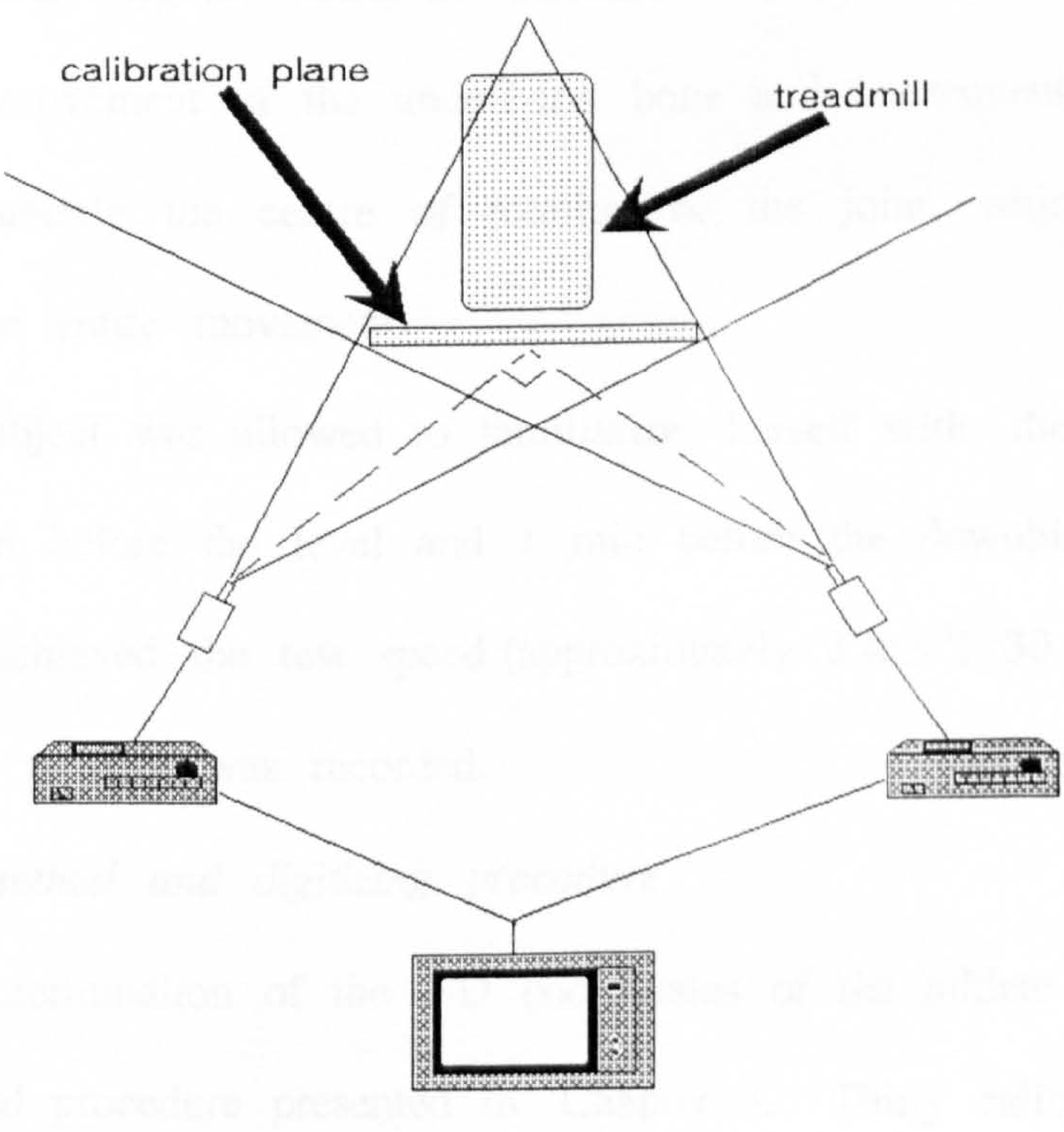

Figure 7.2. The experimental set up for the level and downhill running.

Two S-VHS Panasonic AG-7330-B video recorders recorded the movement with a frequency of 50 field of view per frame. The same S-VHS recorder, an Intel 82386 based-computer and a coded Pascal version of the algorithm described in Chapter 3, were used to review and analyze the recorded data.

Subject

One 21 year old female runner (height 1.73 m and body mass 65 Kg), performed the level and downhill running. Explanation of the experimental procedure was given and anthropometric measures (body mass and height) of the subject were taken before running. Skin markers were not attached to the subject. This was based on the results of a previous study by Ronsky and Nigg (1991), who concluded that relative movement can occur between markers attached to the skin, if the base for the marker is not rigid. Moreover, because of relative movement between the skin and the bone, the markers attached to the skin may not precisely describe the movement of the underlying bone and consequently the marker cannot represent accurately the centre of rotation of the joint, which must be digitized, throughout the entire movement.

The subject was allowed to familiarize herself with the treadmill and warm up for 2 min before the level and 1 min before the downhill running. Once the subject had achieved the test speed (approximately 3 $m.s^{-1}$) 30 seconds of the level and downhill running was recorded.

Polynomial method and digitizing procedure

The determination of the 3-D coordinates of the athlete were estimated using the polynomial procedure presented in Chapter 3. Thirty calibration points and two camera determination points (see Chapter 3) were used, for the estimation of the coordinates of the digitized points. This procedure was performed for each camera. Once the calibration points were digitized (in the video reference system) and stored, the polynomial coefficients in equations (1) and (2) were determined using the closest calibration points of every digitized point. Two complete cycles, one from level and one from downhill running, were digitized. In addition, ten frames before the first footstrike and ten after the last toe-off of the gait cycle, were also digitized to provide a buffer for filtering (Fig 7.3).

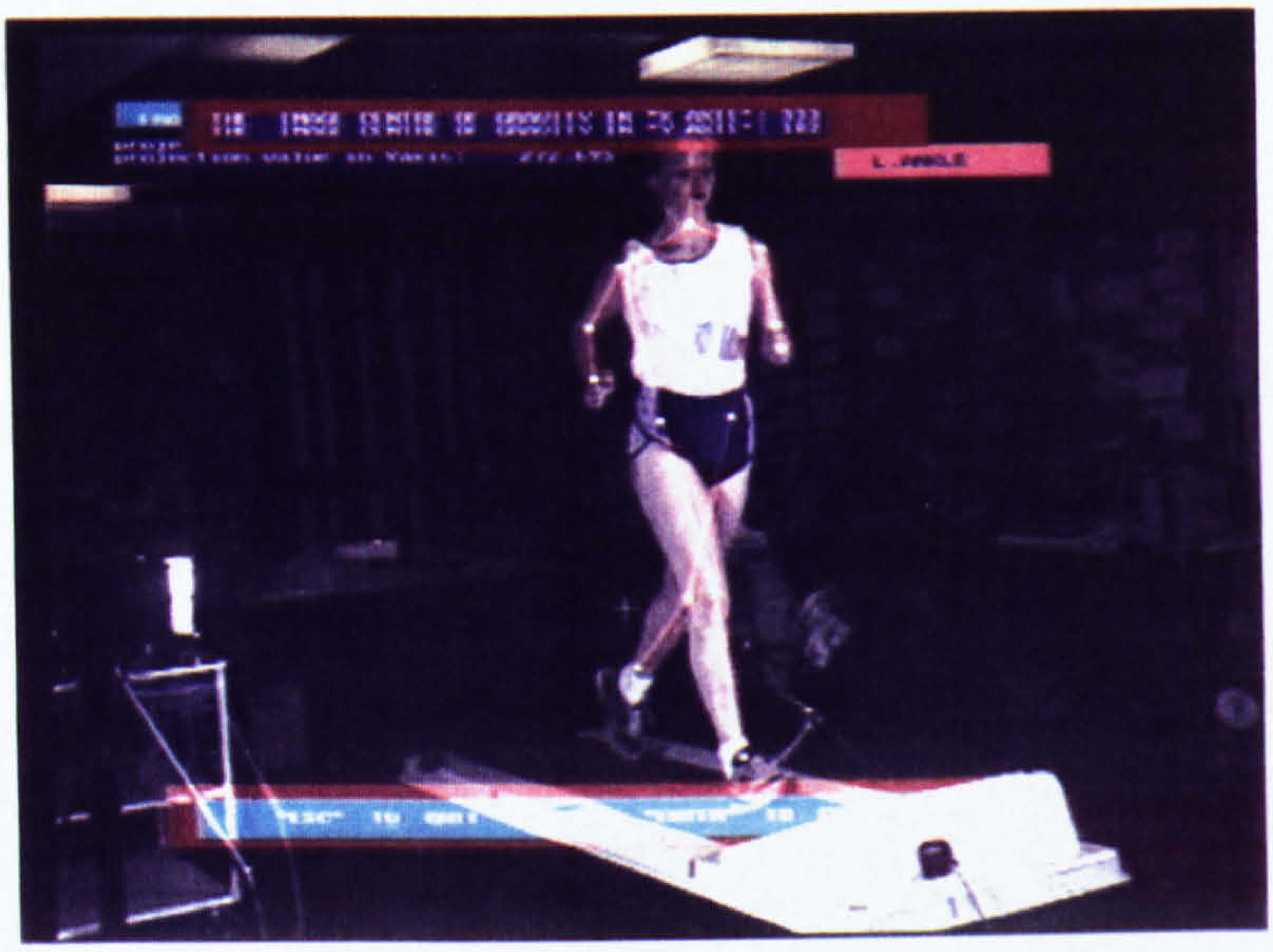

Figure 7.3. The determination of the 3-D joint centre using the polynomial method coded in the computer program. Linking of the adjoining points represents the form of the stick figure digitized.

In the analysis procedure, only the kinematic characteristics of the left knee in the stance phase were extensively analysed, although the entire body was reconstructed. This analysis of the knee was performed to facilitate comparison of the results, using the polynomial method described in Chapter 3, with other published studies (Hamill *et al.*, 1984; Buczek and Cavanagh, 1990; Williams *et al.*, 1991; Hamill, 1992; Iversen and McMahon, 1992; van Woensel and Cavanagh, 1992).

Data analysis - Smoothing procedure

Before the estimation of the kinematic parameters, a filtering procedure was applied to smooth the data and minimize the signal noise (Miller and Nelson 1976; Winter, 1979; Wood, 1982). Different smoothing methods have been reported and implemented in previous studies for the reduction of noise from the raw displacement data (Reinsch, 1967; Reinsch, 1971; Zernicke *et al.*, 1976; McLaughlin *et al.*, 1977; Pezzack *et al.*, 1977; Hatze, 1981; Lanshammar, 1982; Vaughan, 1982; Niinomi *et al.*, 1983; Garhammer and Whiting, 1989). Digital filters are frequently used in kinematic analysis achieving effective reduction of the noise. More specifically, Pezzack *et al.* (1977) compared angular acceleration signals from an accelerometer with those obtained from synchronised film and concluded that the digital filters reduced effectively the signal noise, reflecting the accurate estimation of the kinematic parameters. Vaughan (1982) assessed the displacement data of a falling ball, using cine cameras and different smoothing methods: Cubic spline, quintic spline and digital filter. In this study the results indicated that although the quintic spline was superior to the other methods, digital filters could produce accurate results. Garhammer and Whiting (1989) compared the five point moving arc, spline and digital filter methods and concluded that there was no significant difference in the estimation of kinematic parameters, using the above smoothing methods.

The use of digital filters in running applications

Williams and Cavanagh (1983), in a study for the calculation of mechanical power during distance running, used digital filtering with a cutoff frequency of 5 Hz to smooth the 3-D coordinates. Winter (1983) used a digital filter with a cutoff frequency of 8 Hz to smooth the 2-D raw data obtained during running. A digital filter with a cutoff frequency of 7.5 Hz was also used by Buczec and Cavanagh (1990) to filter the digitized data collected from the level and downhill running. Hamill *et al.* (1992) in the study for the determination of the relationship between the subtalar and knee joint actions, during the support phase of level treadmill running, used digital filters with cutoff frequencies ranging from 8 Hz to 18 Hz. Digital filters and an arbitrary cutoff frequency of 12 Hz were used by Woensal and Cavanagh (1992), to smooth the 3-D reconstructed coordinate of running subjects, using optoelectronics cameras. It is evident that the application of low pass digital filters (Butterworth filters) is an adequate smoothing method for kinematic analysis, extensively implemented in previous running studies. However, the selection of the optimum cutoff frequency remains a significant factor for accurate measurements (Winter, 1979). Winter (1974) reported that for the knee angle (in walking) there are no significant harmonics higher than the 6th (6 Hz). Williams (1993) highlighted that digital filtering frequencies for running kinematic data are typically in the range of 2 to 10 Hz (when a 100 Hz sampling rate is used).

Smoothing procedure

In this study digital filters were used to smooth the raw data. The format of the second order Butterworth digital filter used is the following:

$$F_i = a_0R_i + a_1R_{i-1} + a_2R_{i-2} + b_1F_{i-1} + b_2F_{i-2}$$

where a_0, a_1, a_2 and b_1, b_2 are the filter coefficients which are constant and determined by the ratio of the sampling frequency to cutoff frequency, R_i and F_i

the raw and the filtered data respectively. The algebraic sum of the filter coefficients must be 1 in order to give a response of unity over the pass band. The filtering of data for the second time, but in the reverse direction of time, results in the creation of a fourth-order, zero phase shift filter.

The digital filter was coded in a pascal program and tested using the raw data reported in a previous study (Vaughan, 1982). The criterion for the efficacy of the coded smoothing method was the accurate estimation of the second derivative (acceleration), where the error due to signal noise is high. The cutoff frequency (6 Hz) was that recommended by Vaughan (1982). The second derivative (acceleration) of the movement, with respect to time, was calculated using the mathematical expressions proposed by Miller and Nelson (1976). Forward, central and backward difference formulae were implemented for second derivative of displacement (raw) data using two points on either side of the point to be smoothed:

(1) (Forward)
$$X_i = \frac{-x_{i+3} + 4x_{i+2} - 5x_{i+1} + 2x_i}{(\Delta t)^2}$$

(2) (Central)
$$X_i = \frac{x_{i+2} + 16\,x_{i+1} - 30\,x_i + 16\,x_{i-1} - x_{i-2}}{12\,(\Delta t)^2}$$

(3) (Backward)
$$X_i = \frac{2x_i - 5x_{i-1} + 4x_{i-2} - x_{i-3}}{(\Delta t)^2}$$

where: X_i the acceleration at point x_i.

the point x_{i+1} : the x coordinate of the point one frame before

x_{i+2} : the x coordinate of the point two frames before

x_{i-1} : the x coordinate of the point one frame after

x_{i-2} : the x coordinate of the point two frames after

The results (Fig. 7.4) indicate that the digital filter is an adequate smoothing method for kinematic data and was consequently implemented in the present study.

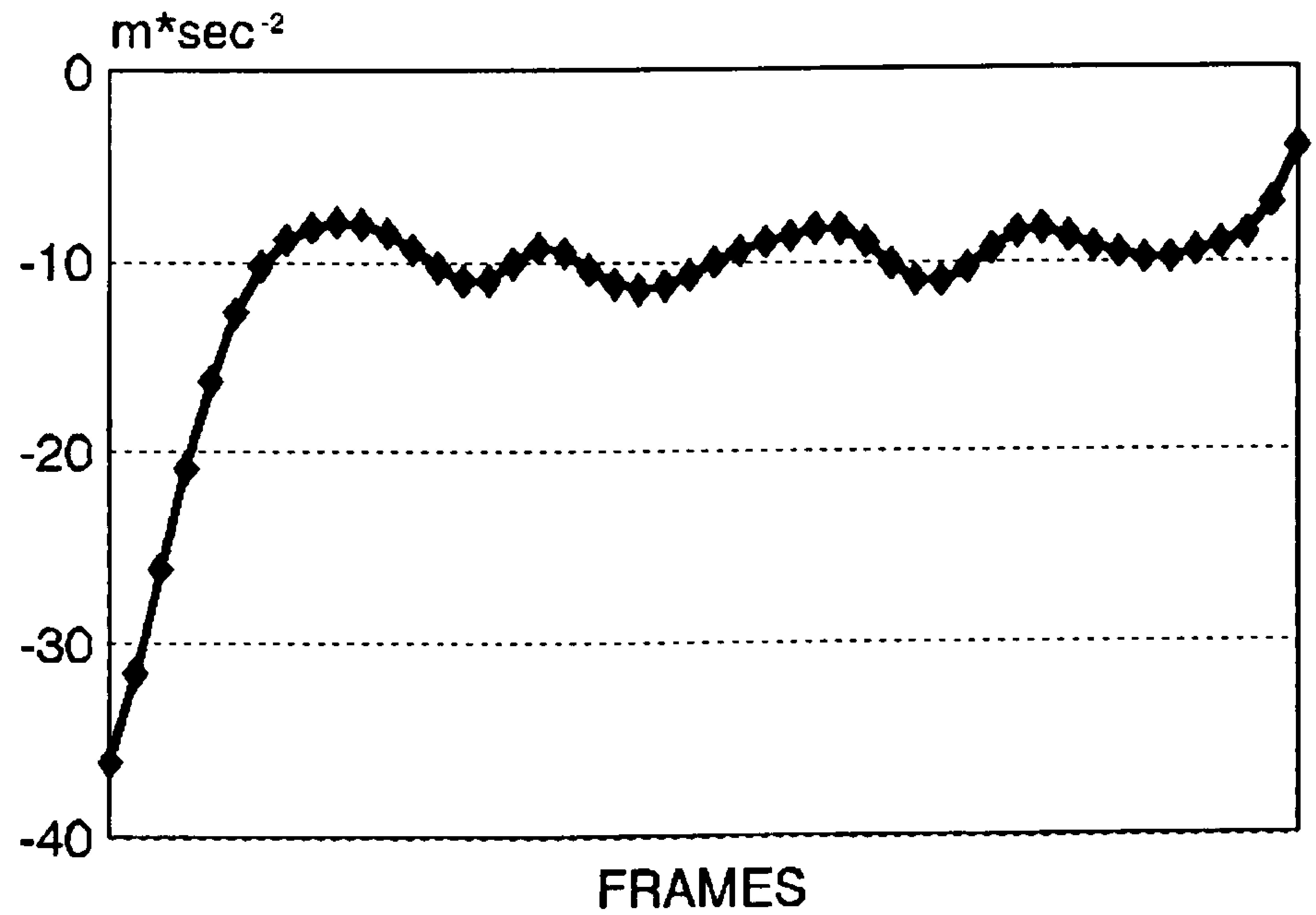

Figure 7.4. Determination of a falling ball's acceleration (Vaughan 1982), using digital filter.

The optimal cutoff frequency of the filter was determined by filtering the data using different cutoff frequencies until the difference between the variance in the raw and the filtered data was minimal (Pezzack *et al.*, 1977) (Fig. 7.5). The selected optimal cutoff frequency was 4 Hz.

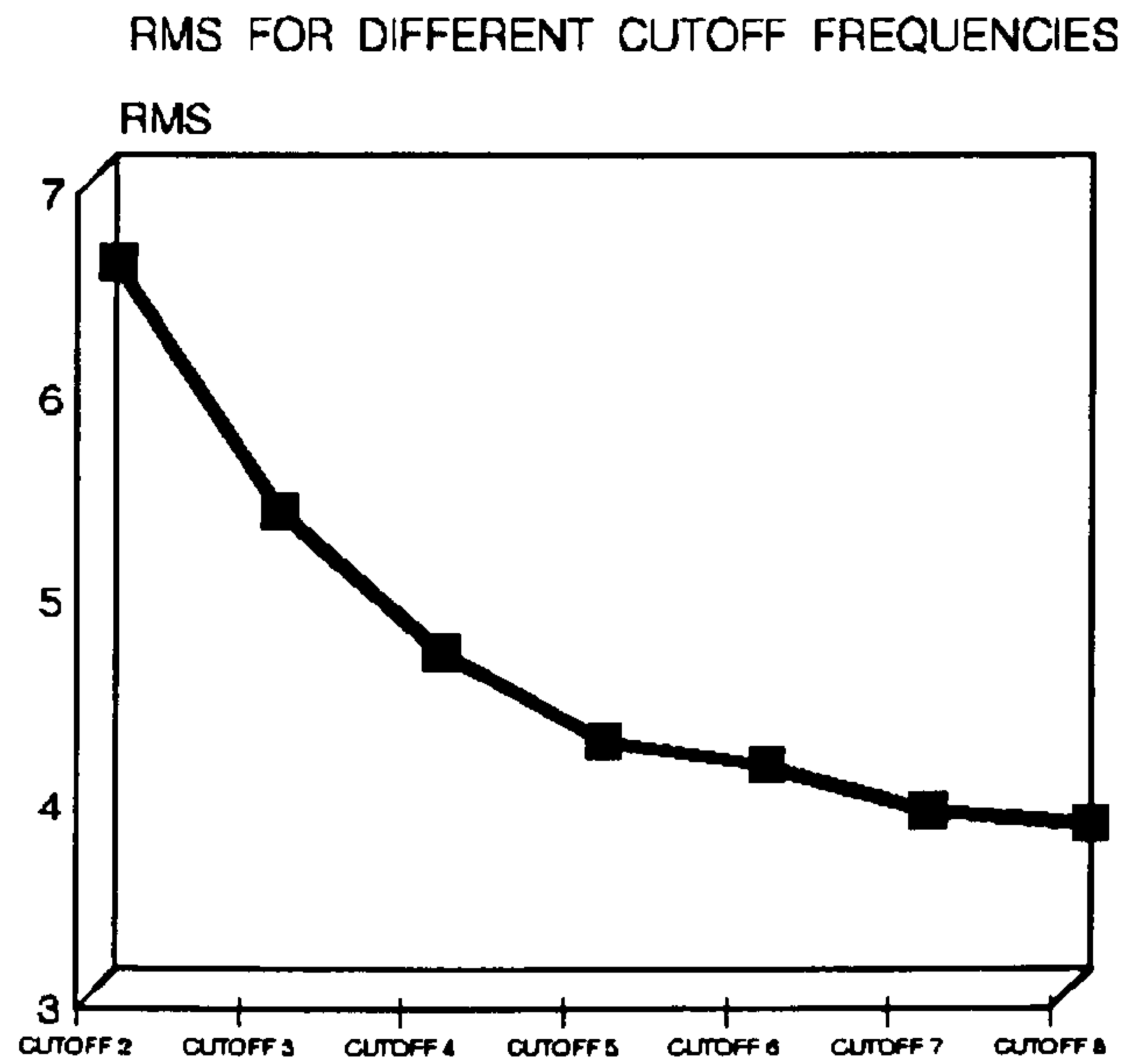

Figure 7.5. The selection of the optimal cutoff frequency was based on the minimum difference variance between the raw and filtered data.

Kinematic parameters

The angles between the segment were calculated using simple geometric expressions consisting of the direction vectors of the two lines formed by (at least) three non collinear points (modified geometrical expression presented in Chapter 5 for lines in space (Bowyer and Woodwark, 1983)) :

(4) $$\theta = \cos^{-1} \frac{f_1 f_2 + g_1 g_2 + h_1 h_2}{\sqrt{(f_1^2 + g_1^2 + h_1^2)(f_2^2 + g_2^2 + h_2^2)}}$$

where f_1, f_2, g_1, g_2 are the directions of the two lines formed by (at least) three non collinear points (see Chapter 5) and θ the angle between the two lines.

The first angular derivative (angular velocity) was calculated using the formulae proposed by Miller and Nelson (1976). The mathematical expressions for the forward, central and backward formulae of angular velocity, using two points on either side of the point to be smoothed, are:

(5) (Forward)

$$X_i = \frac{3x_i - 4x_{i-1} + x_{i-2}}{2(\Delta t)}$$

(6) (Central)

$$X_i = \frac{-x_{i+2} + 8x_{i+1} - 8x_{i-1} + x_{i-2}}{12(\Delta t)}$$

(7) (Backward)

$$X_i = \frac{3x_i - 4x_{i-1} + x_{i-2}}{2(\Delta t)}$$

where: X_i the angular velocity of the x_i point.

the point x_{i+1} : the angle one frame before

x_{i+2} : the angle two frames before

x_{i-1} : the angle one frame after

x_{i-2} : the angle two frames after

Figure 7.6 illustrates the conventions used for the knee angles and angular velocities (ω).

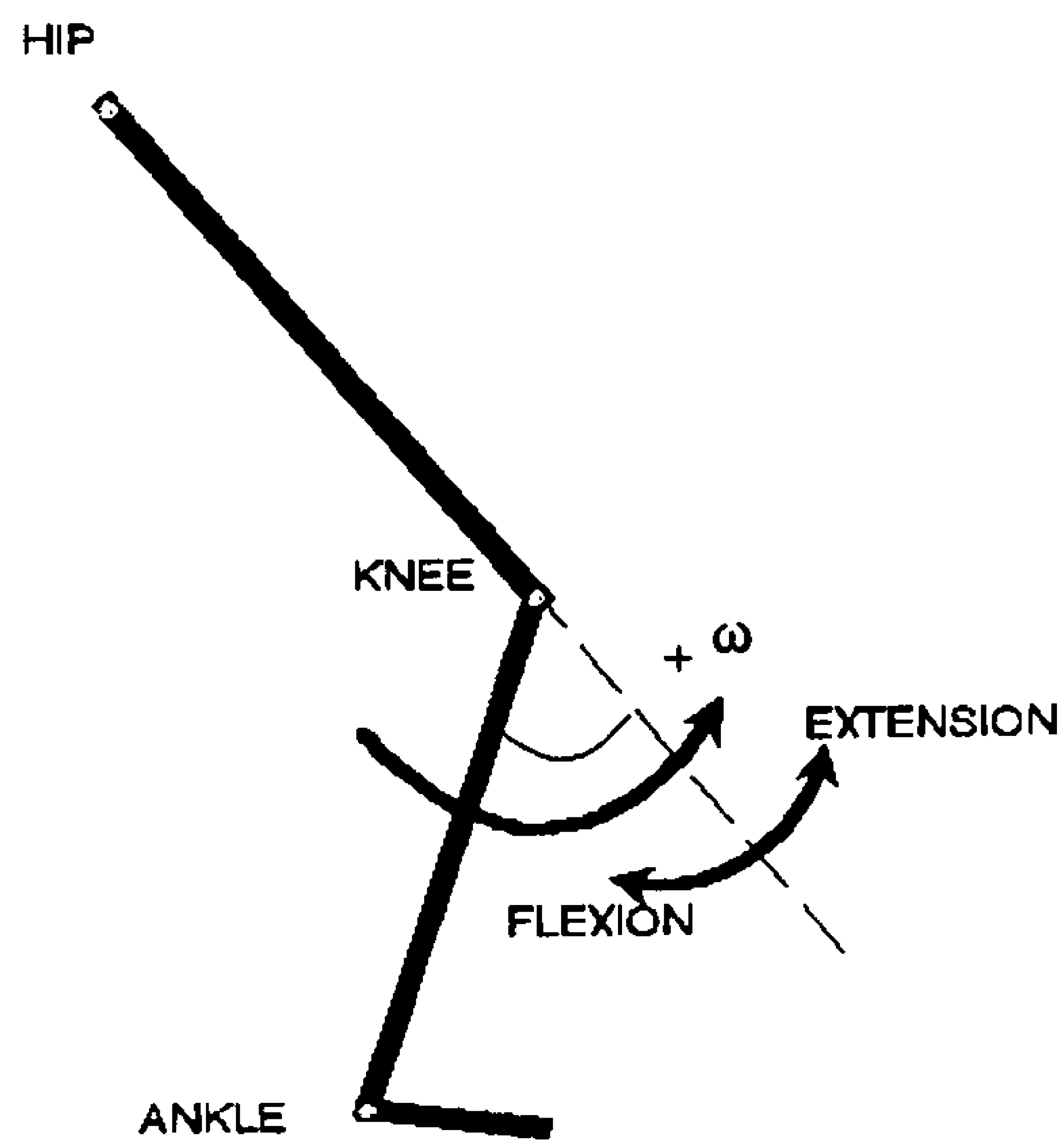

Figure 7.6. Angle convention used in kinematic analysis. Positive angular velocities represent positive rotations about the reference system X-axis according to the right-hand rule.

RESULTS

In order to facilitate comparisons, the values of the angles are expressed in degrees, whereas the angular velocities are expressed in rad.sec^{-1} according to the format of the results in the study by Buczek and Cavanagh (1990). The flexion angle in the footstrike (FA) was 20.9° degrees for the level running and 17.4° for the downhill running (Fig. 7.7). The peak flexion angle during the stance phase (PFA) was 36.2° and 43.1° for the level and downhill running respectively (Fig. 7.8). The time of the peak flexion (TPFA), expressed as a percentage of the total time of the stance phase, was 35.7 % and 50.0 % (Fig. 7.9) . The peak flexion angular velocity (PFAV) was 7.1 rad.s^{-1} and 7.4 rad.s^{-1} for the level and downhill running respectively (Fig. 7.10). The time of the peak angular velocity (TPFAV) was 14.2 % and 21.4 % of stance phase for the level and downhill running respectively (Fig. 7.11). The knee angle throughout the stance phase is illustrated in figure 7.12. The difference between the flexion angle during footstrike and the peak flexion angle (ROM) was 15.3° and 25° for the level and downhill running respectively.

Reliability

Although the reliability of the polynomial method implemented in the reconstruction of 3-D coordinates has been examined in Chapter 3 using spatial coordinates, a different reliability analysis using angular measurements (FA in footstrike) was also performed. In this examining procedure, ten repeated digitizations of a single frame (footstrike) from every camera view were used when the subject performed level running. The low value of the standard deviation (0.89°) and the coefficient of variation (4.40%) of the angular measurements, indicate that the polynomial method is reliable for the 3-D body segment reconstruction (Fig 7.13).

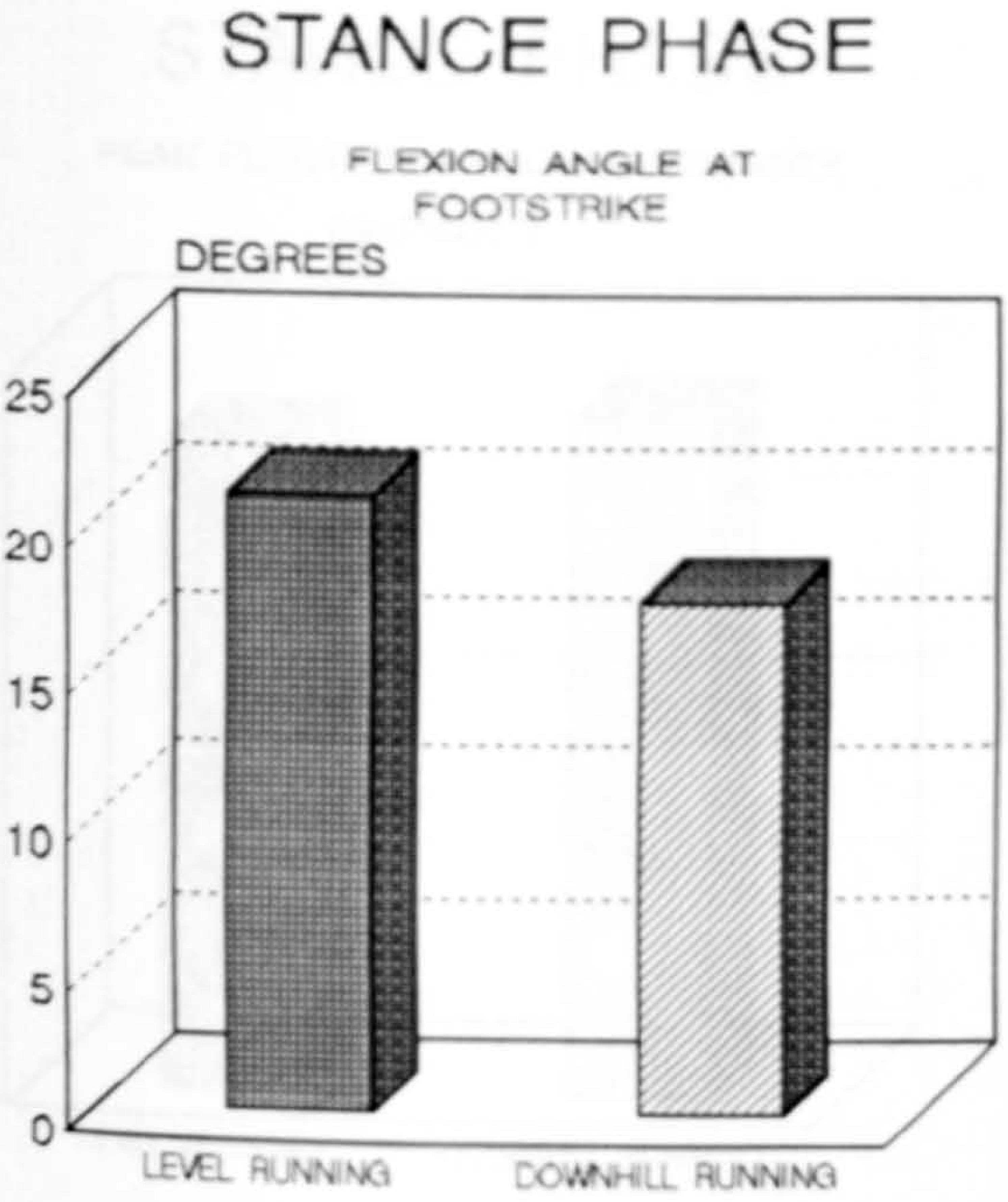

Figure 7.7. Flexion angle in footstrike

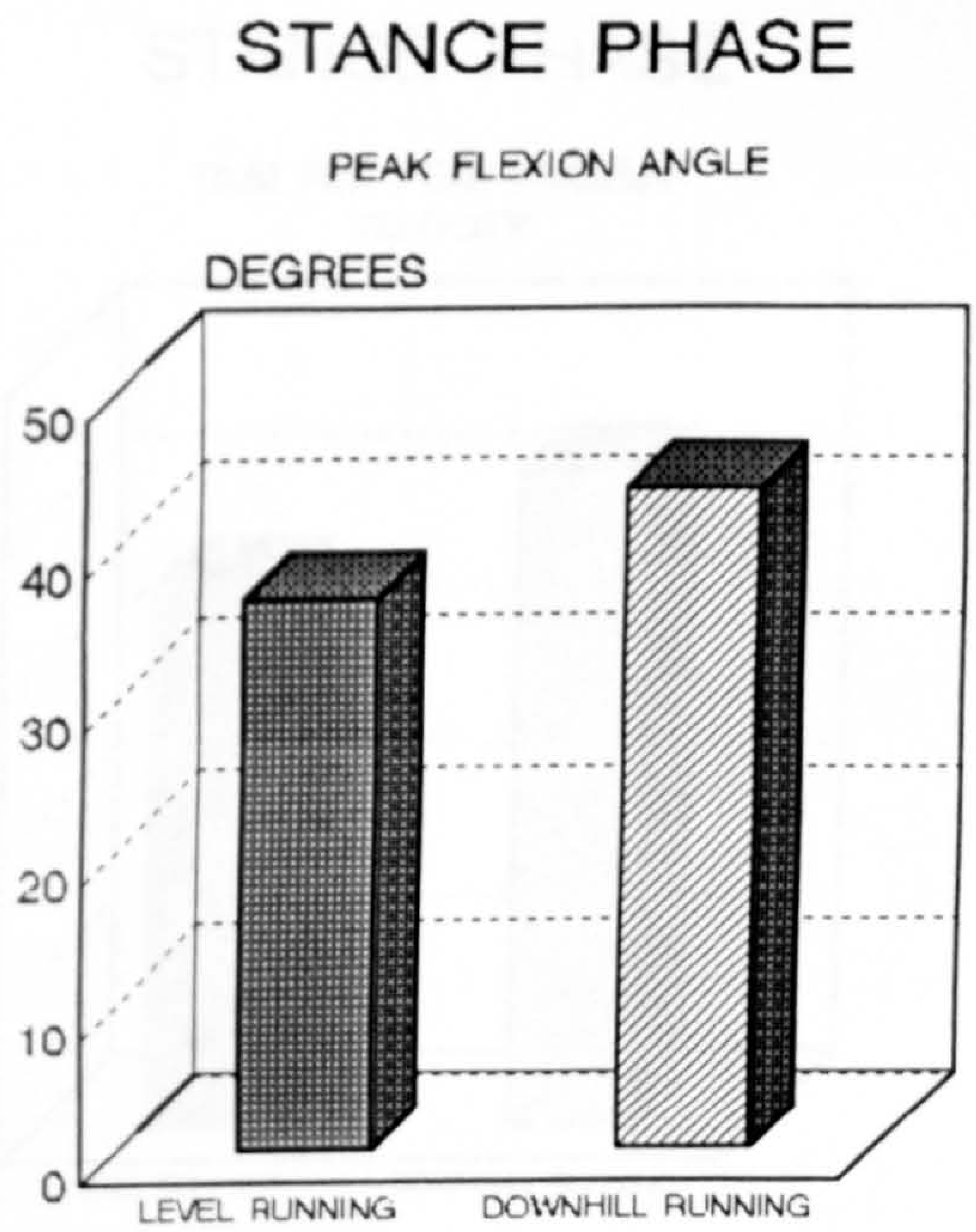

Figure 7.8. Peak flexion angle in stance phase

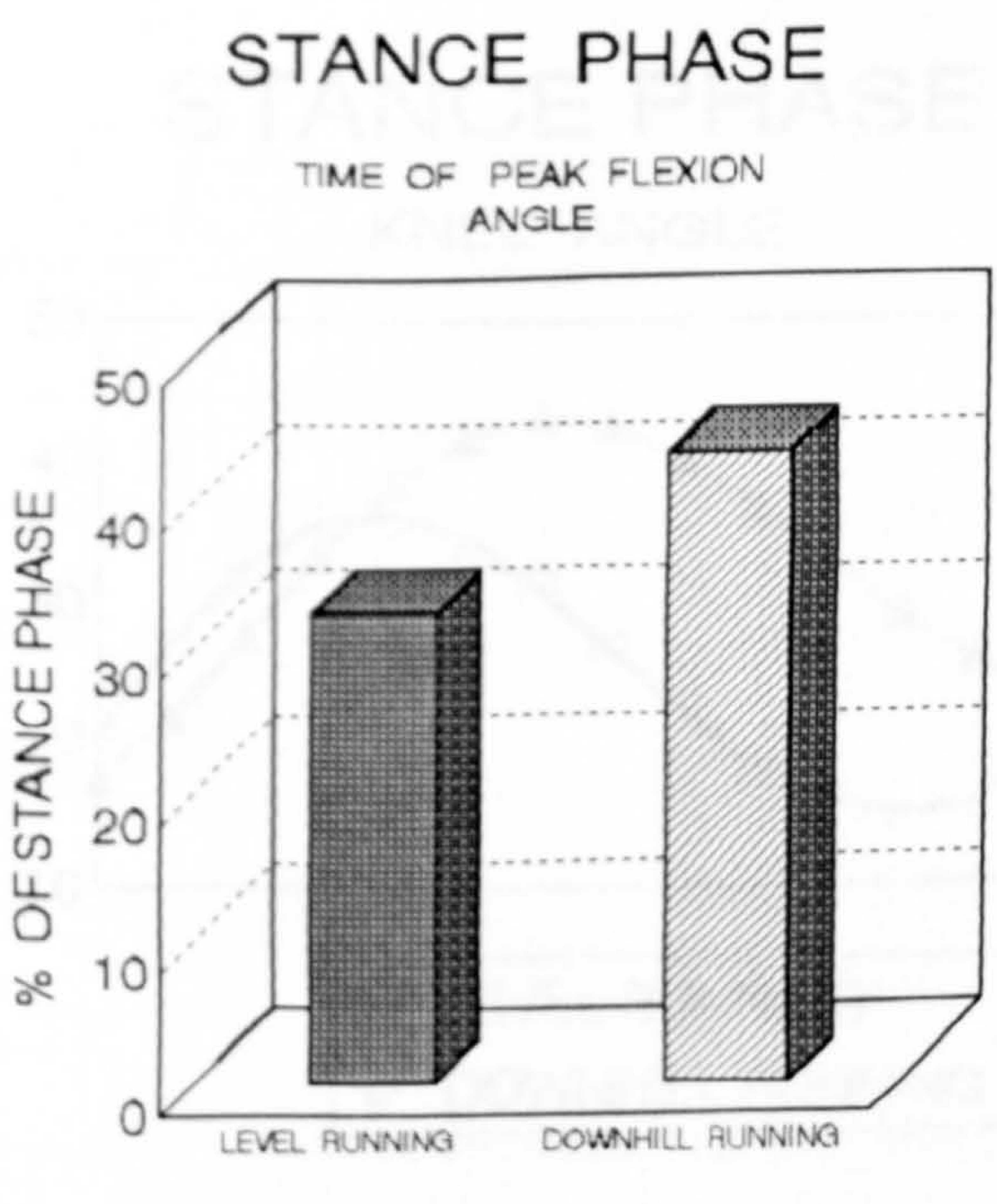

Figure 7.9. Time of the peak flexion angle in stance phase

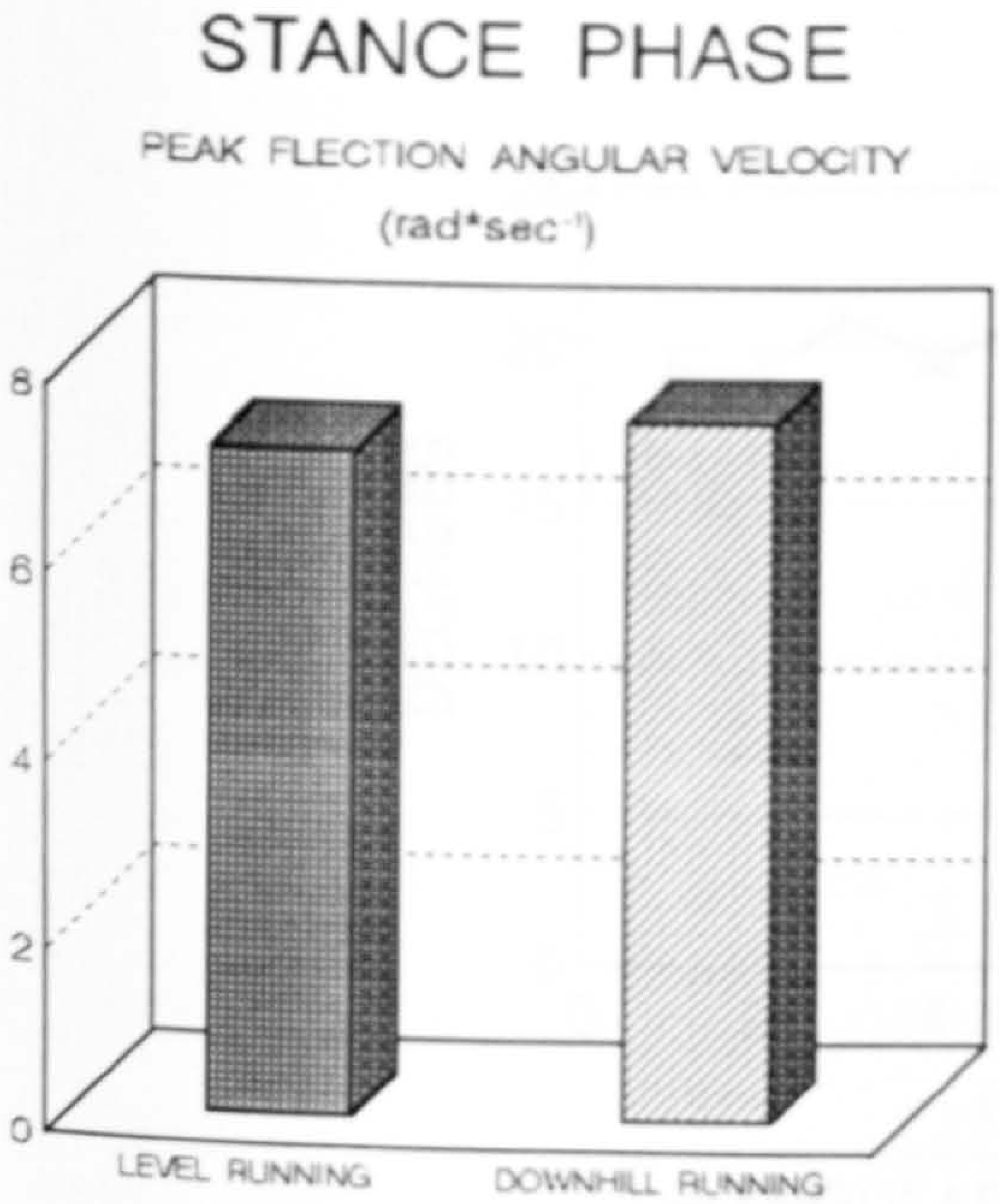

Figure 7.10. Peak flexion angular velocity in stance phase

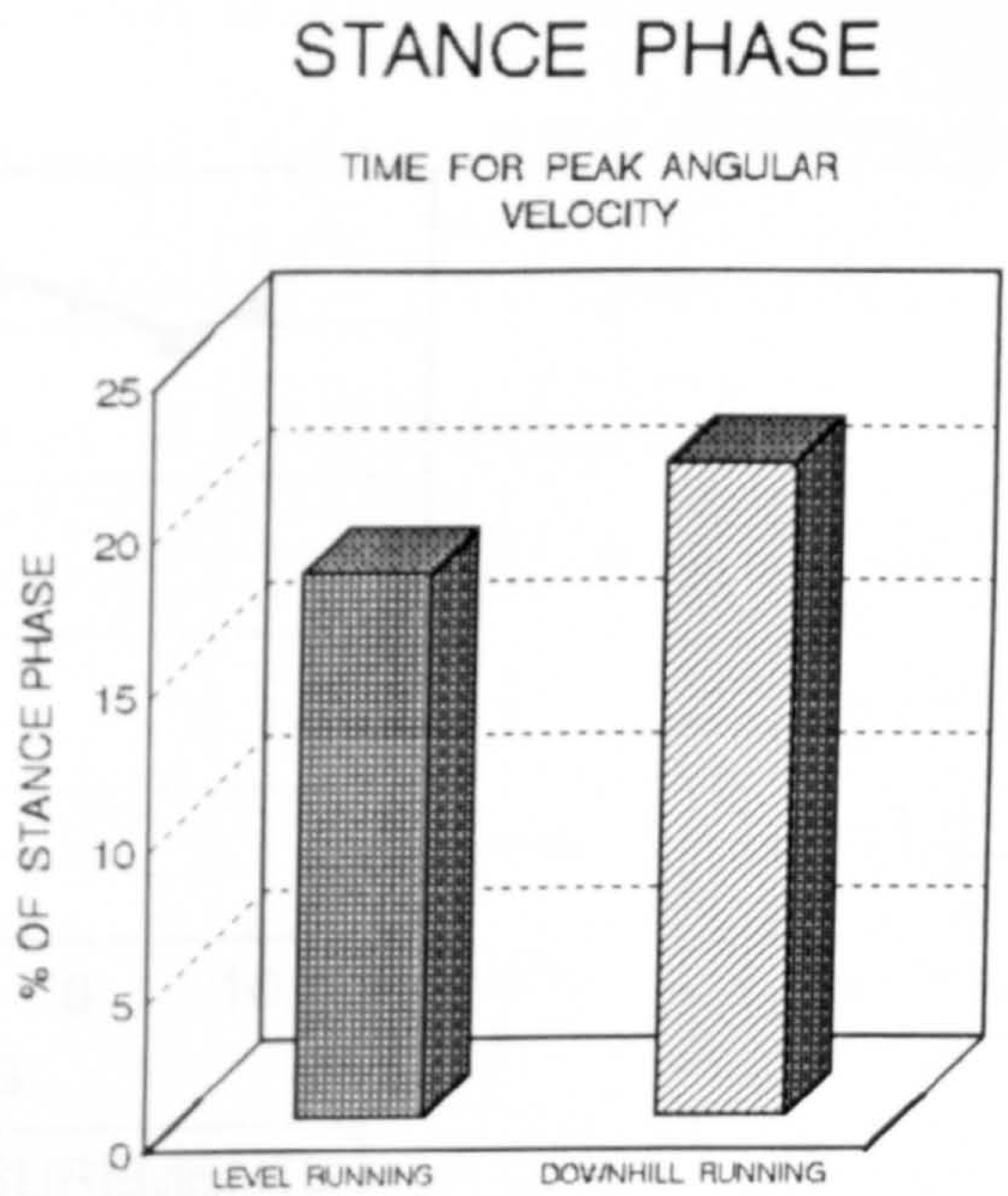

Figure 7.11. Time of the peak angular velocity in stance phase

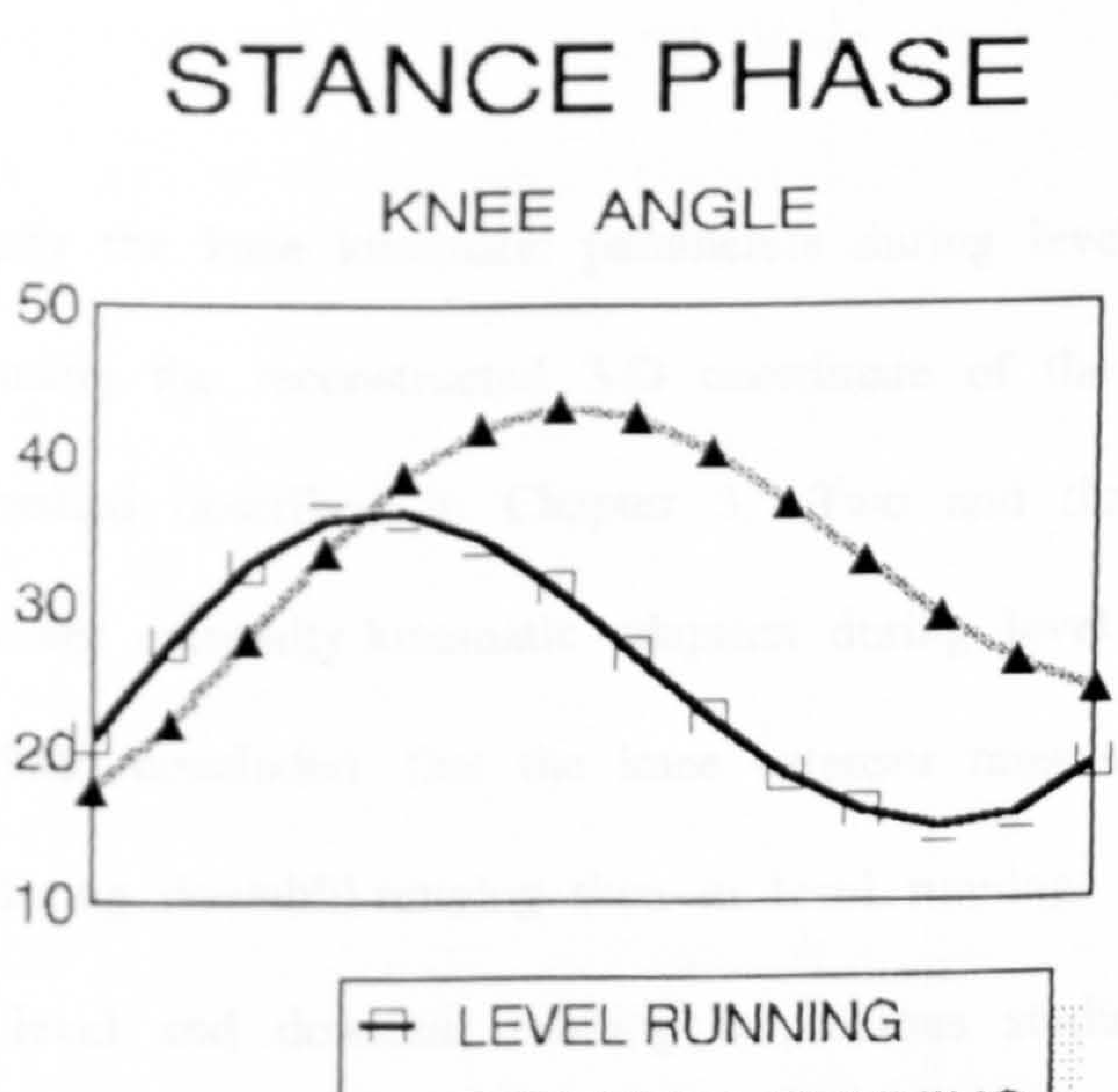

Figure 7.12. The knee angle throughout the stance phase.

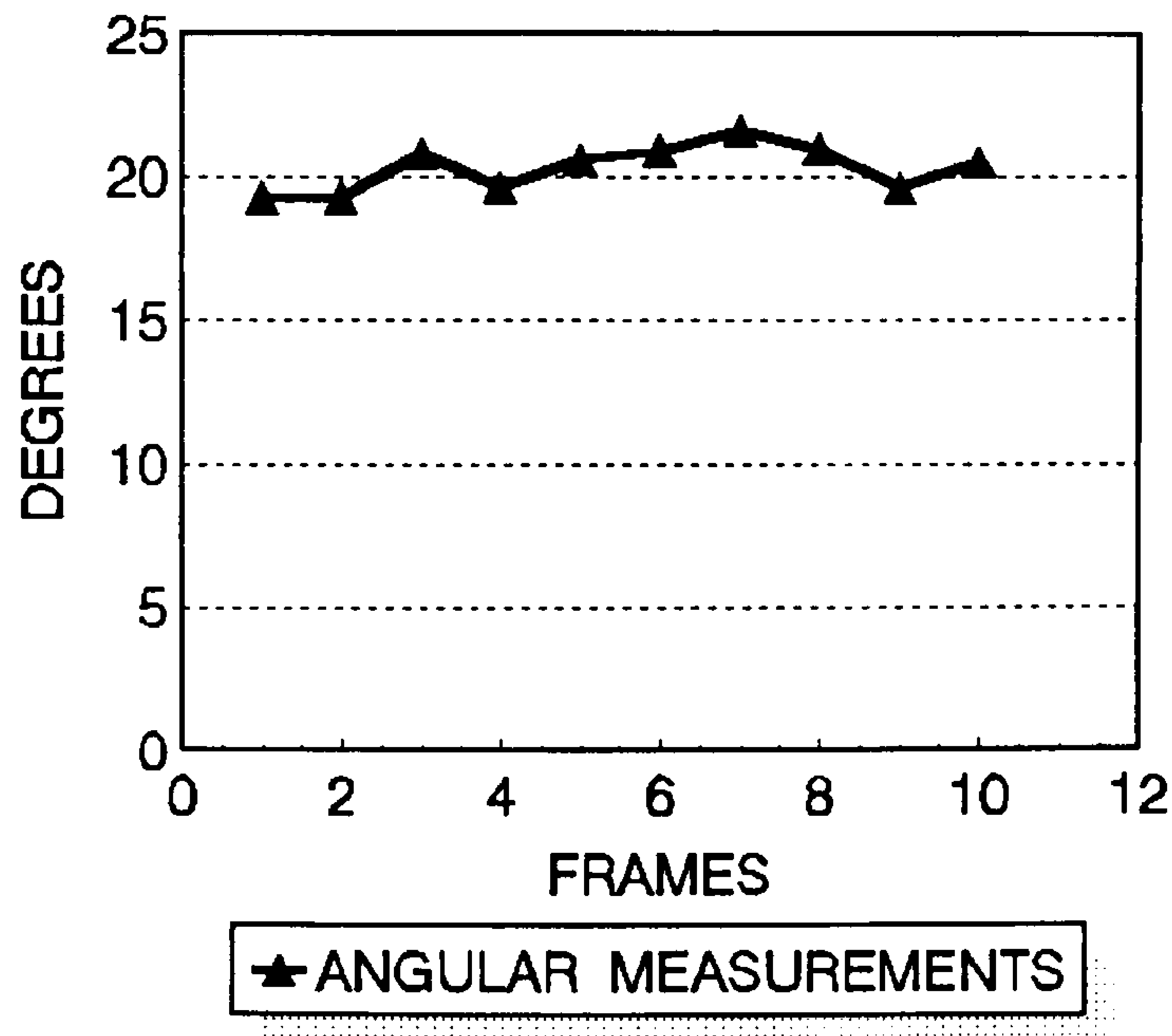

Figure 7.13. Ten repeated measurements of knee angle.

DISCUSSION

In this study the knee kinematic parameters during level and downhill running were calculated using the reconstructed 3-D coordinate of the runner joints applying the polynomial method described in Chapter 3. Two and three dimensional studies have examined lower extremity kinematic adaption during level and downhill running. Newham et al. (1988) concluded that the knee extensor muscle group is worked over a greater range during downhill running than in level running. The kinematic analysis of the knee in level and downhill running in previous studies highlighted that FA in level running is higher than in downhill running, with a difference ranging from 3.3° to 7.6° (Hamill *et al.*, 1984; Buczek and Cavanagh, 1990). Hamill *et al* (1984) reported a direct relationship between knee angle at footstrike and the gradient in downhill running (Fig. 7.14). Buczek and Cavanagh (1990) demonstrated that the PFA is higher in downhill running with a difference of 4° from level running. The PFAV is higher overall, according to previous studies in downhill running, and the difference ranged from 0.6 $rad.s^{-1}$ to 2.3 $rad.s^{-1}$ (Hamill *et al.*, 1984; Buczek and Cavanagh, 1990).

The results of the present study indicate that the values of the kinematic parameters determined using the polynomial method, were within the range of the respective values reported in previous studies.

More specifically, the FA at footstrike in level running was similar with the FA of 20.08° reported by Hamill *et al.* (1984), higher than 11.2° reported by Hamill *et al.* (1991) and lower than 24.6° reported by Buczek and Cavanagh (1990), whereas the FA in downhill running in the present study was higher than Hamill et al. (1984) (15.3°) and similar to Buczek and Cavanagh (17.0°). The PFA for level running was similar with the respective values of 35.4° reported by van Woensel and Cavanagh (1992), but lower than those reported by Buczek and Cavanagh (1990), Williams *et al.* (1991), Hamill *et al.* (1991), and Hamill *et al.* (1992) (43.9°, 44.5°, 43.8 and 44.1° respectively). The PFA for the downhill running was lower than Buczek and Cavanagh (47.9°). The PFAV was similar with the respective values reported by Hamill *et al.* (1992) , but less than those of Hamill *et al.* (1984), Buczek and Cavanagh (1990), Williams *et al.* (1991). The difference between the FA and the PFA (ROM) was similar with the respective ROM in the Buczek and Cavanagh

Table 7.1. **Summary of knee joint kinematic during stance phase of the present and previous studies. (1: Hamill et al., 1984, 2: Buczek and Cavanagh, 1990, 3: Williams et al., 1991, 4: Hamill et al., 1991, 5: Hamill et al., 1992, 6: van Woensel and Cavanagh, 1992.)**

studies	grad %	speed $m.s^{-1}$	FA degrees (±SD)	PFA (±SD) degrees	TPFA % stance (±SD)	PFAV $rad.s^{-1}$ (±SD)	TPFAV % stance (±SD)	ROM FA-PFA
present study	0	3	20.9	36.2	32.1	7.1	14.2	15.3
	- 9	3	17.4	43.1	50.0	7.4	21.4	25.7
1	0	3.8	20.1	-	-	10.1	-	-
	- 9	3.8	15.3	-	-	12.4	-	-
2	0	4.5	24.6 (3.0)	43.9 (3.6)	33.6 (2.4)	7.97 (1.2)	4.3 (1.9)	19.3
	- 8.3	4.5	17.0 (4.2)	47.9 (3.3)	40.7 (1.9)	8.57 (0.38)	15.0 (0.0)	30.9
3	0	5.5	-	44.5	-	-	-	-
	-	-	-	-	-	-	-	-
4	0	2.9	11.2 (6.9)	43.8 (5.1)	184 (55)*	-	-	32.6
	-	-	-	-	-	-	-	-
5	0	**	-	43.4	44.7	7.1	21.5	-
	-	-	-	-	-	-	-	-
6	0	3.8	-	35.4 (4.1)	90.0(7.1)*	7.82 (1.46)	30.6(6.4)*	
	-	-	-	-	-	-	-	-

* The time in these studies was reported in milliseconds and not as % of stance phase. For comparison purposes, the TPFA of the present study was 70 ms for the level and 120 ms for downhill running. The TPFAV was 30 ms and 40 ms respectively.

** The running speed of this study has not been reported.

(1990) study.

A summary of measurement values of left knee kinematic parameters and comparison with other published studies (Hamill *et al.*, 1984; Buczek and Cavanagh, 1990; Williams *et al.*, 1991; Hamill *et al.*, 1991; Hamill *et al.*, 1992; van Woensel and Cavanagh, 1992) are presented in Table 7.1. Motorized treadmills have been used in previous studies.

The variability of kinematic parameters reported in different studies can not provide a criterion for the accurate estimation of the methods. However, the above comparison of the kinematic parameters were considered sufficient to estimate the validity of the polynomial method implemented. The difference between the kinematic parameters reported in different studies, is due to the variability in the individual running style (Williams, 1993) and body mass between the subjects used (McKenzie *et al.*, 1985), kinematic asymmetries of lower limbs (Holden *et al.*, 1985; Vagenas and Hoshizaki, 1992), different recording (type of cameras and set up) and analysis procedures (two or three dimensional analysis, filtering, cutoff frequency, differentiating expressions and algebraically manipulation of the data). In previous studies there is no specification of the analyzed lower limb (left or right). Furthermore, the gradient in downhill running, is also reflected in the variability of the kinematic parameters between the studies (see figure 7.14).

The coded program for the kinematic analysis of the movement enables the facility for rotation of the movement and view of the image in three different pairs of axes: X - Y, Y - Z and X - Z, with varying interval times between the frames. Thus, a better observation of the image movement can be accomplished.

It is important to note that the design of the recording procedure (cameras view point and set up) has not focused in the knee joint, as has been reported in previous studies. Thus, the polynomial method presented is accurate and adequate for the kinematic parameters estimation of any body segment and consequently for the 3-D analysis of the movements.

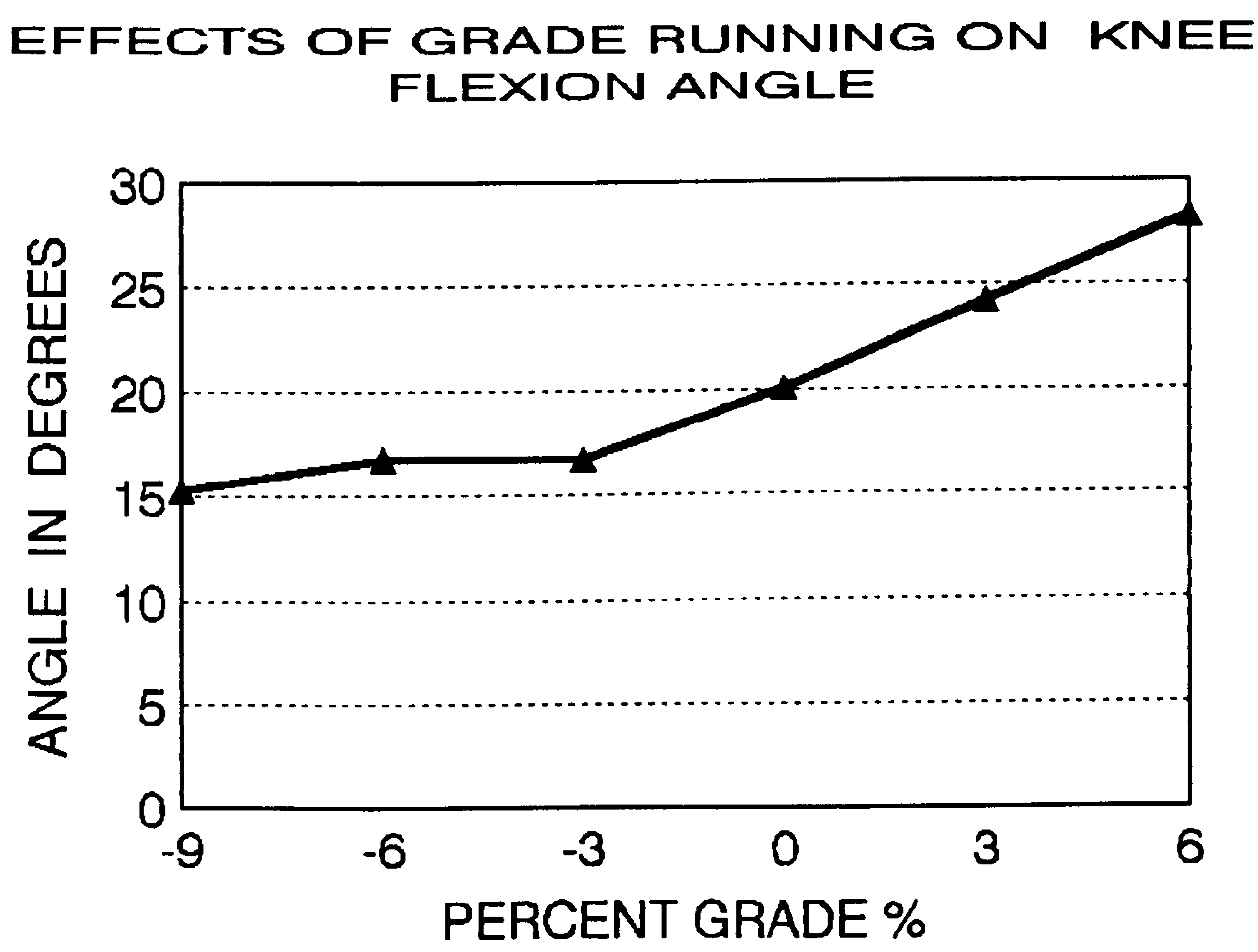

Figure 7.14. Hamill et al. (1984) demonstrated a direct relationship between knee angle at footstrike and gradient.

CONCLUSION

A polynomial method was applied in the 3-D kinematic analysis of the level and downhill running. The comparison of the results, in knee kinematics with previous studies, indicate that the polynomial method is an adequate method for the analysis of the movement. The simplicity and the efficiency of the method in the calibration procedure, compared with previous calibrated methods and the accuracy in the determination of spatial points presented in Chapter 3, render the method suitable for 3-D analysis of movement.

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CHAPTER 8

A COMPUTER PROGRAM FOR 3-D RECONSTRUCTION AND KINEMATIC ANALYSIS

G. PIGOS

ABSTRACT

A user-friendly software for three-dimensional reconstruction and kinematic analysis was developed, using Borland's Turbo Pascal (version 6.0) on an IBM compatible microcomputer (Intel 82386 based) under a MS-Dos (Version 6.2) operating system. This developed software was implemented in Chapters 3 and 7, for 3-D reconstruction and kinematic analysis respectively.

INTRODUCTION

The data collection and the analysis process in biomechanics is highly depended upon the technological advances and the rapid changes in the field of computer programming. The development and implementation of the microcomputer has considerably reduced processing time and has changed the whole concept of accurate mathematically derived data. Extensive developments of software in various fields of applied biomechanics have been reported (i.e. Plagenhoef, 1968; Vaughan, 1982). The polynomial method described in Chapter 3 for image deformation correction and kinematic analysis was coded in a computer program. The software was developed by the author using Borland's Turbo Pascal (version 6.0). An IBM compatible microcomputer (Intel 82386 based) under a MS-Dos (Version 6.2) operating system was used. Turbo Pascal was used because of its modular programming nature and the integrated development environment allowing efficient editing, compilation and debugging of computer programs. Furthermore, Turbo Pascal programming environment incorporates programs from many other languages and development systems.

Modified versions of the main program used in Chapter 7, adjusted for the requirements of every study, were implemented in this thesis. The primary purpose in the development of the computing program, was to create a user-friendly and flexible program for 3-D (or 2-D) reconstruction and kinematic analysis. In this Chapter, only the main program developed for the requirements of Chapter 7 will be presented. The computer program is presented in two parts : 1) the units implemented by the programs and 2) the programs used for data collection, analysis and presentation.

UNITS

Digmodel The declaration section of basic arrays and the sub-routines in graphical form, implemented in the programs, were included in this unit. Furthermore, Dempster's (1955) anthropometric model has been coded in order to determine the location of the centre of gravity of a subject using the reconstructed coordinates. The procedure which enables the operator to construct his/her own anthropometric model is also included.

Mouse A complete set of procedures for handling the basic operations of the graphics cursor including initialization, shape determination and input of video coordinates.

Gcrt2 and Gwin Two complete sets of procedures for text input-output in a graphics environment adapted from Baltzopoulos (1991).

Lsfit A singular value decomposition algorithm implemented for the solution of simultaneous linear equation systems. This unit is based on the algorithm presented by Press *et al.* (1989).

Digit3d This unit includes the manual digitization facility using graphic 'mouse', determination of camera position, two and three-dimensional reconstruction using the polynomial methods described in Chapter 3, image deformation correction (shorting technique), 2-dimensional stick figure display and storing data facility. A more extensive description of this unit can be found in the 'Gdigit' program, which uses this unit.

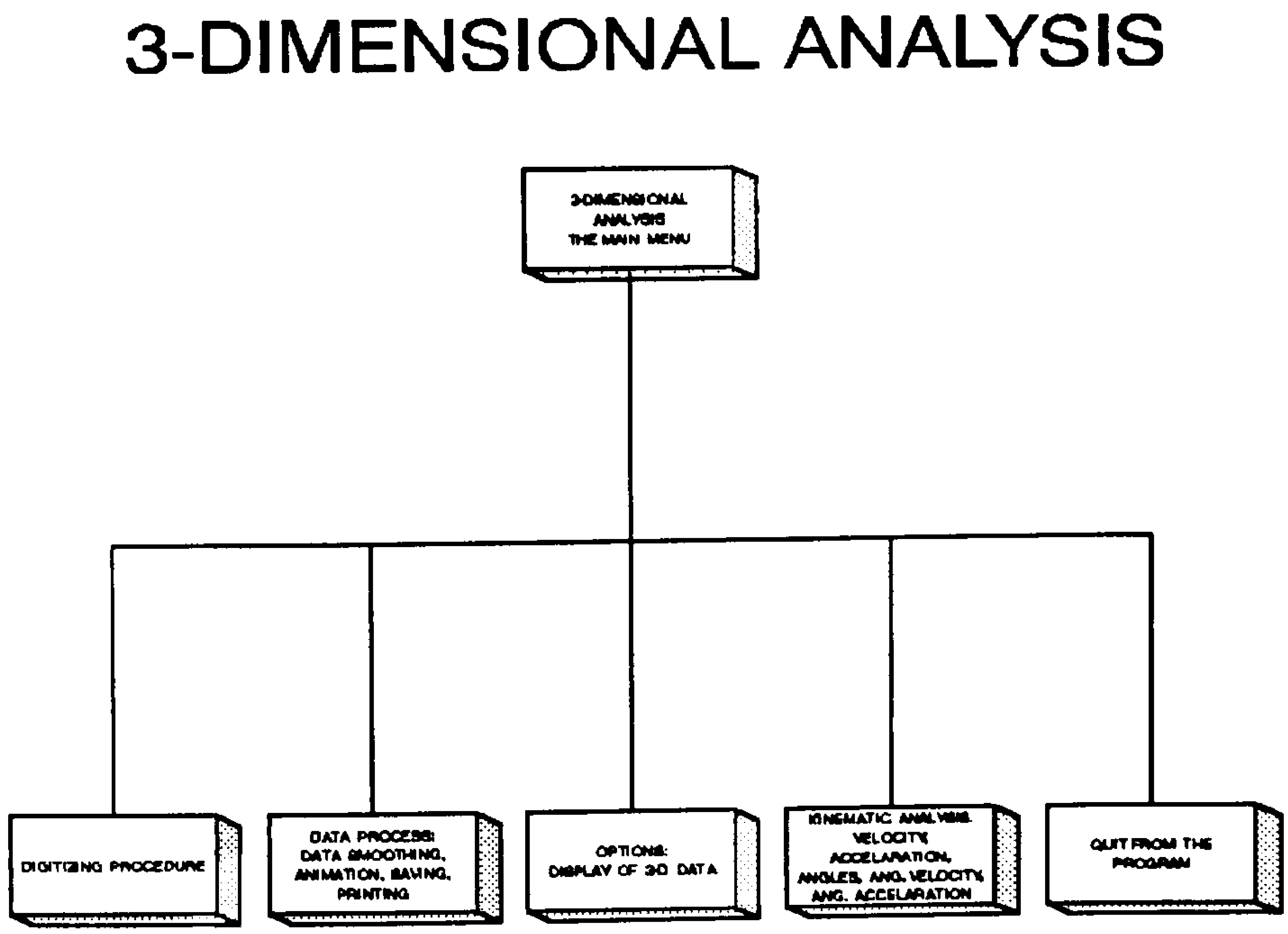

Figure 8.1. The schematic diagram of the computing program.

PROGRAMS

Three programs were developed. All the programs are menu driven. The selection of the section-program is accomplished by typing in the underlined letter. In every section-program there is a " pull down" menu. Once the program has been selected, a pulled down menu presents its options and the specific program is highlighted. A guide-line at the bottom of the screen is provided in order to help the operator use the program.

Gdigit

A complete set of digitizing procedures using the polynomial method presented in Chapter 3 is included in this program.

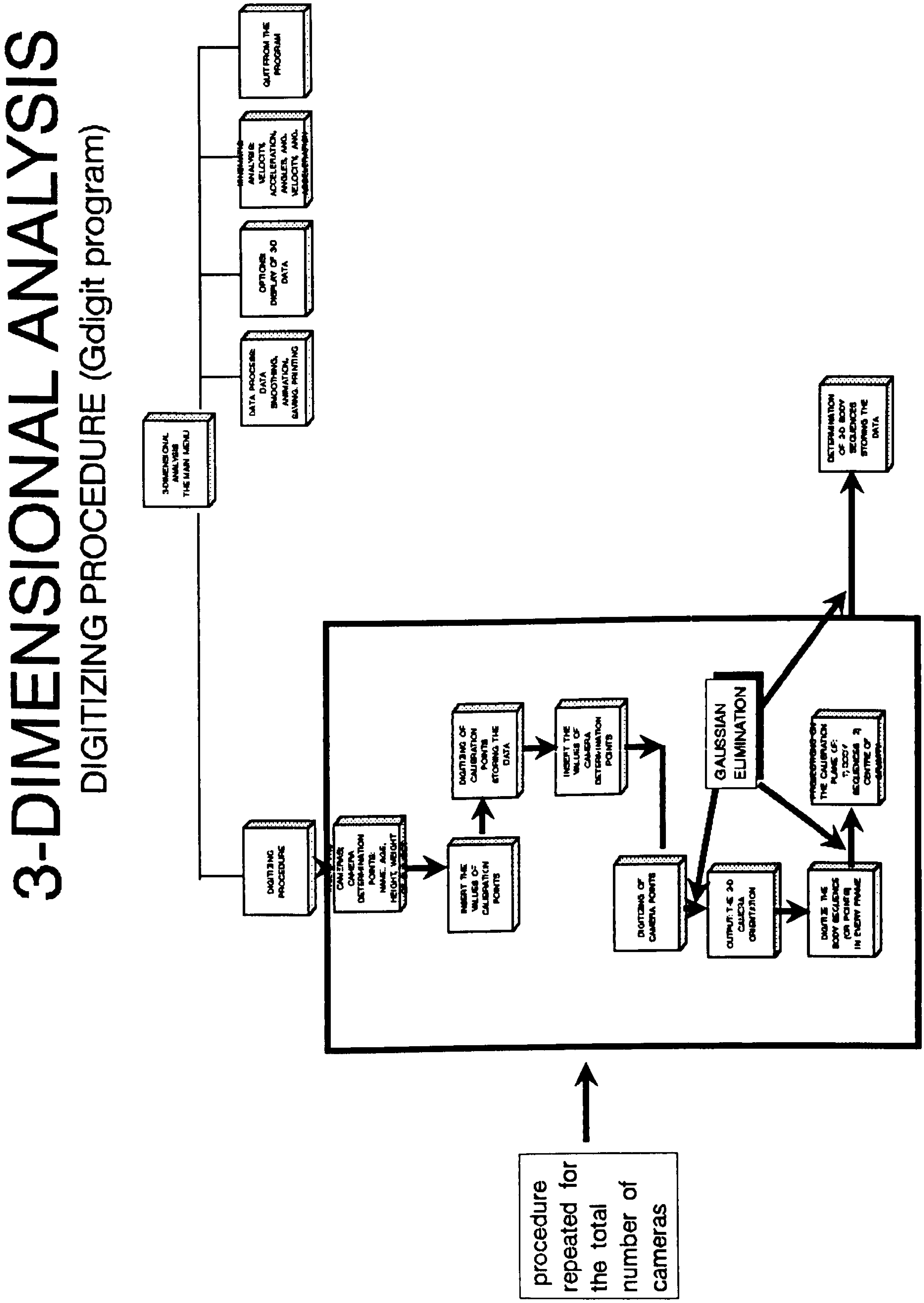

Figure 8.2. The schematic diagram of the digitizing program.

The input data required by the operator is:

a) in a pull down menu the:
1) number of cameras
2) number of camera determination points
3) name of subject (optional)
4) age of subject (optional)
5) height of subject (optional)
6) mass of subject

b) in a text form the X, Y actual values of the calibration points. The respective values in the Z axis are the same for all the calibration points (co-planar points) and equal to the value of the global origin on the calibration plane. The actual 3-D coordinates of the camera determination points are also required.

The determination of the polynomial coefficients for every digitized point presented in Chapter 3 was achieved using the coresponding actual and digitized coordinates of the three closest calibration points (according to their distance from the projection of the digitized point in terms of video coordinates) (Procedure Verify) and a least square method (Procedure estimPCW). A least square method (Gaussian elimination) is implemented for the solution of simultaneous linear equations. The least square method is based on the algorithm presented by Press *et al.* (1989). The selection of the closest calibration points for any digitized point in the 'Verify ' procedure is achieved using a sorting algorithm (Cooper, 1992). The correction of the image deformation (using local planes as described in Chapter 3) and the accurate 3-D reconstruction was accomplished implementing this sorting algorithm.

During the digitizing procedure, links are drawn by the program between adjoining points to form the stick figure model and to help the operator to identify digitizing errors as he/she digitizes joint centres (Procedure Linkpoints). Any errors in the digitizing procedure can be corrected when the operator has completed the digitizing of the frame (Procedure Redigit). The digitized data from every frame is automatically stored in a temporary file (Procedure Save2) to prevent loosing the data from operator or instrumentation errors. This temporary file is overwritten in the next digitized procedure, by the data from the other camera view. When the process of digitizing procedure and the data collection from one camera view has been completed, animation of 2-D stick figure (as it has been viewed from this camera) is performed (Procedure Create). The trace of either the centre of joints or the C.G. is also available. The operator can save the 2-D collected data in a permanent file. This procedure is repeated for the total number of cameras.

This same least square method, is implemented for the determination of 3-D coordinates of any digitized point (and the centre of gravity (C.G.)) using the projections of the digitized point on the calibration plane and the 3-D coordinates of the camera, as described in Chapter 3. A schematic diagram of the digitizing method is illustrated in the figure 8.2.

Process

A complete set of procedures for data smoothing using a Butterworth digital filter, based on the algorithm presented in Chapter 7, and animation of the reconstructed image in three different sets of 2-dimensional axes, are included in this program. Procedures for saving and printing of data is also included.

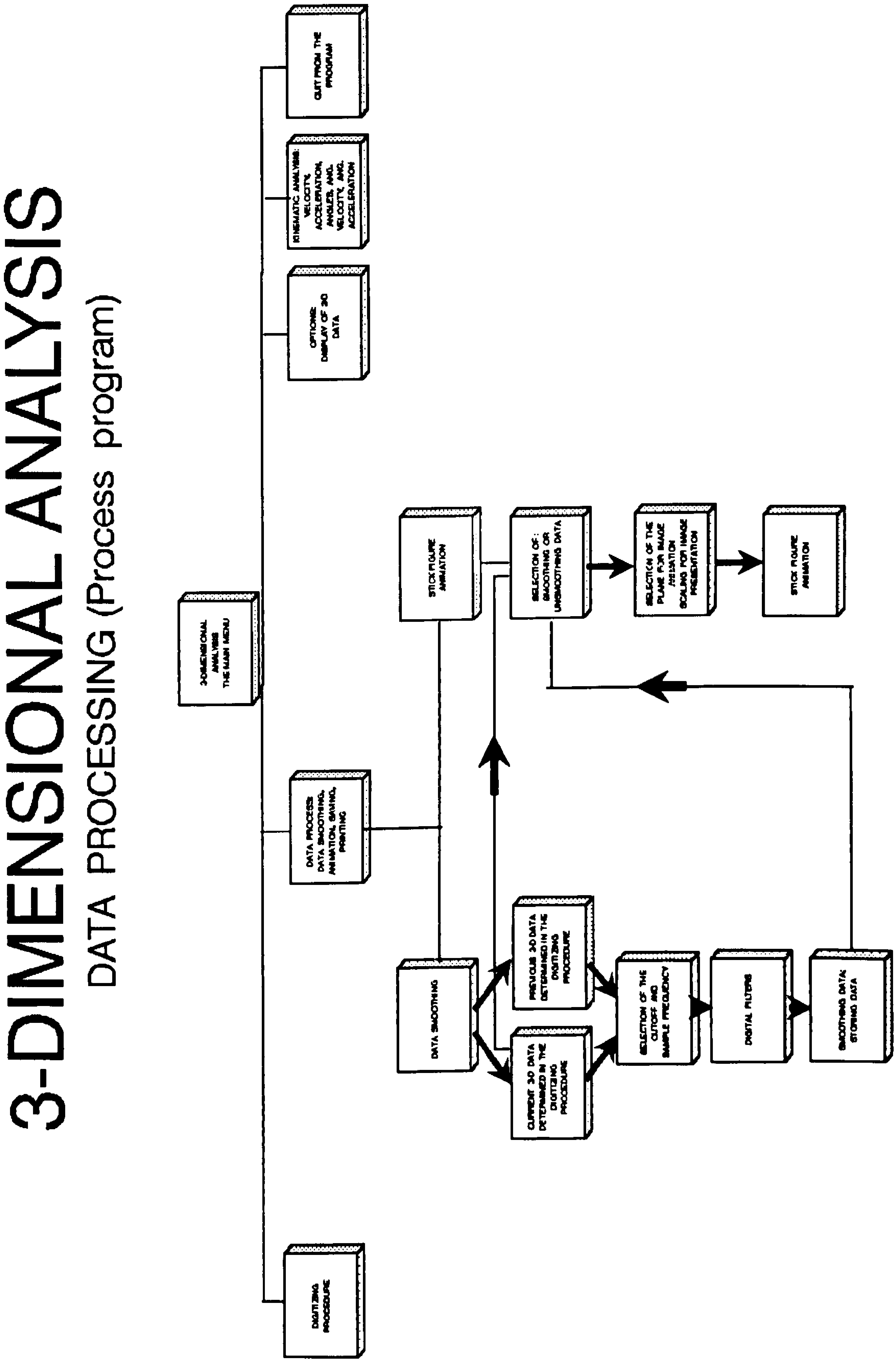

Figure 8.3. The schematic diagram of the process program.

In the smoothing procedure, the operator has the option to select a specific point-joint (included the C.G.) or the whole body. Subsequently, the sampling and cutoff frequency can be selected. It is important to note that the program offers the facility of selecting different cutoff frequencies for every point-joint, in order to minimize the difference in the accurate reconstruction of a point-joint when obscured by a body sequence as it is viewed from the camera.

The observation of a 3-D reconstructed image movement in three different planes, at a preselected interval time between the frames, is also available (Procedure Animation). The animation of the stick figures is based either on the smoothed or unsmoothed 3-D data. An additional option for displaying only the stick figures of the specific frame, or the group of stick figures (echo effect) from the first frame until the last frame (Fig. 8.4) is displayed, is available (Procedure Stick_fig). A scaling

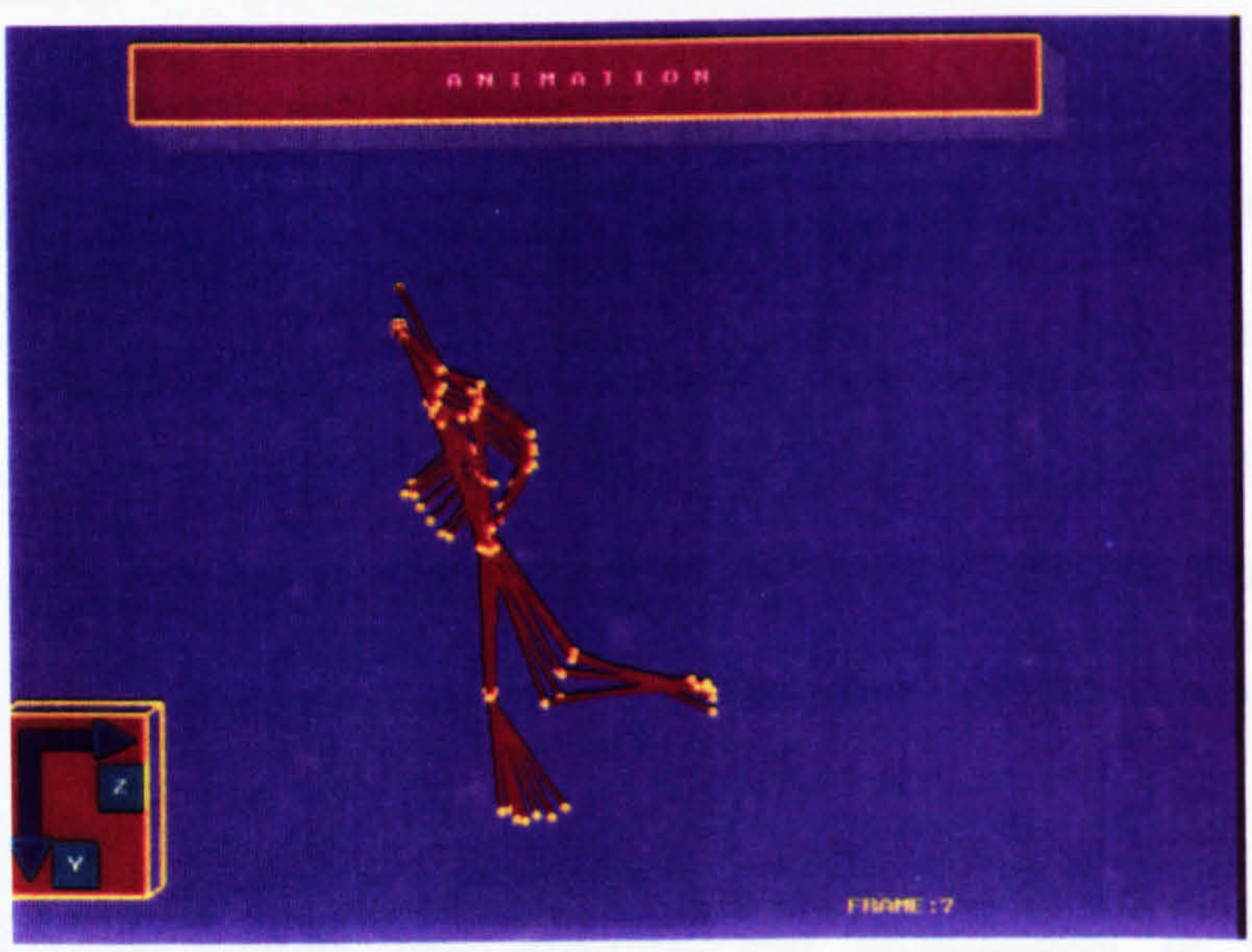

Figure 8.4. **The animation of the stick figures in three different planes (X-Y, X-Z and Y-Z) based either on the smoothing or unsmoothing 3-D data**

procedure is implemented to identify the dimensions of the stick figure throughout the animation in order to fit the entire movement in the screen coordinates, using the highest negative and positive coordinates of the two axes (from all the frames), which has been preselected for the animation (Procedure Scalar_deter).

The 3-D data can be stored in text form or printed using the saving or the printing options respectively.

GRKIN

A complete set of procedures for kinematic analysis and presentation of the 3-D data are included.

The data smoothing procedure precedes the kinematic analysis of the 3-D data. The formulation of the mathematical expressions used for the determination of the kinematic parameters of the movement (velocity, acceleration, angle angular velocity, angular acceleration) was adapted by Miller and Nelson (1976), as described in Chapter 7. The program permits the option of selecting between either a specific joint-point or a C.G. for kinematic analysis. The determination of the angles between the segment were calculated using simple geometric expressions consisting of the direction vectors of the two lines formed by (at least) three non collinear points (Bowyer and Woodwark, 1983). The lack of the 'arcos' routine in Turbo Pascal, resulted in the development of the routine in C programming language. The developed routine was executed and incorporated in Turbo Pascal. Presentation and storage in text form of the determined kinematic values is also available.

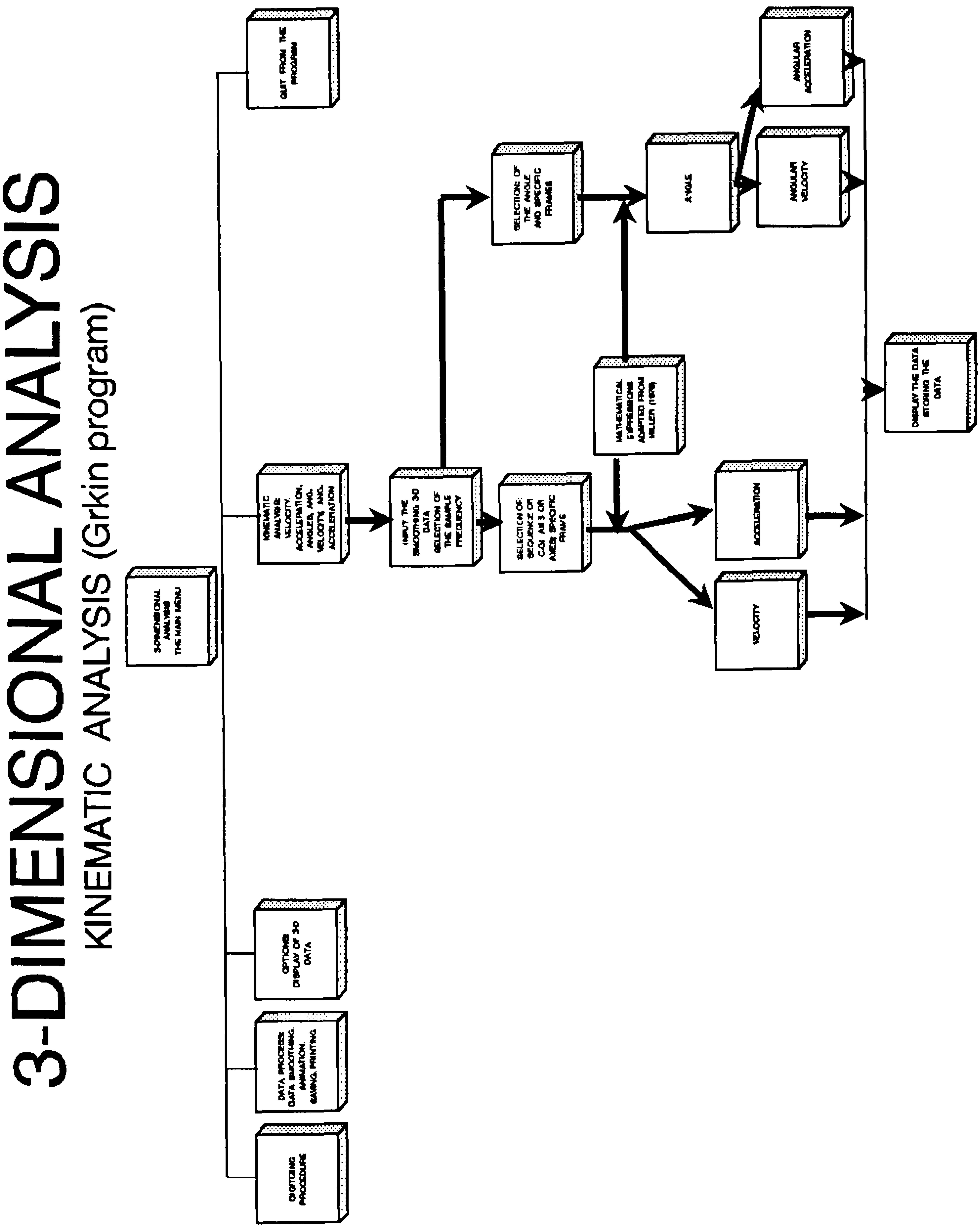

Figure 8.5. The schematic diagram of the Grkin program.

CONCLUSION

A complete and flexible program was developed for three-dimensional analysis. The results from the implementation of the program in the studies presented in this thesis indicate that the developed program is adequate for 3-D kinematic analysis (see Chapter 3. and Chapter 7).

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SUMMARY

Human locomotion is a complex and highly integrated form of activity. For this reason the accuracy of three-dimensional analysis is a significant factor for kinematic analysis of movement. Different techniques for three-dimensional reconstruction have been introduced, and the Direct Linear Transformation is the most frequently used. A polynomial method was developed to overcome the different shortcomings of previous methods concerning the calibration procedure and the accurate reconstruction outside the calibrated area.

To date, 16mm film has dominated as the medium used to record movement, but with the rapid development in technology, it is anticipated that video will be increasingly used for data collection in sports biomechanics. Therefore, the developed method has used video systems for 3-D reconstruction and kinematic analysis.

The developed method was examined for the 3-D coordinate reconstruction using spatial points with known 3-D coordinates. A small calibration plane (2.1 m W x 1.1 m H), relative the to calibrated volume, was implemented. The projection of any point on the calibration plane, viewed from two cameras, was computed using a first degree polynomial model constructed from local calibration points. Three-dimensional coordinates are computed using intersection techniques. The absolute measurement error ranged from 0.04% to 0.07% (of the field of view) in the X axis, from 0.05% to 0.06% in Y and from 0.05% to 0.07% in Z for control points inside the calibrated area (internal) and from 0.15% to 0.51% in X, from 0.16% to 0.42% in Y and from 0.15% to 0.46% in the Z axis for control points outside (external). The measurement error is significantly reduced compared to other video or film systems. Furthermore, this polynomial method allows linear

extrapolation for coordinate reconstruction outside the calibration area and, therefore, is particularly useful in applications requiring large filming areas. In this method, there is no need to survey the camera locations and no assumptions are required for the internal camera parameters.

Panning techniques are the most appropriate methods for the analysis of athlete's movements, when these occurs in a large volume. The measurement error was considerably reduced compared with previous film or video panning studies, when the polynomial method was applied using the panning technique, ranging from 0.053% to 0.095% of the field of view. The image deformation correction algorithm used overcomes the effect of the recording angle during panning.

The accurate assessment of angular measurements was examined using the Biomechanics Workstation (BmWs) system and the developed polynomial method. The accuracy of BmWs when the zoom facility is implemented was also examined. A calibration plane with 19 markers was recorded in an underwater and an indoors environment. Five 90° angles formed by three non linear calibration points were used in the accuracy estimation of the above methods. The mean angular measurements for both environments ranged from 89.983° to 90.000° using the polynomial method, from 90.761 to 89.842 using the BmWs without zooming and from 90.700° to 90.090° using the BmWs with zoom facility. It was concluded that the polynomial method was superior to BmWs and produced accurate angular measurements in every screen location. Furthermore, there was no difference in the accuracy between the angular measurements in different environments when the polynomial method was used.

The analysis of dynamic images for the determination of skeletal deformation and joint kinematics using videofluoroscopy has been frequently implemented. However, image deformation is introduced in different stages of videofluoroscopy, reflected in the accurate reconstruction and consequently in kinematic analysis of dynamic images. The polynomial method, incorporating an image deformation correction method, was examined for the reconstruction of spatial points using videofluoroscopy. Different angles between image intensifier and calibration plane were used, as well as different sets of calibration points. The results indicate that the absolute mean error was considerably reduced compared with previous studies. The different amount of image deformation produced in every screen location has been effectively corrected. The number of calibration points affects the accuracy of the reconstruction. Thirty calibration points is the minimum number of calibration points required using this polynomial method, when the angle between object and X-ray is ranges from 90° to 60°.

Determination of the optimal movement using accurate reconstruction methods affects athlete's performance and prevention of injuries. The knee kinematic parameters determined using the developed polynomial method, were within the range reported in previous studies. The estimated kinematic parameters for level and downhill running were: 20.9° and 17.4° respectively for the flexion angle in the footstrike, 36.2° and 43.1° for the peak flexion angle during the stance phase and 7.1 rad*s^{-1} and 7.4 rad*s^{-1} for the peak flexion angular velocity.

It can be concluded that the polynomial method presented is an accurate and easily implemented method for three-dimensional reconstruction and kinematic analysis. The main advantages of the method are the simple calibration procedure, image deformation correction and possibility for accurate reconstruction outside the calibrated volume.

APPENDIX I

COMPUTER PROGRAM

UNITS

```
unit digmodel;

Interface

 Uses
  Crt,Graph,Gcrt2,Gwin,mouse;

 Const
 maxlineseqs=18;
 MaxFrames= 58;
 maxnumvid= 2 ;
 maxmapPoints=5;
 conpoints=70;
 seqcgr=10;
 del=chr(83);


  Type
   CGravityRec=
      Record
      Xcg,Ycg,Zcg:Array[1..maxnumvid] of Real;
      Hmid,Vmid:Array[1..maxnumvid] of Real;
      Hscg,Vscg:Array[1.. seqcgr] of Real;
   end;


  Type
   lineseq=
    Record
    Hr,Vr,Zr:Array[1..maxnumvid] of real;
    H,V: LongInt;
   end;


  Type
   lineseqs=
    Record
    seqs:Array[ 1..maxlineseqs] of lineseq;
   end;


 Type
  SegmentRec=
     Record
     Proximal: Integer;
     Distal  : Integer;
```

```
   CmWeight: Real;
   CmLength: Real;

  end;


 ModelRec=
  Record
   Name:Array[1..maxlineseqs] of string;
   Link:Array[1..maxlineseqs] of ShortInt;
  end;


 Type
  savfile=Array[1..500] of Real;



 Var
  Segment:Array[1..maxlineseqs] of SegmentRec;
  frames:Array[1..maxframes] of lineseqs;
  InsMo:Array[1..conpoints] of lineseq;
  CM:Array[1..maxframes] of CGravityRec;
  rd,fd,rt:^savfile;
  model:modelRec;
  Height,Xcam,Ycam,Zcam,BW,ds,cutoff:Real;
  fr,j,r,maxfr,a,k,s,ni,gd,gm,m1,m2:integer;
  er,Age,numvid,pref,vid,SegNo,Linking_points,modNo:ShortInt;
  TF:Text;
  FN,Name,str_realnum:string;
  ch:char;
  done:boolean;


  Procedure clear;
  Procedure dem;
  Procedure Mes_error;
  Procedure Mes1;
  Procedure Mes2;
  Procedure Mes3;
  Procedure Mes32;
  Procedure Mes4;
  Procedure Mes5;
  Procedure Mes6;
  Procedure Mes7;
  Procedure Mes8;
  Procedure dis1;
  Procedure prev_file;
  Procedure title2;
  Procedure insert_val;
```

```
Procedure  dis2;
Procedure  Display_file;
Procedure  add;
Procedure  cendeter;
Procedure  develop_model;
Procedure  option;
Procedure  save (Var a,b:ShortInt);
```

```
unit mouse;
interface
uses dos,graph;
const
PointIcon=1;
CrossIcon=2;
Arrowicon=3;
LeftButton=0;
RightButton=1;

type
st=string[16];
var
reg:registers;
mask:array [0..1,0..15] of word;
i,k,l,w,mul:integer;
preint:pointer;
s:st;
procedure MouseInit(MouseIcon:integer);
procedure ShowMouse;
procedure HideMouse;
procedure MouseInput(var X,Y:longInt);
procedure MousePosition(var X,Y:Integer);
function MousePress(Button: Integer):Boolean;
function MouseRelease(Button:Integer):Boolean;
function MouseInArea(Left,Top,Right,Bottom:Integer):Boolean;
```

```
UNIT LSFIT;
INTERFACE
CONST
  np =50;
  mp =6;
  TYPE
  RealArrayNDATA = ARRAY [1..np] OF real;
  RealArrayMP = ARRAY [1..mp] OF real;
  IntegerArrayMFIT = ARRAY [1..mp] OF integer;
  RealArrayMPbyMP = ARRAY [1..mp,1..mp] OF real;
  RealArrayNPbyNP = ARRAY [1..np,1..np] OF real;
  RealArrayNPbyMP = ARRAY [1..np,1..mp] OF real;
  IntegerArrayNP = ARRAY [1..np] OF integer;
PROCEDURE gaussj(VAR a: RealArrayMPbyMP;
               n: integer;
            VAR b: RealArrayNPbyMP;
               m: integer);
PROCEDURE lfit(VAR y,sig: RealArrayNDATA;
               var e: RealArrayNPbyMP;
               ndata: integer;
               VAR a: RealArrayMP;
                 ma: integer;
            VAR lista: IntegerArrayMFIT;
                mfit: integer);
```

```
Unit digit3D;
Interface

{$N+}
 Uses
 Dos,Crt,graph,mouse,gcrt2,printer,gwin,lsfit,digmodel;


Const
 maxcoef=3;
 points=3;


  Type
   MapPointsRec=
    Record
    Hm,Vm:Array[1..maxmapPoints] of real;
   end;


  Type
  Artype=Array[1..conpoints] of Real;
  ImCMtype=Array[1..maxframes,1..maxnumvid] of Real;
  Real_val_array_dp=Array[1..maxmapPoints] of Real;
  Real_val_array_cp=Array[1..conpoints] of Real;
  Scalar_coef=Array[1..maxmapPoints,1..2] of Real;


 Var
  ca,cb:Array[1..maxcoef] of Real;
  imCMX,imCMY:^ImCMtype;
  imcengrX,imcengrY:Array[1..maxframes,1..maxnumvid] of Word;
  mapPoint:^MapPointsRec;
  dis,ver:^Artype;
  Xob,Yob,Zob:^Real_val_array_dp;
  Xr,Yr:^Real_val_array_cp;
  q:Array[1..points] of lineseq;
  distance,tx,ty:Array[1..points] of Real;
  l,m,n:^Scalar_coef;
  coordCamX,coordCamY,coordCamZ:Array[1..maxnumvid] of Real;
  di,d:ShortInt;
  sig,br:RealArrayNdata;
  lista:IntegerArrayMfit;
  cf:RealArrayMP;
  e:RealArrayNPbyMP;

  Procedure digit;
  Procedure digit2;
  Procedure Mes_redig;
  Procedure cal_redig (Var a:integer);
```

```
Procedure  Open_file;
Procedure  calplane;
Procedure  screencoord;
Procedure  estimPCW;
Procedure  SelectMIN;
Procedure  discriminate;
Procedure  Verify;
Procedure  eval;
Procedure  linkpoints;
Procedure  coordinser;
Procedure  identify(a,b:integer; Var  Xkn1,Xkn2,Xun,Ykn1,Ykn2,Yun,Zkn1,Zkn2,Zun:Real);
Procedure  camPosition;
Procedure  evaluate;
Procedure  redigit;
Procedure  valmiddle;
Procedure  imagcengra_14dem;
Procedure  Cengravity_14dem;
Procedure  imagcengra_gen;
Procedure  Cengravity_gen;
Procedure  wholebody;
Procedure  lincen;
Procedure  linkcentre;
Procedure  Save2;
Procedure  ThreeD(var t,ti,f,fi,u:Real);
Procedure  Create;
```

PROGRAMS

```
{$M 8000, 4000, 50000}
program  Gdigit;

Uses
Crt,graph,mouse,gcrt2,gwin,digmodel,digit3D2;

  procedure egavgadriver;external;{$L egavga.obj}


 Procedure digitize;
 begin
   SetlineStyle(solidln,0,thickwidth);
   SetFillstyle(1,5);
  REPEAT
    HideMouse;
     ClearDevice;
    ShowMouse;
  vid:=1;
   Repeat
      HideMouse;
      ClearDevice;
      ShowMouse;
    screencoord;
     HideMouse;
      ClearDevice;
      ShowMouse;
        fr:=1;
          camPosition;
         Repeat
          HideMouse;
           ClearDevice;
           GWriteXY(Xg(0),Yg(0),'              ',15,3);
           GWriteXY(Xg(0),Yg(1),' FRAME : '+Is(fr)+'  ',15,3);
           SetColor(14);
           OutTextXY(GetMaxX div 2, 20,'INPUT   X , Y   OF : ');
         ShowMouse;

       ni:= 1;
        for ni:= 1 to SegNo do
         begin
          clear;
           GWriteXY( 2*GetMaxX div 3 ,33,'              ',1,12);
           GWriteXY( 2*GetMaxX div 3 ,40,'              ',1,12);
           GWriteXY( 2*GetMaxX div 3 ,45,'              ',1,12);
           GWriteXY( 2*GetMaxX div 3 ,40,''+ model.Name[ni],1,12);
           SetColor(4);
```

```
        digit;
        verify;
        evaluate;
        if modNo=1 then
        valmiddle;
      end;

        HideMouse;
         Mes_redig;
           ShowMouse;
           if (ch= 'y') or (ch='Y')  then
            redigit;
        if modNo=1  then
        Cengravity_14dem
     else
      Cengravity_gen;
  if ch<>esc then
  Inc(fr);
  save2;
   until  ch=esc;
    maxfr:=fr;
    Create;
   HideMouse;
    ClearDevice;
   ShowMouse;

  Inc(vid);
 until  vid>numvid;
 Dispose(Xr);
   Dispose(Yr);
   for fr:=1 to maxfr do
    begin
      HideMouse;
        ClearDevice;
       ShowMouse;
    for ni:=1 to SegNo+1 do
     begin
        GWriteXY(Xg(1),Yg(0),'Values  of  Frame: '+is(fr),5,1);
         if ni=15 then
        begin
        clear;
        ThreeD(CM[fr].Xcg[vid],CM[fr].Xcg[vid+1],
        CM[fr].Ycg[vid],CM[fr].Ycg[vid+1],CM[fr].Zcg[vid]);
       vid:=1;
       GWriteXY(Xg(0),Yg(SegNo+3),' CENTRE OF GRAVITY  VALUES : '
              + ' X  ' +Rs( CM[fr].Xcg[vid],8,3)
              + ' Y  ' +Rs( CM[fr].Ycg[vid],8,3)
              + ' Z  ' +Rs( CM[fr].Zcg[vid],8,3),15,1);
         end{if ni}
```

```
  else
       begin
       clear;

       ThreeD(frames[fr].seqs[ni].Hr[vid],
              frames[fr].seqs[ni].Hr[vid+1],
              frames[fr].seqs[ni].Vr[vid],
              frames[fr].seqs[ni].Vr[vid+1],
              frames[fr].seqs[ni].Zr[vid]);
       vid:=1;
       GWriteXY(Xg(1),Yg(ni+2),'VALUES  OF  ' + Is(ni) +'  POINT  IN  '
              +' X :' +Rs(frames[fr].seqs[ni].Hr[vid],8,3)
              +' Y :' +Rs(frames[fr].seqs[ni].Vr[vid],8,3)
              +' Z :' +Rs(frames[fr].seqs[ni].Zr[vid],8,3),15,1);
        end;

  end; {for}
  mes2;
  end; {for2}
  s:=2;
  d:=10;
  di:=5;
  save(d,di);
  mes4;
  ch:=Upcase(ch);
  if ch='Y' then
    begin
    s:=1;
     d:=10;
  di:=5;
  save(d,di);
    end;
     HideMouse;
     ClearDevice;
     ShowMouse;
mes1;
UNTIL ch=esc ;
ch:='z';
end;



begin

  if RegisterBgiDriver(@EgaVgaDriver)<0 then halt(1);
 gd:=detect;
 initgraph(gd,gm,'');
  Repeat
   dem;
```

```
          GWriteXY(Xg(2),Yg(1),'              ',15,1);
          GWriteXY(Xg(2),Yg(2),'  Digitize   ',15,1);
          GWriteXY(Xg(2),Yg(3),'  -           ',15,1);
           dis1;
           Mes1;

      if ch<>esc then
       begin
        Insert_val;
        option;
        MouseInit(CrossIcon);
        digitize;
       end;
      until ch=esc;
  closegraph;

 end.
```

```
{$M 8000,4000,60000}
program process;

{$N+}
 Uses
Dos, Crt,graph,printer,gcrt2,gwin,digmodel;

  procedure egavgadriver;external;{$L egavga.obj}


  Type
  typver=Array[1..500] of Real;


  Var
  sa,d,di:ShortInt;
  n,i,ii,dl:integer;
  Vel:^typver;
  taf:text;
  dt:real;


  Procedure Draw_Outln;
   Const
    polygon1: Array[1..5] of pointType=
         ( (x:440; y:110), (x:455; y:120),(x:455; y:210),
         (x:188; y:210),(x:168; y:200));
    polygon2: Array[1..4] of pointType=
         ( (x:170; y:110), (x:440; y:110),(x:440; y:200),
         (x:170; y:200));

   begin
    clear;
    setBkColor(9);
    setcolor(1);
    SetlineStyle(1,0,1);
    SetFillstyle(9,7);
    FillPoly(5,polygon1);
    setcolor(14);
    SetlineStyle(solidln,0,thickwidth);
    SetFillstyle(1,5);
    FillPoly(4,polygon2);

   end;



   Procedure Filter_procedure;
   label filter;
    Var
```

```
c1,c2,c3,c4,c5,z,z1,z2,sv,ai,b,wc,pi:real;
ki,ii:integer;

begin

 n:=15;

   for fr:=1 to maxfr do
     rt^[fr]:=rd^[fr];

  For i:=1 to n do
     rd^[n-i+1]:=2*rt^[1]-rt^[i];
  For i:=1 to maxfr do
     rd^[n+i]:=rt^[i];
  For i:=1 to n do
    rd^[maxfr+n+i]:=2*rt^[maxfr]-rt^[maxfr-i];

     maxfr:=maxfr+2*n;


    ds:=1/dt;


cutoff:=cutoff/0.802;
sv:=1.0/(cutoff*ds);
 if sv<4 then
  begin
   GWriteXY(Xg(1),Yg(2),'Violation' ,15,3);
   halt;
  end;
 pi:=4*arctan(1);
 z:=pi*cutoff*ds;
 z1:=sin(z);
 z2:=cos(z);
 wc:=z1/z2;
 ai:=2.0*wc*sqrt(0.5);
 b:=0.5*ai*ai;

  c1:=b/(1.0+ai+b);
  c2:=2*c1;
  c3:=c1;
  c4:=2.0*(1.0-b)/(1.0+ai+b);
  c5:=(ai-b-1.0)/(1.0+ai+b);

  for fr:=1 to maxfr do
   begin
    rt^[fr]:=rd^[fr];
   end;
   ii:=1;
   filter:
```

```
    fd^[1]:=rt^[1];
    fd^[2]:=rt^[2];

    for fr:=3 to maxfr do
      fd^[fr]:=c1*rt^[fr]+c2*rt^[fr-1]+c3*rt^[fr-2]+c4*fd^[fr-1]+c5*fd^[fr-2];

    ki:=maxfr+1;
    for fr:=1 to maxfr do
      rt^[fr]:=fd^[ki-fr];
   { GWriteXY(Xg(1),Yg(2), 'Pass '+Is(ii),15,3);
    mes2;}
     inc(ii);
     if ii<=2  then  goto  filter;


     For fr:=1 to maxfr-2*n do
        fd^[fr]:=rt^[fr+n];

        vid:=1;
       maxfr:=maxfr-2*n;

      cutoff:=0.802*cutoff;
 end;


Procedure  Filter_seg;
 begin
         for  fr:=1  to  maxfr  do
         rd^[fr]:=frames[fr].seqs[ni].Hr[1];
         Filter_procedure;
         for  fr:=1  to  maxfr  do
         frames[fr].seqs[ni].Hr[1]:= fd^[fr];
         for  fr:=1  to  maxfr  do
         rd^[fr]:=frames[fr].seqs[ni].Vr[1];
         Filter_procedure;
         for  fr:=1  to  maxfr  do
         frames[fr].seqs[ni].Vr[1]:= fd^[fr];
         for  fr:=1  to  maxfr  do
         rd^[fr]:=frames[fr].seqs[ni].Zr[1];
         Filter_procedure;
         for  fr:=1  to  maxfr  do
         frames[fr].seqs[ni].Zr[1]:= fd^[fr];
       end;




 Procedure  Filter_cen;
  begin
```

```
        for fr:=1 to maxfr do
        rd^[fr]:=CM[fr].Xcg[1];
        Filter_procedure;
        for fr:=1 to maxfr do
        CM[fr].Xcg[1]:=fd^[fr];
        for fr:=1 to maxfr do
        rd^[fr]:=CM[fr].Ycg[1];
        Filter_procedure;
        for fr:=1 to maxfr do
        CM[fr].Ycg[1]:=fd^[fr];
        for fr:=1 to maxfr do
        rd^[fr]:=CM[fr].Zcg[1];
        Filter_procedure;
        for fr:=1 to maxfr do
        CM[fr].Zcg[1]:=fd^[fr];
      end;


Procedure digital_filter2;
  begin
       n:=15;
       Display_file;
        if er=0 then
        begin
        clear;
        title2;
        GWriteXY(Xg(16),Yg(9),'   SELECT  THE  SEGMENT  FOR  SMOOTHING    ',14,1);
       for i:=1 to SegNo do
       GWriteXY(Xg(19),Yg(2*i-1+10), Is(i)+': '+model.Name[i] ,15,3);
       GWriteXY(Xg(19),Yg(2*i+1+10), Is(i+1)+':CENTRE OF MASS ' ,15,3);
       GWriteXY(Xg(19),Yg(2*i+3+10), Is(i+2)+':  WHOLE BODY   ' ,15,3);
       GWriteXY(Xg(19),Yg(2*i+5+10),'ENTER NUMBER >     ',1,11);
       GWriteXY(Xg(19),Yg(2*i+7+10),'CUTOFF FREQUENCY >     FRAMES FREQUENCY >   ',1,11);
         Repeat
         MoveTo(Xg(37),Yg(2*i+5+10));
         if not GInt(ni,14,1) then;
           if not  (ni in [1..segNo+2])  then
            begin
               Mes_error;
               GWriteXY(Xg(37),Yg(2*i+5+10),'  ',1,5);
               GWriteXY(Xg(37),Yg(2*i+6+10),'  ',1,5);
            end;
         until ni in [1..SegNo+2];
         MoveTo(Xg(37),Yg(2*i+7+10));
         if not Greal(cutoff,14,1) then;
         MoveTo(Xg(63),Yg(2*i+7+10));
         if not Greal(dt,14,1) then;
      Getmem(rd,(maxfr+2*n+2)*6);
      Getmem(fd,(maxfr+2*n+2)*6);
```

```
    Getmem(rt,(maxfr+2*n+2)*6);
    clear;
      Draw_Outln;
        GWriteXY(Xg(25),Yg(16),'                          ',15,3);
        GWriteXY(Xg(25),Yg(17),' SMOOTHING  IN  PROGRESS ',15,3);
        GWriteXY(Xg(25),Yg(18),'                          ',15,3);
        GWriteXY(Xg(25),Yg(19),'      PLEASE WAIT        ',15,4);
        GWriteXY(Xg(25),Yg(20),'                          ',15,3);
    if  ni  in [1..SegNo] then
       Filter_seg;

    if  ni=SegNo+1 then
         Filter_cen;

    if ni=SegNo+2  then
      begin
          for ni:=1  to  SegNo do
           Filter_seg;
        Filter_cen;
      end;{SegNo+2}

   Freemem(rt,(maxfr+2*n+2)*6);
   Freemem(fd,(maxfr+2*n+2)*6);
   Freemem(rd,(maxfr+2*n+2)*6);


  s:=3;
  d:=20;
  di:=10;
  save(d,di);
     ClearDevice;
  setBkColor(0);
 end;
END;


Procedure title;
 Const
 polygon1: Array[1..5] of  pointType=
      ( (x:540; y:10), (x:555; y:20),(x:555; y:65),
      (x:90; y:65),(x:68; y:51));
 polygon2:
  Array[1..4] of  pointType=
      ( (x:70; y:10), (x:540; y:10),(x:540; y:50),
      (x:70; y:50));

begin
 clear;
 setBkColor(9);
 setcolor(1);
```

```
  SetlineStyle(1,0,1);
  SetFillstyle(9,7);
  FillPoly(5,polygon1);
  setcolor(14);
  SetlineStyle(solidln,0,thickwidth);
  SetFillstyle(1,5);
  FillPoly(4,polygon2);
 end;





Procedure anim_proc;
begin
Draw_Outln;
        GWriteXY(Xg(25),Yg(16),'                         ',15,3);
        GWriteXY(Xg(25),Yg(17),'  1:  SMOOTHING DATA     ',15,3);
        GWriteXY(Xg(25),Yg(18),'                         ',15,3);
        GWriteXY(Xg(25),Yg(19),'  2:  UNSMOOTHING DATA  ',15,3);
        GWriteXY(Xg(25),Yg(20),'                         ',15,3);
        GWriteXY(Xg(25),Yg(21),'  ENTER NUMBER >         ',1,11);
        GWriteXY(Xg(25),Yg(22),'                         ',1,11);
         Repeat
         MoveTo(Xg(44),Yg(21));
          if not GInt(i,14,4) then;
          sa:=i;
          if not  (sa in [1..2])  then
          begin
            Mes_error;
            GWriteXY(Xg(44),Yg(21),'     ',1,11);
            GWriteXY(Xg(44),Yg(22),'     ',1,11);
          end;
            until sa in [1..2];
      ClearDevice;
     title;


 end;



Procedure stick_fig;
   begin
        ii:=0;
        Draw_Outln;
        GWriteXY(Xg(25),Yg(16),'                         ',15,3);
        GWriteXY(Xg(25),Yg(17),'  1:  ALL THE FIGURES    ',15,3);
        GWriteXY(Xg(25),Yg(18),'                         ',15,3);
```

```
        GWriteXY(Xg(25),Yg(19),'  2:  SINGLE FIGURE      ',15,3);
        GWriteXY(Xg(25),Yg(20),'                        ',15,3);
        GWriteXY(Xg(25),Yg(21),'  ENTER NUMBER >         ',1,11);
        GWriteXY(Xg(25),Yg(22),'                        ',1,11);
         Repeat
         MoveTo(Xg(44),Yg(21));
          if not GInt(ii,14,4) then;
          if not  (ii in [1..2])  then
          begin
             Mes_error;
             GWriteXY(Xg(44),Yg(21),'     ',1,11);
             GWriteXY(Xg(44),Yg(22),'     ',1,11);
          end;
             until ii in [1..2];
      ClearDevice;
     title;

         GWriteXY(Xg(22),Yg(3),'     A N I M A T I O N     ',15, 5);
end;


Procedure sel_file;
begin
    i:=0;
    if not OpenGWindow(0,Xg(19),(GetmaxY div 2)-Yg(6),Xg(56),(GetmaxY div 2)+Yg(6),0,Red,1,Blue)
then;
          GWriteXY(Xg(5),Yg(2),'                        ',15,3);
          GWriteXY(Xg(5),Yg(3),'  1:  CURRENT DATA       ',15,3);
          GWriteXY(Xg(5),Yg(4),'                        ',15,3);
          GWriteXY(Xg(5),Yg(5),'  2:  PREVIOUS DATA      ',15,3);
          GWriteXY(Xg(5),Yg(6),'                        ',15,3);
          GWriteXY(Xg(5),Yg(7),'  ENTER NUMBER >         ',1,11);
          GWriteXY(Xg(5),Yg(8),'                        ',1,11);
            MoveTo(Xg(24),Yg(7));
            if not GInt(i,14,4) then;
             pref:=i;
             CloseGwindow(0);
end;


 Procedure linkpoints;
begin
     MoveTo(frames[fr].seqs[ni].H,
            frames[fr].seqs[ni].V);
      LineTo(frames[fr].seqs[model.Link[ni]].H,
            frames[fr].seqs[model.Link[ni]].V);
end;
```

```
Procedure print_file;
 begin
      Writeln(lst,'NUMBER OF SEGMENTS:  ', SegNo);
      Writeln(lst,'NUMBER OF FRAMES :  ', MaxFr);
      Writeln(lst,'NAME OF THE SUBJECT : ',Name);
      Writeln(lst,'AGE OF THE SUBJECT : ',Age);
      Writeln(lst,'HEIGHT OF THE SUBJECT  : ',Height:6:3);
      Writeln(lst,'WEIGHT OF THE SUBJECT  : ',BW:5:2);
        Writeln(lst,' SEGMENTS ' );
        for i:=1 to SegNo do
         Writeln(lst,model.Name[i]);
          for fr:=1 to maxfr do
           begin
             for ni:=1 to SegNo do
              begin
               Writeln(lst,fr,' FRAME THE ',ni,' POINT IN X AXIS : ',frames[fr].seqs[ni].Hr[1]:8:3);
               Writeln(lst,fr,' FRAME THE ',ni,' POINT IN Y AXIS : ',frames[fr].seqs[ni].Vr[1]:8:3);
               Writeln(lst,fr,' FRAME THE ',ni,' POINT IN Z AXIS : ',frames[fr].seqs[ni].Zr[1]:8:3);
              end;
            Writeln(lst,' THE CENTRE OF MASS IN ',fr,' FRAME IN X AXIS : ',CM[fr].Xcg[1]:8:3);
            Writeln(lst,' THE CENTRE OF MASS IN ',fr,' FRAME IN Y AXIS : ',CM[fr].Ycg[1]:8:3);
            Writeln(lst,' THE CENTRE OF MASS IN ',fr,' FRAME IN Z AXIS : ',CM[fr].Zcg[1]:8:3);
          end;
 end;



Procedure SelectMIN_Max ;
  var
   min:integer;

  begin
   for i:=1 to k do
    begin
     min:=i;
     for j:=i+1 to k do
      if Vel^[j]<Vel^[min] then min:=j;
       Xcam:=Vel^[min];
       Vel^[min]:=Vel^[i];
       Vel^[i]:=Xcam;
    end;
  end;


Procedure Scalar_deter;
 Const
```

```
 polygon1: Array[1..3] of  pointType=
        ( (x:4; y:425), (x:14; y:446),(x:24; y:425));
polygon2: Array[1..3] of  pointType=
        ( (x:69; y:373), (x:49; y:382),(x:49; y:363));
 var
 sc1,sc2:real;
 begin
   repeat
   if not OpenGWindow(0,Xg(7),Yg(30),Xg(68),Yg(40),0,Red,1,Blue) then;
    GWriteXY(Xg(1),Yg(1),'                                            ',15,3);
    GWriteXY(Xg(1),Yg(2),'  PLEASE, SPECIFY  THE  TWO  AXES  FOR  THE  ANIMATION ',15,3);
    GWriteXY(Xg(1),Yg(3),'                                            ',15,3);
    GWriteXY(Xg(1),Yg(4),'  1: X, Y   2: X, Z   3: Y, Z   ENTER NUMBER  >        ',15,3);
    GWriteXY(Xg(1),Yg(5),'                                            ',15,3);
    GWriteXY(Xg(1),Yg(6),'  ENTER DELAY TIME BETWEEN THE FRAMES (in sec) >        ',15,3);
    GWriteXY(Xg(1),Yg(7),'                                            ',15,3);
    MoveTo(Xg(50),Yg(4));
    If not GInt(a,14,1) then;
    if not  (a in [1..3])  then
     begin
      CloseGWindow(0);
      Mes_error;
     end;
      until a in [1..3];
     MoveTo(Xg(50),Yg(6));
    If not GInt(dl,14,1) then;
      dl:=dl*1000;
      CloseGWindow(0);
     SetBkColor(9);
     setcolor(14);
    clear;
    SetlineStyle(solidln,0,thickwidth);
    SetFillstyle(1,4);
     Bar3d(0,360,75,455,8,true);
    SetFillstyle(1,1);
    setcolor(3);
    bar(9,369,19,426);
    FillPoly(3,polygon1);
    bar(10,368,55,378);
    FillPoly(3,polygon2);

     GWriteXY(Xg(30),Yg(10),'                  ',15,3);
     GWriteXY(Xg(30),Yg(11),'  PLEASE,  WAIT   ',15,3);
     GWriteXY(Xg(30),Yg(12),'                  ',15,3);
    case a of
    1:begin
    clear;
       GWriteXY(Xg(3),Yg(53),'   ',15,3);
       GWriteXY(Xg(3),Yg(54),' Y ',15,3);
       GWriteXY(Xg(3),Yg(55),'   ',15,3);
```

```
    GWriteXY(Xg(6),Yg(48),'   ',15,3);
    GWriteXY(Xg(6),Yg(49),' X ',15,3);
    GWriteXY(Xg(6),Yg(50),'   ',15,3);
 Getmem(Vel,(maxfr*SegNo+2)*6);
 k:=0;
 for fr:=1 to maxfr do
  for ni:=1 to SegNo do
   begin
    inc(k);
    Vel^[k]:=frames[fr].seqs[ni].Hr[1]; {3d value for X, Y or Z}
   end;
  SelectMin_Max;
     sc1:= ((abs(Vel^[1])+abs(Vel^[k]))/640)*(Abs(1.5));
     k:=0;
 for fr:=1 to maxfr do
  for ni:=1 to SegNo do
   begin
    inc(k);
    Vel^[k]:=frames[fr].seqs[ni].Vr[1]; {3d value for X, Y or Z}
   end;
   SelectMin_Max;
     sc2:= ((abs(Vel^[1])+abs(Vel^[k]))/480)*(Abs(1.5));
    Freemem(Vel,(maxfr*SegNo+2)*6);

 end;

  2:begin
  clear;
    GWriteXY(Xg(3),Yg(53),'   ',15,3);
    GWriteXY(Xg(3),Yg(54),' Z ',15,3);
    GWriteXY(Xg(3),Yg(55),'   ',15,3);
    GWriteXY(Xg(6),Yg(48),'   ',15,3);
    GWriteXY(Xg(6),Yg(49),' X ',15,3);
    GWriteXY(Xg(6),Yg(50),'   ',15,3);
     Getmem(Vel,(maxfr*SegNo+2)*6);
 k:=0;
 for fr:=1 to maxfr do
     for ni:=1 to SegNo do
    begin
    inc(k);
     Vel^[k]:=frames[fr].seqs[ni].Hr[1]; {3d value for X, Y or Z}
    end;
   SelectMin_Max;
     sc1:= ((abs(Vel^[1])+abs(Vel^[k]))/640)*(Abs(1.5));
     k:=0;
 for fr:=1 to maxfr do
  for ni:=1 to SegNo do
   begin
   inc(k);
    Vel^[k]:=frames[fr].seqs[ni].Zr[1];
```

```
    end;
    SelectMin_Max;
      sc2:= ((abs(Vel^[1])+abs(Vel^[k]))/480)*(Abs(1.5));
     Freemem(Vel,(maxfr*SegNo+2)*6);

    end;

  3:begin
  clear;
     GWriteXY(Xg(3),Yg(53),'    ',15,3);
     GWriteXY(Xg(3),Yg(54),' Y ',15,3);
     GWriteXY(Xg(3),Yg(55),'    ',15,3);
     GWriteXY(Xg(6),Yg(48),'    ',15,3);
     GWriteXY(Xg(6),Yg(49),' Z ',15,3);
     GWriteXY(Xg(6),Yg(50),'    ',15,3);
     Getmem(Vel,(maxfr*SegNo+2)*6);
 k:=0;
 for fr:=1  to  maxfr  do
   for ni:=1  to  SegNo  do
    begin
     inc(k);
     Vel^[k]:=frames[fr].seqs[ni].Zr[1];
    end;
   SelectMin_Max;
      sc1:= ((abs(Vel^[1])+abs(Vel^[k]))/640)*(Abs(1.5));
      k:=0;
  for fr:=1  to  maxfr  do
    for ni:=1  to  SegNo  do
     begin
      inc(k);
      Vel^[k]:=frames[fr].seqs[ni].Vr[1];
     end;
     SelectMin_Max;
       sc2:= ((abs(Vel^[1])+abs(Vel^[k]))/480)*(Abs(1.5));
      Freemem(Vel,(maxfr*SegNo+2)*6);
     end;

    end;



      If sc1>sc2  then
       ds:=sc1

      else
       ds:=sc2;



  end;
```

```
Procedure draw_fig;
begin
        if ni=2 then
         begin
          SetColor(14);
          Rectangle(frames[fr].seqs[ni-1].H-1,frames[fr].seqs[ni-1].V-1,
          frames[fr].seqs[ni-1].H+1,frames[fr].seqs[ni-1].V+1);
         end;
          SetColor(4);
          linkpoints;
          SetColor(14);
          Rectangle(frames[fr].seqs[ni].H-1,frames[fr].seqs[ni].V-1,
          frames[fr].seqs[ni].H+1,frames[fr].seqs[ni].V+1);

end;




Procedure Animation;
 begin
 vid:=1;
 stick_fig;
  Scalar_deter;
  add;
    case a of
    1:begin
       For fr:=1  to  maxfr do
        for ni:=1  to  SegNo  do
         begin
          frames[fr].seqs[ni].H:=-Round(frames[fr].seqs[ni].Hr[1]/ds);
          frames[fr].seqs[ni].V:=-Round(frames[fr].seqs[ni].Vr[1]/ds);
          clear;
         end;
      end;

    2:begin
       For fr:=1  to  maxfr do
       for ni:=1  to  SegNo  do
        begin
         frames[fr].seqs[ni].H:=-Round(frames[fr].seqs[ni].Hr[1]/ds);
         frames[fr].seqs[ni].V:=-Round(frames[fr].seqs[ni].Zr[1]/ds);
        end;
     end;

    3:begin
       For fr:=1  to  maxfr do
       for ni:=1  to  SegNo  do
```

```
      begin
       frames[fr].seqs[ni].H:=-Round(frames[fr].seqs[ni].Zr[1]/ds);
       frames[fr].seqs[ni].V:=-Round(frames[fr].seqs[ni].Vr[1]/ds);
      end;
    end;

end;
GWriteXY(Xg(30),Yg(10),'                ',0,0);
GWriteXY(Xg(30),Yg(11),'                ',0,0);
GWriteXY(Xg(30),Yg(12),'                ',0,0);

clear;

  Case a of
   3:
  SetViewport(GetmaxX div 2 - Xg(6),GetMaxY div 2 + Yg(25),
   GetmaxX div 2 + Xg(30),GetMaxY div 2 + Yg(26),Clipoff);
   2:
  SetViewport(GetmaxX div 2 + Xg(3),GetMaxY div 2 + Yg(0),
   GetmaxX div 2 + Xg(30),GetMaxY div 2 + Yg(10),Clipoff);
   1:
  SetViewport(GetmaxX div 2 - Xg(2),GetMaxY div 2 + Yg(19),
   GetmaxX div 2 + Xg(30),GetMaxY div 2 + Yg(26),Clipoff);
  end;
  for fr:=1 to maxfr do
   begin
GWriteXY(Xg(20),Yg(2),' FRAME:'+Is(fr)  ,14,9);
    if a=3  then
      begin
       for ni:=segNo downto 2  do
       Draw_fig;
      end
    else
      begin
       for ni:=2 to SegNo  do
       Draw_fig;
      end;
   Delay(dl);
   if (ii=2) and (fr<maxfr) then
    begin
        for ni:=2 to SegNo  do
      begin
        if ni=2  then
         begin
          SetColor(0);
          Rectangle(frames[fr].seqs[ni-1].H-1,frames[fr].seqs[ni-1].V-1,
          frames[fr].seqs[ni-1].H+1,frames[fr].seqs[ni-1].V+1);
         end;
          SetColor(0);
          linkpoints;
```

```
            SetColor(0);
            Rectangle(frames[fr].seqs[ni].H-1,frames[fr].seqs[ni].V-1,
            frames[fr].seqs[ni].H+1,frames[fr].seqs[ni].V+1);
        end;
       end;
      end;
   mes2;
  setBkColor(0);
 end;



Begin

     if RegisterBgiDriver(@EgaVgaDriver)<0 then halt(1);
     gd:=detect;
     initgraph(gd,gm,'');

          dem;
          Repeat
          GWriteXY(Xg(15),Yg(1),'           ',15,1);
          GWriteXY(Xg(15),Yg(2),' Process   ',15,1);
          GWriteXY(Xg(15),Yg(3),' -         ',15,1);

           Dis2;
           Mes32;
           if ch<>esc then
            begin
            CloseGWindow(0);
            case ch of

         'D','d':
         begin
             CloseGWindow(0); {menu window}
             title;
             GWriteXY(Xg(19),Yg(3),'     D A T A    S M O O T H I N G       ',15,5);
               Repeat
               sel_file;
               if not  (pref in [1..2])  then
               Mes_error;
               until pref in [1..2];
        case  pref of
         1:
           begin
            Assign(TF,'c:\file1.txt');
           end;

        2:begin
          prev_file;
         end;
```

```
end;
  digital_filter2;

  Ch:='z';
  end;


    'A', 'a':
    begin
    CloseGWindow(0);
    s:=0;
    title;

    GWriteXY(Xg(22),Yg(3),'       A N I M A T I O N     ',15, 5);

    if s=3  then
     begin
      anim_proc;
      GWriteXY(Xg(22),Yg(3),'       A N I M A T I O N     ',15, 5);
     end;
    if  sa=1  then
     begin
     Assign(TF,'c:\smootry1.txt');
     display_file;
     end

    else
      begin
       if  pref=2  then
         begin
          Assign(TF,FN);
          display_file;
         end
      else
        begin
         Assign(TF,'c:\smootry1.txt');
         display_file;
        end;
   end;{if<>}


    if er=0 then
    Animation;
    ClearDevice;
    Ch:='z';
    end;



    'S','s': begin
```

```
CloseGWindow(0);

Assign(TF,'c:\file1.txt');
    display_file;
s:=1;
d:=15;
di:=6;
save (d,di);
end;


'P','p': begin
 CloseGWindow(0); {menu window}
  setBkColor(4);
  GWriteXY(Xg(25),Yg(10),'                           ',15,3);
  GWriteXY(Xg(25),Yg(11),'  1:  CURRENT DATA       ',15,3);
  GWriteXY(Xg(25),Yg(12),'                           ',15,3);
  GWriteXY(Xg(25),Yg(13),'  2:  PREVIOUS DATA      ',15,3);
  GWriteXY(Xg(25),Yg(14),'                           ',15,3);
  GWriteXY(Xg(25),Yg(15),'  ENTER NUMBER >         ',1,11);
  GWriteXY(Xg(25),Yg(16),'                           ',1,11);
    Mes1;
        if ch<>esc then
         begin
          MoveTo(Xg(43),Yg(15));
          if not GInt(i,4,14) then;
          case i of
   1:begin
      Assign(TF,'c:\file1.txt');
       display_file;
       print_file;
    end;

  2: begin

        Prev_file;
          display_file;
          if er=0 then
          print_file;
     end;


    end;
 end
else
  CloseGWindow(0);

   ClearDevice;
  setBkColor(0);
 Ch:='z';
```

```
        end;


     end;

    setBkColor(0);
    ClearDevice;
    dem;
   end

  Else
  CloseGWindow(0);
  setBkColor(0);
    GWriteXY(Xg(15),Yg(1),'              ',15,3);
    GWriteXY(Xg(15),Yg(2),'  Process     ',15,3);
    GWriteXY(Xg(15),Yg(3),'  -           ',15,3);

  until ch=esc;
   s:=0;
   Closegraph;

 End.
```

```
{$M 16000,8400,64000}
program Grkin;
 {$N+}

uses
 Crt,Dos,graph,mouse,gcrt2,gwin,digmodel;

  procedure egavgadriver;external;{$L egavga.obj}

 Type
  typver=Array[1..500] of Real;
  angtype=Array[1..maxframes] of Real;


  Var
  path:pathstr;
  theta:^angtype;
  t1,t2,t3,t4,sa,d,di:ShortInt;
  n,i,ii,dl:integer;
  Vel:^typver;
  taf:text;
  dt:real;


  Procedure  Draw_Outln;
   Const
    polygon1: Array[1..5] of  pointType=
         ( (x:440; y:110), (x:455; y:120),(x:455; y:210),
         (x:188; y:210),(x:168; y:200));
    polygon2: Array[1..4] of  pointType=
         ( (x:170; y:110), (x:440; y:110),(x:440; y:200),
         (x:170; y:200));

   begin
    clear;
    setBkColor(9);
    setcolor(1);
    SetlineStyle(1,0,1);
    SetFillstyle(9,7);
    FillPoly(5,polygon1);
    setcolor(14);
    SetlineStyle(solidln,0,thickwidth);
    SetFillstyle(1,5);
    FillPoly(4,polygon2);

   end;



  Procedure title;
```

```
 Const
 polygon1: Array[1..5] of pointType=
      ( (x:540; y:10), (x:555; y:20),(x:555; y:65),
      (x:90; y:65),(x:68; y:51));
 polygon2: Array[1..4] of pointType=
      ( (x:70; y:10), (x:540; y:10),(x:540; y:50),
      (x:70; y:50));

begin
 clear;
 setBkColor(9);
 setcolor(1);
 SetlineStyle(1,0,1);
 SetFillstyle(9,7);
 FillPoly(5,polygon1);
 setcolor(14);
 SetlineStyle(solidln,0,thickwidth);
 SetFillstyle(1,5);
 FillPoly(4,polygon2);
end;



Procedure anim_proc;
begin
Draw_Outln;
        GWriteXY(Xg(25),Yg(16),'                          ',15,3);
        GWriteXY(Xg(25),Yg(17),'  1:  SMOOTHING DATA     ',15,3);
        GWriteXY(Xg(25),Yg(18),'                          ',15,3);
        GWriteXY(Xg(25),Yg(19),'  2:  UNSMOOTHING DATA  ',15,3);
        GWriteXY(Xg(25),Yg(20),'                          ',15,3);
        GWriteXY(Xg(25),Yg(21),'  ENTER NUMBER >        ',1,11);
        GWriteXY(Xg(25),Yg(22),'                          ',1,11);
         Repeat
         MoveTo(Xg(44),Yg(21));
          if not GInt(i,14,4) then;
          sa:=i;
          if not  (sa in [1..2])  then
          begin
            Mes_error;
            GWriteXY(Xg(44),Yg(21),'     ',1,11);
            GWriteXY(Xg(44),Yg(22),'     ',1,11);
          end;
            until sa in [1..2];
     ClearDevice;
    title;


 end;
```

```
Procedure  dis3;
 begin
  if not OpenGWindow(0,Xg(25),Yg(5),Xg(55),Yg(16),0,14,1,1) then;
              GWriteXY(Xg(3),Yg(1),'                          ',14,4);
              GWriteXY(Xg(3),Yg(2),'   HELP...                ',14,4);
              GWriteXY(Xg(3),Yg(3),'   -                      ',14,4);
              GWriteXY(Xg(3),Yg(4),'   DISPAY  THE FILE       ',14,4);
              GWriteXY(Xg(3),Yg(5),'   -                      ',14,4);
              GWriteXY(Xg(3),Yg(6),'   CHANGE DIRECTORY       ',14,4);
              GWriteXY(Xg(3),Yg(7),'   -                      ',14,4);
              GWriteXY(Xg(3),Yg(8),'                          ',14,4);
 end;



 Procedure directory ;
  begin
  CloseGWindow(0);
  CloseGraph;
              SwapVectors;

              Chdir(path);
              Exec('\COMMAND.COM','/path');
              SwapVectors;
              Chdir('c:\');
               gd:=detect;
               initgraph(gd,gm,'');
 end;




 Procedure sel_fr;
 begin
  Repeat
         MoveTo(Xg(64),Yg(2*i+7+8));
         if not GInt(a,14,5) then;
         if not  (a in [1..3])  then
            begin
               Mes_error;
               GWriteXY(Xg(64),Yg(2*i+7+8),'    ',1,11);
            end;
         until  a  in [1..3];
        if a in [1..2] then
         begin
         if not OpenGWindow(0,Xg(15),(GetmaxY div 2)-Yg(14),Xg(68),(GetmaxY div 2)-Yg(4),0,Red,1,Blue)
then;
               GWriteXY(Xg(2),Yg(2),'                                         ',15,3);
```

```
        GWriteXY(Xg(2),Yg(3),'                                         ',15,3);
        GWriteXY(Xg(2),Yg(3),'   THE NUMBER OF FRAMES ARE : ' + Is(maxfr),15,3);
        GWriteXY(Xg(2),Yg(4),'                                         ',15,3);
        if a=1 then
        GWriteXY(Xg(2),Yg(5),'   ENTER THE NUMBER OF SPECIFIC FRAME :   ',15,3);
        if a=2 then
        GWriteXY(Xg(2),Yg(5),'   FROM THE :       FRAME  TO :            ',15,3);
        GWriteXY(Xg(2),Yg(6),'                                         ',15,3);

      if a=1 then
         Repeat
         MoveTo(Xg(47),Yg(5));
          if not GInt(fr,14,1) then;
          if not  (fr in [1..maxfr])  then
        begin
        Mes_error;
        GWriteXY(Xg(47),Yg(5),'   ',15,3);
        GWriteXY(Xg(47),Yg(6),'   ',15,3);
      end;
      d:=fr;
    until  fr  in [1..maxfr]
     else
      begin
      Repeat
       MoveTo(Xg(18),Yg(5));
           if not GInt(j,14,1) then;
            d:=j;
           if not (d in [1..maxfr-5])  then
         begin
         Mes_error;
         GWriteXY(Xg(18),Yg(5),'   ',15,3);
         GWriteXY(Xg(18),Yg(6),'   ',15,3);
       end;
    until  d  in [1..maxfr-5];
       Repeat
       MoveTo(Xg(37),Yg(5));
           if not GInt(j,14,1) then;
            di:=j;
           if not  (di in [1..maxfr])  then
         begin
         Mes_error;
         GWriteXY(Xg(37),Yg(5),'   ',15,3);
         GWriteXY(Xg(37),Yg(6),'   ',15,3);
       end;
    until  di  in [1..maxfr];
    end;
  CloseGwindow(0);
    end;

end;
```

```
Procedure  dem_win;
 begin
  title2;
   for i:=1 to segNo  do
       GWriteXY(Xg(18),Yg(2*i-1+8), Is(i)+': '+model.Name[i] ,15,3);
       GWriteXY(Xg(18),Yg(2*i+1+8), Is(i+1)+':CENTRE OF MASS ' ,15,3);
       GWriteXY(Xg(18),Yg(2*i+3+8),' ENTER NUMBER >          ',1,11);
       GWriteXY(Xg(18),Yg(2*i+5+8),' 1: X,  2: Y,  3: Z,  4: X,Y,Z  >     ',1,11);
       GWriteXY(Xg(18),Yg(2*i+7+8),' 1: SPECIFIC FRAME, 2: FROM.. TO..  , 3: ALL >      ',1,11);
         Repeat
         MoveTo(Xg(34),Yg(2*i+3+8));
         if not GInt(ni,14,5) then;
           if not  (ni in [1..segNo+1])  then
           begin
              Mes_error;
              GWriteXY(Xg(34),Yg(2*i+3+8),'    ',1,11);
           end;
         until  ni in [1..SegNo+1];
         Repeat
         MoveTo(Xg(53),Yg(2*i+5+8));
         if not GInt(k,14,5) then;
         if not  (k in [1..4])  then
           begin
              Mes_error;
              GWriteXY(Xg(53),Yg(2*i+5+8),'    ',1,11);
           end;
         until  k in [1..4];
       sel_fr;

  end;



 Procedure velocity;
  Var
  Val:Array [1..3] of  real;


  Procedure  vel_deter;
    begin

     dt:=1/dt;

    If fr<=2 then
    case k of
     1: Vel^[fr]:=(-frames[fr+2].seqs[ni].Hr[1] + 4*frames[fr+1].seqs[ni].Hr[1] -
3*frames[fr].seqs[ni].Hr[1])/(2*dt);
     2: Vel^[fr]:=(-frames[fr+2].seqs[ni].Vr[1] + 4*frames[fr+1].seqs[ni].Vr[1] -
3*frames[fr].seqs[ni].Vr[1])/(2*dt);
```

```
    3: Vel^[fr]:=(-frames[fr+2].seqs[ni].Zr[1] + 4*frames[fr+1].seqs[ni].Zr[1] -
3*frames[fr].seqs[ni].Zr[1])/(2*dt);
   end;

  if fr>=maxfr-2 then
   case k of
    1: Vel^[fr]:=(3*frames[fr].seqs[ni].Hr[1] - 4*frames[fr-1].seqs[ni].Hr[1] + frames[fr-2].seqs[ni].Hr[1])/(2*dt);
    2: Vel^[fr]:=(3*frames[fr].seqs[ni].Vr[1] - 4*frames[fr-1].seqs[ni].Vr[1] + frames[fr-2].seqs[ni].Vr[1])/(2*dt);
    3: Vel^[fr]:=(3*frames[fr].seqs[ni].Zr[1] - 4*frames[fr-1].seqs[ni].Zr[1] + frames[fr-2].seqs[ni].Zr[1])/(2*dt);
   end

  else
   case k of

    1: Vel^[fr]:=(-frames[fr+2].seqs[ni].Hr[1] + 8*frames[fr+1].seqs[ni].Hr[1]
                 - 8*frames[fr-1].seqs[ni].Hr[1] + frames[fr-2].seqs[ni].Hr[1])/(12*dt);
    2: Vel^[fr]:=(-frames[fr+2].seqs[ni].Vr[1] + 8*frames[fr+1].seqs[ni].Vr[1]
                 - 8*frames[fr-1].seqs[ni].Vr[1] + frames[fr-2].seqs[ni].Vr[1])/(12*dt);
    3: Vel^[fr]:=(-frames[fr+2].seqs[ni].Zr[1] + 8*frames[fr+1].seqs[ni].Zr[1]
                 - 8*frames[fr-1].seqs[ni].Zr[1] + frames[fr-2].seqs[ni].Zr[1])/(12*dt);
   end;

end;


 Procedure vel_deter2;
   begin
    dt:=1/dt;

   If fr<=2 then
    begin
     Val[1]:=(-frames[fr+2].seqs[ni].Hr[1] + 4*frames[fr+1].seqs[ni].Hr[1] - 3*frames[fr].seqs[ni].Hr[1])/(2*dt);
     Val[2]:=(-frames[fr+2].seqs[ni].Vr[1] + 4*frames[fr+1].seqs[ni].Vr[1] - 3*frames[fr].seqs[ni].Vr[1])/(2*dt);
     Val[3]:=(-frames[fr+2].seqs[ni].Zr[1] + 4*frames[fr+1].seqs[ni].Zr[1] - 3*frames[fr].seqs[ni].Zr[1])/(2*dt);
   end;

  if fr>=maxfr-2 then
    begin
    Val[1]:=(3*frames[fr].seqs[ni].Hr[1] - 4*frames[fr-1].seqs[ni].Hr[1] + frames[fr-2].seqs[ni].Hr[1])/(2*dt);
    Val[2]:=(3*frames[fr].seqs[ni].Vr[1] - 4*frames[fr-1].seqs[ni].Vr[1] + frames[fr-2].seqs[ni].Vr[1])/(2*dt);
    Val[3]:=(3*frames[fr].seqs[ni].Zr[1] - 4*frames[fr-1].seqs[ni].Zr[1] + frames[fr-2].seqs[ni].Zr[1])/(2*dt);
   end

  else
   begin
    Val[1]:=(-frames[fr+2].seqs[ni].Hr[1] + 8*frames[fr+1].seqs[ni].Hr[1]
                 - 8*frames[fr-1].seqs[ni].Hr[1] + frames[fr-2].seqs[ni].Hr[1])/(12*dt);
    Val[2]:=(-frames[fr+2].seqs[ni].Vr[1] + 8*frames[fr+1].seqs[ni].Vr[1]
                 - 8*frames[fr-1].seqs[ni].Vr[1] + frames[fr-2].seqs[ni].Vr[1])/(12*dt);
    Val[3]:=(-frames[fr+2].seqs[ni].Zr[1] + 8*frames[fr+1].seqs[ni].Zr[1]
```

```
                    - 8*frames[fr-1].seqs[ni].Zr[1] + frames[fr-2].seqs[ni].Zr[1])/(12*dt);
   end;

   Vel^[fr]:= SQRT(SQR(Val[1]) + SQR(Val[2]) + SQR(Val[3]));
 end;

 Procedure ce_gr_vel;
  begin
    case k of
    1: Vel^[fr]:=(3*CM[fr].Xcg[1] - 4*CM[fr-1].Xcg[1] + CM[fr-2].Xcg[1])/(2*dt);
    2: Vel^[fr]:=(3*CM[fr].Ycg[1] - 4*CM[fr-1].Ycg[1] + CM[fr-2].Ycg[1])/(2*dt);
    3: Vel^[fr]:=(3*CM[fr].Zcg[1] - 4*CM[fr-1].Zcg[1] + CM[fr-2].Zcg[1])/(2*dt);
    end;

  end;

Procedure ce_gr_vel2;
 begin
    Val[1]:=(3*CM[fr].Xcg[1] - 4*CM[fr-1].Xcg[1] + CM[fr-2].Xcg[1])/(2*dt);
    Val[2]:=(3*CM[fr].Ycg[1] - 4*CM[fr-1].Ycg[1] + CM[fr-2].Ycg[1])/(2*dt);
    Val[3]:=(3*CM[fr].Zcg[1] - 4*CM[fr-1].Zcg[1] + CM[fr-2].Zcg[1])/(2*dt);
    Vel^[fr]:= SQRT(SQR(Val[1]) + SQR(Val[2]) + SQR(Val[3]));
 end;



  begin
   Getmem(Vel,(maxfr*SegNo+2)*6);
   dem_win;
    GWriteXY(Xg(3),Yg(2),' THE VELOCITY IN FRAME  : ',9,1);
   if ni<segNo+1 then
   begin
    if k<4 then
    begin
      if a=2 then
       for fr:=d to  di do
       begin
       vel_deter;
       GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
       end;
       if a=3 then
          for fr:=1 to maxfr do
            begin
             vel_deter;
             GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
            end;
      if a=1 then
        begin
         vel_deter;
```

```
      GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
     end;
 end

 else
   begin
     if a=2 then
     for fr:=d to  di do
      begin
       vel_deter2;
       GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
      end;
     if a=3 then
      for fr:=1 to maxfr do
       begin
        vel_deter2;
        GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
       end;
     if a=1 then
      begin
      vel_deter2;
      GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
      end;
  end;
end;

if ni=segNo+1 then
 begin
 if k<4 then
 begin
 if a=2 then
     for fr:=d to  di do
     begin
      ce_gr_vel;
      GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
     end;
     if a=3 then
      for fr:=1 to maxfr do
       begin
        ce_gr_vel;
        GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
       end;
      if a=1 then
     begin
      ce_gr_vel;
      GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
     end;
  end;

 if k=4 then
```

```
    begin
    if a=2 then
      for fr:=d to  di do
       begin
       ce_gr_vel2;
       GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
       end;
      if a=3 then
       for fr:=1 to maxfr do
        begin
         ce_gr_vel2;
         GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
        end;
      if a=1 then
       begin
        ce_gr_vel2;
        GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
       end;
   end;
  end;



  Freemem(Vel,(maxfr*SegNo+2)*6);
  mes2;
end;



 Procedure Acceler;
  Var
  Val:Array [1..3] of  real;


  Procedure  accel_deter;
   begin

   dt:=1/dt;

   If fr<=2 then
   case k of
    1: Vel^[fr]:=(-frames[fr+3].seqs[ni].Hr[1] + 4*frames[fr+2].seqs[ni].Hr[1]
              - 5*frames[fr+1].seqs[ni].Hr[1] + 2*frames[fr+1].seqs[ni].Hr[1])/SQR(dt);
    2: Vel^[fr]:=(-frames[fr+3].seqs[ni].Vr[1] + 4*frames[fr+2].seqs[ni].Vr[1]
              - 5*frames[fr+1].seqs[ni].Vr[1]+ 2*frames[fr+1].seqs[ni].Vr[1])/SQR(dt);
    3: Vel^[fr]:=(-frames[fr+3].seqs[ni].Zr[1] + 4*frames[fr+2].seqs[ni].Zr[1]
              - 5*frames[fr+1].seqs[ni].Zr[1] + 2*frames[fr+1].seqs[ni].Zr[1])/SQR(dt);
   end;
```

```
    if fr>=maxfr-2 then
    case k of
     1: Vel^[fr]:=(2*frames[fr].seqs[ni].Hr[1] - 5*frames[fr-1].seqs[ni].Hr[1]
             + 4*frames[fr-2].seqs[ni].Hr[1] - frames[fr-3].seqs[ni].Hr[1])/SQR(dt);
     2: Vel^[fr]:=(2*frames[fr].seqs[ni].Vr[1] - 5*frames[fr-1].seqs[ni].Vr[1]
             + 4*frames[fr-2].seqs[ni].Vr[1] - frames[fr-3].seqs[ni].Vr[1])/SQR(dt);
     3: Vel^[fr]:=(2*frames[fr].seqs[ni].Zr[1] - 5*frames[fr-1].seqs[ni].Zr[1]
             + 4*frames[fr-2].seqs[ni].Zr[1] - frames[fr-3].seqs[ni].Zr[1])/SQR(dt);
    end

   else
   begin
    case k of
     1: Vel^[fr]:=(-frames[fr+2].seqs[ni].Hr[1] + 16*frames[fr+1].seqs[ni].Hr[1]
              - 30*frames[fr].seqs[ni].Hr[1] + 16*frames[fr-1].seqs[ni].Hr[1]
              - frames[fr-2].seqs[ni].Hr[1])/(12*SQR(dt));
     2: Vel^[fr]:=(-frames[fr+2].seqs[ni].Vr[1] + 16*frames[fr+1].seqs[ni].Vr[1]
              - 30*frames[fr].seqs[ni].Vr[1] + 16*frames[fr-1].seqs[ni].Vr[1]
              - frames[fr-2].seqs[ni].Vr[1])/(12*SQR(dt));
     3: Vel^[fr]:=(-frames[fr+2].seqs[ni].Zr[1] + 16*frames[fr+1].seqs[ni].Zr[1]
              - 30*frames[fr].seqs[ni].Zr[1] + 16*frames[fr-1].seqs[ni].Zr[1]
              - frames[fr-2].seqs[ni].Zr[1])/(12*SQR(dt));
    end;
    mes2;
    end;
end;


 Procedure  accel_deter2;
    begin
     dt:=1/dt;

     If fr<=2 then
      begin
      Val[1]:=(-frames[fr+3].seqs[ni].Hr[1] + 4*frames[fr+2].seqs[ni].Hr[1]
             - 5*frames[fr+1].seqs[ni].Hr[1] + 2*frames[fr+1].seqs[ni].Hr[1])/SQR(dt);
      Val[2]:=(-frames[fr+3].seqs[ni].Vr[1] + 4*frames[fr+2].seqs[ni].Vr[1]
             - 5*frames[fr+1].seqs[ni].Vr[1]+ 2*frames[fr+1].seqs[ni].Vr[1])/SQR(dt);
      Val[3]:=(-frames[fr+3].seqs[ni].Zr[1] + 4*frames[fr+2].seqs[ni].Zr[1]
              - 5*frames[fr+1].seqs[ni].Zr[1] + 2*frames[fr+1].seqs[ni].Zr[1])/SQR(dt);
     end;

    if fr>=maxfr-2 then
      begin
     Val[1]:=(2*frames[fr].seqs[ni].Hr[1] - 5*frames[fr-1].seqs[ni].Hr[1]
             + 4*frames[fr-2].seqs[ni].Hr[1] - frames[fr-3].seqs[ni].Hr[1])/SQR(dt);
     Val[2]:=(2*frames[fr].seqs[ni].Vr[1] - 5*frames[fr-1].seqs[ni].Vr[1]
             + 4*frames[fr-2].seqs[ni].Vr[1] - frames[fr-3].seqs[ni].Vr[1])/SQR(dt);
     Val[3]:=(2*frames[fr].seqs[ni].Zr[1] - 5*frames[fr-1].seqs[ni].Zr[1]
             + 4*frames[fr-2].seqs[ni].Zr[1] - frames[fr-3].seqs[ni].Zr[1])/SQR(dt);
```

```
    end

   else
    begin


    Val[1]:=(-frames[fr+2].seqs[ni].Hr[1] + 16*frames[fr+1].seqs[ni].Hr[1]
                - 30*frames[fr].seqs[ni].Hr[1] + 16*frames[fr-1].seqs[ni].Hr[1]
                - frames[fr-2].seqs[ni].Hr[1])/(12*SQR(dt));
    Val[2]:=(-frames[fr+2].seqs[ni].Vr[1] + 16*frames[fr+1].seqs[ni].Vr[1]
                - 30*frames[fr].seqs[ni].Vr[1] + 16*frames[fr-1].seqs[ni].Vr[1]
                - frames[fr-2].seqs[ni].Vr[1])/(12*SQR(dt));
    Val[3]:=(-frames[fr+2].seqs[ni].Zr[1] + 16*frames[fr+1].seqs[ni].Zr[1]
                - 30*frames[fr].seqs[ni].Zr[1] + 16*frames[fr-1].seqs[ni].Zr[1]
                - frames[fr-2].seqs[ni].Zr[1])/(12*SQR(dt));
    end;


    Vel^[fr]:= SQRT(SQR(Val[1]) + SQR(Val[2]) + SQR(Val[3]));
 end;



 Procedure  ce_gr_acc;
  begin
  case k of
  1: Vel^[fr]:=(2*CM[fr].Xcg[1] - 5*CM[fr-1].Xcg[1] + 4*CM[fr-2].Xcg[1]
            - CM[fr-3].Xcg[1])/SQR(dt);
  2: Vel^[fr]:=(2*CM[fr].Ycg[1] - 5*CM[fr-1].Ycg[1] + 4*CM[fr-2].Ycg[1]
            - CM[fr-3].Ycg[1])/SQR(dt);
  3: Vel^[fr]:=(2*CM[fr].Zcg[1] - 5*CM[fr-1].Zcg[1] + 4*CM[fr-2].Zcg[1]
            - CM[fr-3].Zcg[1])/SQR(dt);
  end;
 end;


 Procedure  ce_gr_acc2;
  begin
  Val[1]:=(2*CM[fr].Xcg[1] - 5*CM[fr-1].Xcg[1] + 4*CM[fr-2].Xcg[1]
            - CM[fr-3].Xcg[1])/SQR(dt);
  Val[2]:=(2*CM[fr].Ycg[1] - 5*CM[fr-1].Ycg[1] + 4*CM[fr-2].Ycg[1]
            - CM[fr-3].Ycg[1])/SQR(dt);
  Val[3]:=(2*CM[fr].Zcg[1] - 5*CM[fr-1].Zcg[1] + 4*CM[fr-2].Zcg[1]
            - CM[fr-3].Zcg[1])/SQR(dt);
   Vel^[fr]:= SQRT(SQR(Val[1]) + SQR(Val[2]) + SQR(Val[3]));

 end;

   begin
    Getmem(Vel,(maxfr*SegNo+2)*6);
```

```
dem_win;
 GWriteXY(Xg(3),Yg(2),' THE ACCELARATION IN FRAME  : ',9,1);
if ni<segNo+1 then
begin
 if k<4 then
 begin
   if a=2 then
    for fr:=d to  di do
    begin
     accel_deter;
     GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
    end;
    if a=3 then
       for fr:=1 to maxfr do
         begin
          accel_deter;
          GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
         end;
   if a=1 then
     begin
      accel_deter;
      GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
     end;
end

else
  begin
    if a=2 then
    for fr:=d to  di do
     begin
      accel_deter2;
      GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
     end;
    if a=3 then
     for fr:=1 to maxfr do
      begin
       accel_deter2;
       GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
      end;
    if a=1 then
     begin
     accel_deter2;
     GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
     end;
 end;
end;

if ni=segNo+1 then
 begin
 if k<4 then
```

```
begin
if a=2 then
   for fr:=d to  di do
   begin
    ce_gr_acc;
    GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
   end;
   if a=3 then
    for fr:=1 to maxfr do
     begin
      ce_gr_acc;
      GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
     end;
    if a=1 then
   begin
    ce_gr_acc;
    GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
   end;
 end;

if k=4 then
  begin
  if a=2 then
    for fr:=d to  di do
     begin
     ce_gr_acc2;
     GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
     end;
    if a=3 then
     for fr:=1 to maxfr do
      begin
       ce_gr_acc2;
       GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
      end;
    if a=1 then
     begin
      ce_gr_acc2;
      GWriteXY(Xg(3),Yg(fr+3),Is(fr)+'  '+Rs(VEL^[fr]/1000,8,3),15,3);
     end;
  end;
 end;

  Freemem(Vel,(maxfr*SegNo+2)*6);
  mes2;
end;
```

```
procedure Select_kinem;
 begin

        if s=3  then
           begin
             anim_proc;
             GWriteXY(Xg(19),Yg(3),' K I N E M A T I C    A N A L Y S I S  ',15,5);


           if  sa=1  then
             begin
               Assign(TF,'c:\smootry1.txt');
               display_file;
             end;
           end {if si}

          else
           begin
            Assign(TF,'c:\file1.txt');
            display_file;
           end
end;




Procedure Angl_velocity;


  Procedure  vel_ang_deter;
   begin
    If fr<=2 then
     Vel^[fr]:=(-theta^[fr+2] + 4*theta^[fr+1] - 3*theta^[fr])/(2*dt);

    if fr>=maxfr-2 then
     Vel^[fr]:=(3*theta^[fr] - 4*theta^[fr-1] + theta^[fr-2])/(2*dt)

    else
     Vel^[fr]:=(-theta^[fr+2] + 8*theta^[fr+1] - 8*theta^[fr-1] + theta^[fr-2])/(12*dt);
  end;


 begin
   dt:=1/dt;
   Getmem(Vel,(maxfr*SegNo+2)*6);
    for fr:=1 to maxfr do
     vel_ang_deter;
     ClearDevice;
     j:=1;
```

```
   if a=2 then
    for fr:=d to  di do
    begin
    GWriteXY(Xg(10),Yg(j+2), 'ANGULAR VELOCITY :  '+Rs(Vel^[fr],10,3)+' m/sec ' ,14,1);
    inc(j);
    end;

    if a=3 then
       for fr:=1 to maxfr do
       begin
    GWriteXY(Xg(10),Yg(j+2), 'ANGULAR VELOCITY :  '+Rs(Vel^[fr],10,3)+' m/sec ' ,14,1);
    inc(j);
    end

   else
    GWriteXY(Xg(10),Yg(j+2), 'ANGULAR VELOCITY :  '+Rs(Vel^[d],10,3)+' m/sec ' ,14,1);

  Assign(taf,'c:\angvel.txt');
   rewrite(taf);
   writeln(taf,maxfr);
   for fr:=1 to maxfr do
   writeln(taf,  Vel^[fr]:8:3);
   close(taf);
  Freemem(Vel,(maxfr*SegNo+2)*6);
  mes2;
end;




 Procedure  angle;
  Var
  t1,t2,t3,t4:ShortInt;
  begin
          title2;
       for i:=1 to segNo  do
       GWriteXY(Xg(18),Yg(2*i-1+8), Is(i)+': '+model.Name[i] ,15,3);
       GWriteXY(Xg(18),Yg(2*i+2+8),'           POINTS  :  1   2   3   4  ',14,5);
       GWriteXY(Xg(18),Yg(2*i+3+8),' ENTER FOUR NUMBERS >                  ',1,11);
       GWriteXY(Xg(18),Yg(2*i+7+8),' 1: SPECIFIC FRAME, 2: FROM.. TO..  , 3: ALL >    ',1,11);
       MoveTo(Xg(42),Yg(2*i+3+8));
       if not GInt(ni,14,5) then;
       t1:=ni;
       MoveTo(Xg(47),Yg(2*i+3+8));
       if not GInt(ni,14,5) then;
       t2:=ni;
       MoveTo(Xg(52),Yg(2*i+3+8));
       if not GInt(ni,14,5) then;
       t3:=ni;
```

```
            MoveTo(Xg(57),Yg(2*i+3+8));
            if not GInt(ni,14,5) then;
            t4:=ni;
            sel_fr;
            ClearDevice;
  for fr:=1 to maxfr do
  begin

 ds:= ((frames[fr].seqs[t2].Hr[1]-frames[fr].seqs[t1].Hr[1])
          *(frames[fr].seqs[t4].Hr[1]-frames[fr].seqs[t3].Hr[1])+
          (frames[fr].seqs[t2].Vr[1]-frames[fr].seqs[t1].Vr[1])
          *(frames[fr].seqs[t4].Vr[1]-frames[fr].seqs[t3].Vr[1])+
          (frames[fr].seqs[t2].Zr[1]-frames[fr].seqs[t1].Zr[1])
          *(frames[fr].seqs[t4].Zr[1]-frames[fr].seqs[t3].Zr[1]))/
           (SQRT((SQR(frames[fr].seqs[t2].Hr[1]-frames[fr].seqs[t1].Hr[1])
            +SQR(frames[fr].seqs[t2].Vr[1]-frames[fr].seqs[t1].Vr[1])
            +SQR(frames[fr].seqs[t2].Zr[1]-frames[fr].seqs[t1].Zr[1]))*
           (SQR(frames[fr].seqs[t4].Hr[1]-frames[fr].seqs[t3].Hr[1])
            +SQR(frames[fr].seqs[t4].Vr[1]-frames[fr].seqs[t3].Vr[1])
            +SQR(frames[fr].seqs[t4].Zr[1]-frames[fr].seqs[t3].Zr[1]))));


 theta^[fr]:=ds;
 end;

 Assign(taf,'c:\angle');
   rewrite(taf);
   writeln(taf,maxfr);
   for fr:=1 to maxfr do
   writeln(taf, theta^[fr]:8:3);
   close(taf);
Exec('c:\angle3.exe',' ');
 Assign(taf,'c:\amgle4.TXT');
   reset(taf);
   for fr:=1 to 20 do
   readln(taf, theta^[fr]);
   close(taf);
   for fr:=1 to maxfr do
theta^[fr]:=theta^[fr]*pi/180;
for fr:=1 to maxfr do
GWriteXY(Xg(3),Yg(1+fr),' VALUES OF ANGLE IN '+Is(fr)+' FRAME :'+ Rs(theta^[fr],9,4),1,11);

mes2;
end;


procedure options;
 begin
  Repeat
```

```
        GWriteXY(Xg(28),Yg(1),'           ',15,1);
        GWriteXY(Xg(28),Yg(2),' Options   ',15,1);
        GWriteXY(Xg(28),Yg(3),' -         ',15,1);

        Dis3;
        mes32;
  if ch<>esc then
   begin
    Case ch of


     'D','d':
       begin
        CloseGWindow(0);
        CloseGWindow(0);
        title;
         GWriteXY(Xg(21),Yg(3),' THE DISPAYMENT OF THE FILE    ',15,5);
         prev_file;
         Display_file;
         if er=0 then
           begin
             CloseGWindow(0); {menu window }
             clear;
             GWriteXY(Xg(2),Yg(8),' SEGNO:           '+Is(segNo) ,15,3);
             GWriteXY(Xg(2),Yg(10),' MAXFRAMES:       '+Is(maxfr) ,15,3);
             GWriteXY(Xg(2),Yg(12),' NAME OF SUBJECT : '+Name,15,3);
             GWriteXY(Xg(2),Yg(14),' AGE OF SUBJECT : '+Is(Age),15,3);
             GWriteXY(Xg(2),Yg(16),' HEIGHT OF SUBJECT : '+Rs(Height,5,2),15,3);
             GWriteXY(Xg(2),Yg(18),' WEIGHT OF SUBJECT : '+Rs(BW,6,3),15,3);

            for i:=1 to SegNo do
            GWriteXY(Xg(2),Yg(2*i+20),model.Name[i],15,3);
           for fr:=1 to maxfr do
            begin
              clear;
              GWriteXY(Xg(2),Yg(20),' FRAME : '+ Is(fr),1,11);
              GWriteXY(Xg(2),Yg(2*SegNo+22),'CENTRE OF GRAVITY IN X :
'+Rs(CM[fr].Xcg[1],8,3)+
              ' Y : '+Rs(CM[fr].Ycg[1],8,3)+' Z : '+Rs(CM[fr].Zcg[1],8,3),14,4);
              for i:=1 to SegNo do
               begin
                GWriteXY(Xg(length(model.Name[i])+3),Yg(2*i+20),' X : '+Rs(frames[fr].seqs[i].Hr[1],8,3)
                +' Y : ' +Rs(frames[fr].seqs[i].Vr[1],8,3)+
                ' Z : '+Rs(frames[fr].seqs[i].Zr[1],8,3),14,4);
               end;
              mes2;
            end;
           end;
         ClearDevice;
         SetBkColor(0);
```

```
        end;

   'C', 'c': begin
        Repeat
        i:=0;
        if not OpenGWindow(0,Xg(35),Yg(17),Xg(75),Yg(33),0,14,1,1) then;
          GWriteXY(Xg(2),Yg(1),'                                   ',14,4);
          GWriteXY(Xg(2),Yg(2),' EXIT  TO ...                      ',14,4);
          GWriteXY(Xg(2),Yg(3),'                                   ',14,4);
          GWriteXY(Xg(2),Yg(4),' 1. WINDOWS       2. WORDPERFECT  ',14,4);
          GWriteXY(Xg(2),Yg(5),'                                   ',14,4);
          GWriteXY(Xg(2),Yg(6),' 3. T. PASCAL 6    4. HAR GRAPHICS ',14,4);
          GWriteXY(Xg(2),Yg(7),'                                   ',14,4);
          GWriteXY(Xg(2),Yg(8),' 5. DOS                            ',14,4);
          GWriteXY(Xg(2),Yg(9),'                                   ',14,4);
          GWriteXY(Xg(2),Yg(10),' PLEASE  ENTER  THE  NUMBER >      ',14,4);
          GWriteXY(Xg(2),Yg(11),'                                  ',14,4);

        MoveTo(Xg(32),Yg(10));
         if not GInt(i,14,4) then;
       if not  (i in [1..5])  then
        begin
          CloseGWindow(0);
          Mes_error;
        end;
      until  i  in [1..5];
      case i of

      1:
       begin
         path:='c:\Wingk';
         directory;
        end;


      2:
       begin
         path:='c:\Wp51 ';
         directory;
        end;


      3:
        begin
         path:='c:\TP6';
         directory;
        end;

      4:
      begin
```

```
            path:='c:\hg';
            directory;
          end;


       5:
       begin
            path:='c:\';
            directory;
          end;

       end;
     end;


      end;
  CloseGWindow(0);
  dem;
  end;

 until ch=esc;
 ch:='z';
 CloseGWindow(0);
 CloseGWindow(0);

end;



 Procedure  show;
   begin
    ClearDevice;
       Dem;
        Repeat
        mes3 ;
       case ch of

       'D','d':begin
                CloseGWindow(0);
                closegraph;
                Exec('c:\Gdigit.exe',' ');
                gd:=detect;
                initgraph(gd,gm,'');
                Dem;
              end;


     'P','p': begin
              CloseGWindow(0);
```

```
            closegraph;
            Exec('c:\process.exe', ' ');
            gd:=detect;
            initgraph(gd,gm,'');
            Dem;
           end;

     'O','o':
     begin
            options;
            Dem;
           end;



          'K', 'k': begin
            GWriteXY(Xg(41),Yg(1),'              ' ,15,1);
            GWriteXY(Xg(41),Yg(2),'  Kinematic ' ,15,1);
            GWriteXY(Xg(41),Yg(3),'  -           ' ,15,1);
            begin
             CloseGWindow(0);
             New(theta);
             title;

 GWriteXY(Xg(19),Yg(3),' K I N E M A T I C    A N A L Y S I S  ',15,5);
 mes1;
if ch<>esc then
begin
 Repeat
 if not OpenGWindow(0,Xg(10),(GetmaxY div 2)-Yg(6),Xg(70),(GetmaxY div 2)+Yg(7),0,Red,1,Blue) then;
  GWriteXY(Xg(2),Yg(1),'                                              ',15,3);
  GWriteXY(Xg(2),Yg(2),' 1:  VELOCITY          4:  ANGULAR  VELOCITY      ',15,3);
  GWriteXY(Xg(2),Yg(3),'                                              ',15,3);
  GWriteXY(Xg(2),Yg(4),' 2:  ACCELERATION       5:  ANGULAR  ACCELERATION  ',15,3);
  GWriteXY(Xg(2),Yg(5),'                                              ',15,3);
  GWriteXY(Xg(2),Yg(6),' 3:  ANGLES                                       ',15,3);
  GWriteXY(Xg(2),Yg(7),'                                              ',15,3);
  GWriteXY(Xg(2),Yg(8),' ENTER NUMBER >                                    ',1,11);
  GWriteXY(Xg(2),Yg(9),'                                              ',1,11);
  GWriteXY(Xg(2),Yg(10),' SAMPLING  FREQUENCY  (FRAMES PER SECOND) >         ',1,11);
              GWriteXY(Xg(2),Yg(11),'                                          ',1,11);
                pref:=0;
                MoveTo(Xg(17),Yg(8));
                if not GInt(i,4,11) then;
                 pref:=i;
                 if not  (pref in [1..5])  then
                 begin
                 CloseGwindow(0);
                 Mes_error;
                 end;
```

```
        until pref in [1..5];
       MoveTo(Xg(47),Yg(10));
       if not GInt(i,4,11) then;
       dt:=i;
       CloseGwindow(0);
Case pref of
   1:
   begin
   Select_kinem;
   if er=0 then
   Velocity;
   end;

   2:
   begin
   select_kinem;
   if er=0 then
   Acceler;
   end;

   3:
   begin
    Select_kinem;
    if er=0 then
     angle;
   end;

    4:
   begin
   Select_kinem;
   if er=0 then
   angle;
   Angl_velocity;
   end;

    5:
   begin
   Select_kinem;
   if er=0 then
   Angl_Accel;
   end;

 end;

     Dispose(theta);
  end;
      ClearDevice;
     setBkColor(0);
    Ch:='z';
    end;
```

```
     dem;
    end;


    'Q','q':begin
          GWriteXY(Xg(54),Yg(1),'            ' ,15,1);
          GWriteXY(Xg(54),Yg(2),'    Quit    ' ,15,1);
          GWriteXY(Xg(54),Yg(3),'            ' ,15,1);
          if not OpenGWindow(0,Xg(42),Yg(5),Xg(75),Yg(14),0,Red,1,Red) then;
          GWriteXY(Xg(0),Yg(2),'                                  ' ,15,3);
          GWriteXY(Xg(0),Yg(3),' HAVE YOU SAVE YOUR FILE ?(Y/N) ' ,15,3);
          GWriteXY(Xg(0),Yg(4),'                                  ' ,15,3);
          Repeat until KeyPress(ch);
          CloseGWindow(0);
          ch:=Upcase(ch);
          if ch<>'Y' then
          begin
          pref:=1;
          d:=10;
          di:=5;
          save(d,di);
          end;
           if not OpenGWindow(0,Xg(41),Yg(5),Xg(73),Yg(18),0,Blue,1,Red) then;
          GWriteXY(Xg(2),Yg(1),'                             ',15,3);
          GWriteXY(Xg(2),Yg(2),'     C O N F I R M           ',15,3);
          GWriteXY(Xg(2),Yg(3),'                             ',15,3);
          GWriteXY(Xg(2),Yg(4),'     "ESC" TO QUIT           ',15,3);
          GWriteXY(Xg(2),Yg(5),'                             ',15,3);
          GWriteXY(Xg(2),Yg(6),'  OR "ENTER" TO RETERN       ',15,3);
          GWriteXY(Xg(2),Yg(7),'                             ',15,3);
          GWriteXY(Xg(2),Yg(8),'   IN THE MAIN "MENU"        ',15,3);
          GWriteXY(Xg(2),Yg(9),'                             ',15,3);
          Repeat until KeyPress(ch);
          CloseGWindow(0);
          GWriteXY(Xg(54),Yg(1),'            ' ,15,3);
          GWriteXY(Xg(54),Yg(2),'    Quit    ' ,15,3);
          GWriteXY(Xg(54),Yg(3),'            ' ,15,3);
          end;
      end;

 until ch=esc;
  CloseGWindow(0);
 exit;
end;


begin

  if RegisterBgiDriver(@EgaVgaDriver)<0 then halt(1);
```

```
    gd:=detect;
    initgraph(gd,gm,'');
    SHOW;
   Closegraph;
End.
```

APPENDIX II

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RELEVANT PUBLISHED STUDIES

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Muscular and tibiofemoral joint forces during isokinetic knee extension

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Isokinetic dynamometry has widespread applications in the assessment of dynamic muscle function in normal and pathological conditions and in rehabilitation of muscular and ligamentous injuries (Baltzopoulous and Brodie, 1989, *Sports Medicine*, **8**, 101–116). The measurement of muscular and joint forces in isokinetics is therefore important. The purpose of this study was to examine muscle and tibiofemoral contact forces during isokinetic knee extension at angular velocities ranging from 0.52 to 3.66 rad s^{-1}, using a two-dimensional biomechanical model.

Five males ($\bar{x} \pm$ S.D.: age 20.8 ± 3.1 years; body mass 79.2 ± 7.2 kg; height 179 ± 32 cm) without a history of knee joint injury participated in the study. The resultant isokinetic moments during knee extension at 0.52, 1.57, 2.62 and 3.66 rad s^{-1} were measured on a computerized AKRON system (Baltzopoulos and Brodie, 1989, *Clinical Biomechanics*, **4**, 118–20). Muscular and tibiofemoral compressive and shear forces were calculated using a biomechanical model of the knee. This was determined by calculating the tibiofemoral contact point, patellar tendon moment arm, patellar tendon–tibial plateau and tibial plateau–tibial axis angles from video X-rays of a complete knee extension movement. The measurement error was 0.13% and the coefficient of variation for repeated measurements ranged from 0.4 to 1.3% for the above parameters. Differences in muscular and joint forces and moments at different angular velocities were examined using one-way analysis of variance and Tukey tests for *post-hoc* comparisons. Homogeneity of variance and therefore use of parametric statistics was ensured using Cochran's tests.

The maximum moment ($\bar{x} \pm$ S.D.) ranged from 226.2 ± 39.5 N·m at 0.52 rad s^{-1} to 160.0 ± 27.6 N·m at 3.66 rad s^{-1}. These differences were significant ($F_{3,12} = 17.9$, $P < 0.05$) and *post-hoc* tests revealed that the significant differences were between the moments at 0.52 rad s^{-1} and 2.62–3.66 rad s^{-1}. The maximum muscular force ranged from 7.55 ± 0.49 times body weight (BW) at 0.52 rad s^{-1} to 5.72 ± 0.94 BW at 3.66 rad s^{-1}. The compressive tibiofemoral force ranged from 7.53 ± 0.49 BW at 0.52 rad s^{-1} to 5.68 ± 0.91 BW at 3.66 rad s^{-1}, and the shear tibiofemoral force from 0.94 ± 0.48 to 0.83 ± 0.35 BW respectively. These differences were significant for both maximum muscular force ($F_{3,12} = 13.7$, $P < 0.05$) and compressive tibiofemoral force ($F_{3,12} = 13.57$, $P < 0.05$). Differences between the shear forces at the different angular velocities were not significant ($F_{3,12} = 0.64$, $P > 0.05$).

The conclusions within the limitations of the present study are that muscular and compressive tibiofemoral forces increase significantly with decreasing angular velocity during isokinetic knee extension. The shear tibiofemoral force remains relatively constant for the range of angular velocities examined. This information is essential for the development of appropriate protocols for isokinetic assessment and rehabilitation of muscular and ligamentous injuries.

Assessment of angular measurement accuracy using a video analysis system

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In recent years, video-recording systems have been developed for the recording and kinematic analysis of human movement (Kennedy *et al.*, 1989 *International Journal of Sport Biomechanics*, **5**, 457–60; Shapiro *et al.*, 1987, *International Journal of Sport Biomechanics*, **3**, 80–86). The purpose of this study was to examine the accuracy of angular measurements using the two-dimensional Biomechanics Workstation System.

A calibration plane (76 cm high × 180 cm wide) was used, with black, round adhesive markers (9 mm in diameter) on a white background. The horizontal and vertical linear alignment of markers was achieved using a Wild N20 level instrument, forming five angles of 90° (four in every corner and one in the centre of the calibration plane). A S-VHS Panasonic video system was used to film the calibration plane (a) underwater (for swimming applications) and (b) in an indoor sports hall. Twenty-five frames from each recorded sequence were digitized using the workstation, with and without the zoom facility. Differences in the unsmoothed angular measurements between zoom conditions, underwater and indoors, the five screen positions and interactions were examined using 3 factor ($2 \times 2 \times 5$) repeated measures (angular measurements) analysis of variance. The statistical results indicate that there was not an overall significant difference between the zoom conditions ($F = 1.60$, $P < 0.01$), but there was an overall difference between underwater and indoors ($F = 27.7$, $P < 0.01$), and between angle positions ($F = 18.8$, $P < 0.01$). The underwater angular measurements ranged ($\bar{x} \pm$ S.E.M.) from $89.9° \pm 0.134°$ to $90.9° \pm 0.123°$. The respective indoor measurements ranged from $90.0° \pm 0.123°$ to $90.5° \pm 0.136°$.

The results of this study indicate that, overall, the video analysis system used was capable of measuring accurately an angle of 90°. Horizontal misalignment of the calibration plane and camera, and optical distortion during underwater filming, are the probable explanations for the differences between underwater and indoor filming. The accuracy of angular measurements is relatively higher without use of the zoom facility and is reduced at the periphery of the screen and therefore careful alignment of the camera with the movement plane is required.

PART III: PSYCHOLOGY

Schema predictions ignored in the stampede

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In the regular stampede of the migrating motor research herd, at least two hypotheses which arise from careful consideration of the seemingly deserted schema-based theories of human motor memory and learning remain untested (Schmidt, 1975, *Psychological Review*, **82**, 225–60; Lee and Genovese, 1988, *Research Quarterly for Exercise and Sport*, **59**, 227–87). Practice conditions organized to strengthen an underlying control schema so that it will accommodate novel variations of a task should also work in relation to performing an *unchanged task* when the initial conditions – in this case the mass of a limb – are changed. Additionally, the processing *time to prepare a novel movement* should be reduced in the same way and should be reflected in reaction time (RT) when subjects are presented with a novel variation of a task.

The two experiments reported here used a basic transfer paradigm with three practice groups. These were a fixed practice group (FP), a blocked varied practice group (BVP) and a random varied practice group (RVP). In both experiments, 10 subjects were allocated to each group. Four blocks of 10 practice trials and two blocks of 10 transfer trials at a throwing task were completed.

In the first study, initial conditions (IC) relating to the motor system were varied. The varied practice subjects had additional mass added to the limb between each throw (RVP) or between each block (BVP). The subjects in the FP group had a fixed mass added to the throwing limb throughout the practice trials. The throwing task was an underarm throw to a line using shuttlecocks prepared with

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A POLYNOMIAL METHOD FOR IMAGE DISTORTION CORRECTION AND 3-D KINEMATIC ANALYSIS USING VIDEO SYSTEMS.

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INTRODUCTION

Three dimensional coordinate reconstruction techniques allow the accurate analysis of complex human motion. The disadvantages of these techniques are the requirements for a complicated and time consuming calibration procedure, additional recording equipment and more complex steps in the analysis process. A number of modifications of the Direct Linear Transformation (DLT) method have been developed in order to facilitate the recording procedure and improve measurement error (Andriacchi *et al.* 1979; Dapena 1982;). Furthermore, the construction of accurate 3-D calibration structures for large filming areas is complicated and therefore a significant limitation of the DLT method. Extrapolation techniques, using relatively small calibration structures in large filming areas increase measurement error. (Angulo and Dapena 1992; Wood and Marshall 1986). Recently, video systems have been used as an effective alternative recording method (Angulo and Dapena 1992; Kennedy *et al.* 1989; Shapiro *et al.* 1987).

The purpose of this study is the evaluation of a polynomial method for image distortion correction resulting from video lenses and 3-D coordinate reconstruction using video systems. This method allows linear extrapolation for coordinate reconstruction outside the calibrated area and therefore is particularly useful in applications requiring large filming areas.

INSTRUMENTATION

A calibration plane (3 m W x 2.5 m H) was formed using a total of 20 calibration points on four survey poles. Another pole was fixed in a horizontal position 1.9 m from the calibration plane and 0.8 m from the ground. The markers on the external pole were used for the determination of the 3-D camera position relative to the calibration plane. Four control points with known coordinates relative to the calibration plane were used for the determination of the reconstruction error. Two of these were inside the area formed by the camera position and the calibration plane (internal) and two outside the formed area (external). Horizontal and vertical linear alignment of calibration and control points was achieved using a Wild N20 level instrument. Distances were measured accurately by a Rabone Chesterman Digi-Rod 4000, electronic digital measuring rod (measurement error ≤ 0.5 mm). The two S-VHS Panasonic F-15 cameras used to videotape the calibration and control points, were positioned 1.20 m and 1.50 m (left and right camera respectively) from the ground and 5m from the calibration plane. The distance between the cameras was approximately 8 m.

PROCEDURE

Sixteen calibration points, two external and two internal control points were digitized in 10 different frames, from both cameras, using a computer system with appropriate software, interfaced to a Panasonic S-VHS video recorder. The average field of view for every frame was approximately 3.5 m W x 3 m H. With this method the projection of any digitized point on the calibration plane is calculated using a first degree polynomial. The coefficients of the polynomial are evaluated from the three most proximal calibration points.

This allows correction of the different degrees of optical image distortion produced by the video lenses (e.g. in the periphery and in the centre of the screen).

A sorting algorithm is used for the arrangement of the calibration points according to their distance from any digitized point, collinearity control and selection of the appropriate calibration points (to form a "local" calibration plane) for the determination of the polynomial coefficients. This allows the determination of the line formed by the camera position and the projection of any digitised point on the calibration plane. The three dimensional coordinates of the digitised point are then calculated as the intersection of these lines from the two cameras. In practice, the location of the 3-D coordinates is achieved using least square techniques, because of the absence of an intersection point due to the systematic (asymmetrical lens distortion) and random error (operator digitization error).

RESULTS

Measurement error was defined as the difference between known and reconstructed control point coordinates. Mean ($\pm$ standard error of the mean) measurement error was 2.921 $\pm$ 0.681 mm (0.083% of field of view) and 2.032 $\pm$ 0.436 mm (0.058%) for the external and internal control points respectively. A Student's t-test indicated that this difference was not statistically significant ($t_9 = 1.53$, $p < 0.01$).

DISCUSSION

The measurement error of this method is significantly reduced compared to other video kinematic systems (Angulo and Dapena 1992; Kennedy *et al.* 1989; Shapiro *et al.* 1987). Furthermore, this method is suitable for applications requiring large filming areas because measurement error is not significantly increased outside the calibration area. The calibration procedure is also simplified because planar calibration points are required instead of large three dimensional calibration structures. Higher degree polynomial models can be used for different degrees of optical distortion although first degree models are more suitable for extrapolation purposes.

Measurement error depends on the area of the local calibration plane and therefore an increase in the number of calibration points used will reduce measurement error. In conclusion, the method presented for 3-D coordinate reconstruction using video systems is easily implemented, reduces measurement error significantly and is suitable for large filming areas.

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3-D KINEMATIC ANALYSIS USING PANNING VIDEO SYSTEMS

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INTRODUCTION

According to recent studies (Shapiro *et al.*, 1987; Kennedy *et al.*, 1989; Angulo and Dapena, 1992) video systems offer an accurate and less expensive alternative to cine-photographic systems. In previous studies for 2 and 3 dimensional analysis, different techniques have been developed in order to minimize the measurement error, when a large field of view is required, using different camera placements (Whittle,1982; Wood and Marshall,1986) or multiple cameras (Huntington *et al.*,1979; Dillman *et al.*,1985). The limitations in kinematic analysis using cinematography, optoelectronic or video systems, when a wide field of view is required, can be overcome with camera panning. In this technique the camera is free to rotate about the vertical axis (Dapena, 1978; Chow, 1987; Gervais and Wronko,1988; Hay and Koh,1988; Gervais *et al.*,1989; Yeadon,1989; Chow,1993; Yu *et al.*, 1993). However, the limitations in previous panning studies, relate to the recording systems (metric cameras in Dapena (1978) and Yeadon (1989)), the large measurement error and the time-comsuming digitizing procedures(Yu *et al.*,1993). The purpose of this study was to develop and evaluate a polynomial method for image distortion correction and coordinate reconstruction, in order to improve the 3-D reconstruction accuracy of spatial coordinates, using panning video techniques.

METHOD

COORDINATE RECONSTRUCTION MODEL

The three dimensional coordinates of any point are determined as the intersection of two lines formed by the position of the cameras and the projection of the point on a calibration plane viewed from the two cameras respectively. These projections are determined using a first degree polynomial model:

$$X_p = a_1+a_2x+a_3y \qquad (1)$$

$$Y_p = b_1+b_2x+b_3y \qquad (2)$$

where X_p, Y_p are the coordinates of the projection of any 3-D digitized point on a calibration plane mapped from the 2-dimensional x, y camera image coordinates. The polynomial coefficients $a_1..a_3$ and $b_1..b_3$ are determined from three calibration points. The 3-D camera position (coordinates relative to the calibration plane) is determined as the intersection point of (at least) two lines formed by two points (camera determination points) with known 3-D coordinates and their projections on the calibration plane using the following equation:

$${}_{cam}X = {}^{P}_{cd}X_1 + t\,({}_{cd}X_1 - {}^{P}_{cd}X_1) = {}^{P}_{cd}X_2 + s\,({}_{cd}X_2 - {}^{P}_{cd}X_2) \qquad (3)$$

where t,s :scalar factors, ${}^{P}_{cd}X_1$, ${}^{P}_{cd}X_2$: the projections of the two camera determination points on the calibration plane in the X axis, ${}_{cd}X_1$, ${}_{cd}X_2$: the known coordinates of the two camera determination points in the X axis, ${}_{cam}X$:the coordinate of the camera in the X axis.

The same equation is used to calculate the ${}_{cam}Y$ and ${}_{cam}Z$ coordinates of the camera. Consequently, the 3-D coordinates of any point, can be determined by solving the overdetermined system of equations for t_j and s_j:

$$ {}^{R}_{cp}X_j = {}_{cam}X_1 + t_j\,({}^{P}_{cp}X_j - {}_{cam}X_1) = {}_{cam}X_2 + s_j\,({}^{P}_{cp}X_j - {}_{cam}X_2) \qquad (4) $$

where ${}^{R}_{cp}X_j$: the X coordinate of any digitized j=1...N point.

The same equation is used to calculate the ${}^{R}_{cp}Y_j$ and ${}^{R}_{cp}Z_j$ coordinates of any point.

In order to reduce the measurement error the polynomial model was used in combination with a sorting procedure for the calibration points. This sorting technique was used for the selection of the three closest calibration points (according to their distance (in video coordinates) from the projection of any digitized point) from a total of 16 available, in order to form a local plane and determine the polynomial coefficients. Consequently, the projection of any digitized point on the calibration plane was calculated from a local plane (and not a global plane fitted to all calibration points), correcting the different degrees of image deformation produced by the video lenses at different screen locations and the effects of acute recording angle-perspective error (Figure 1).

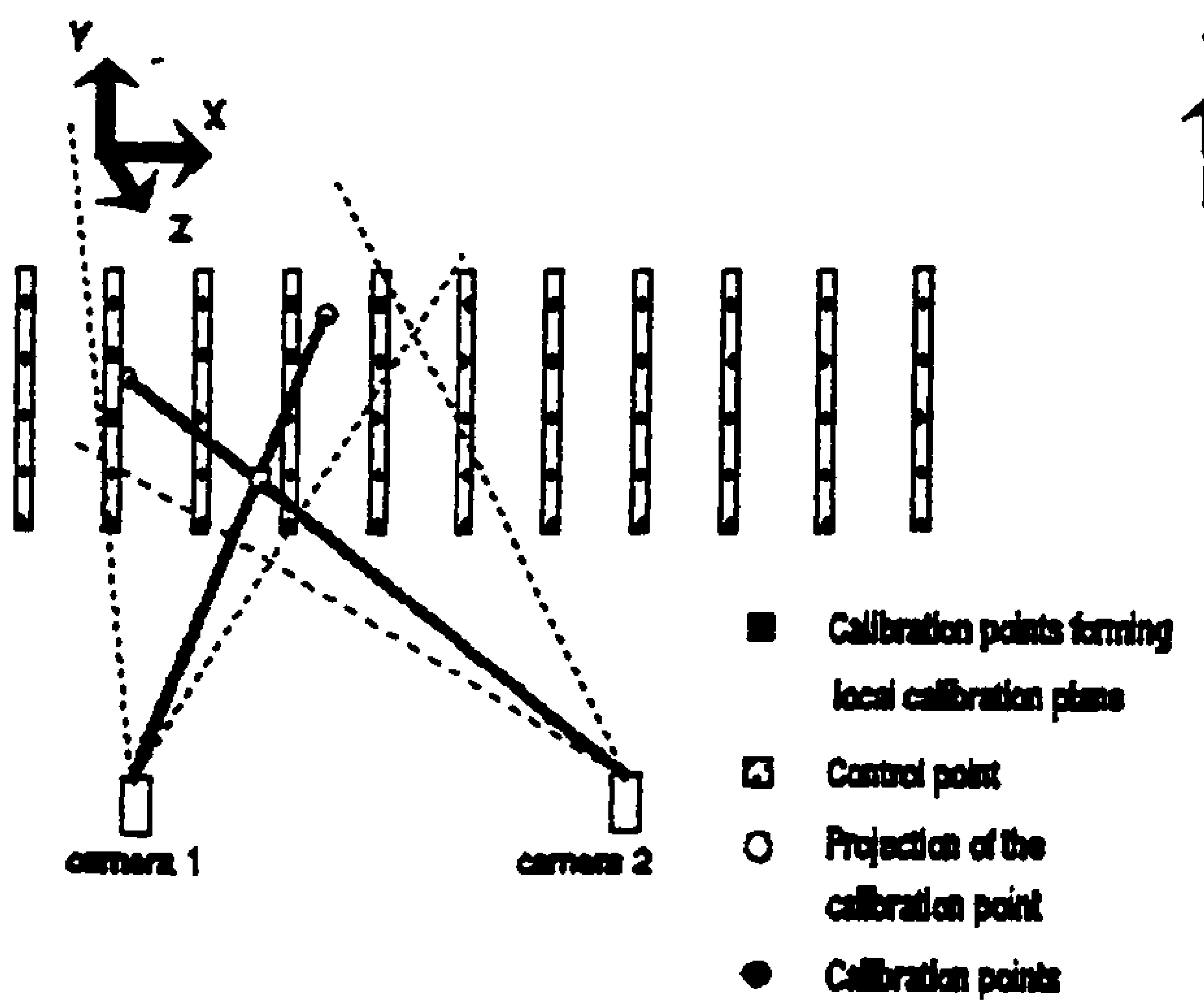

Figure 1 The projection of any digitized point and the formed local calibration plane.

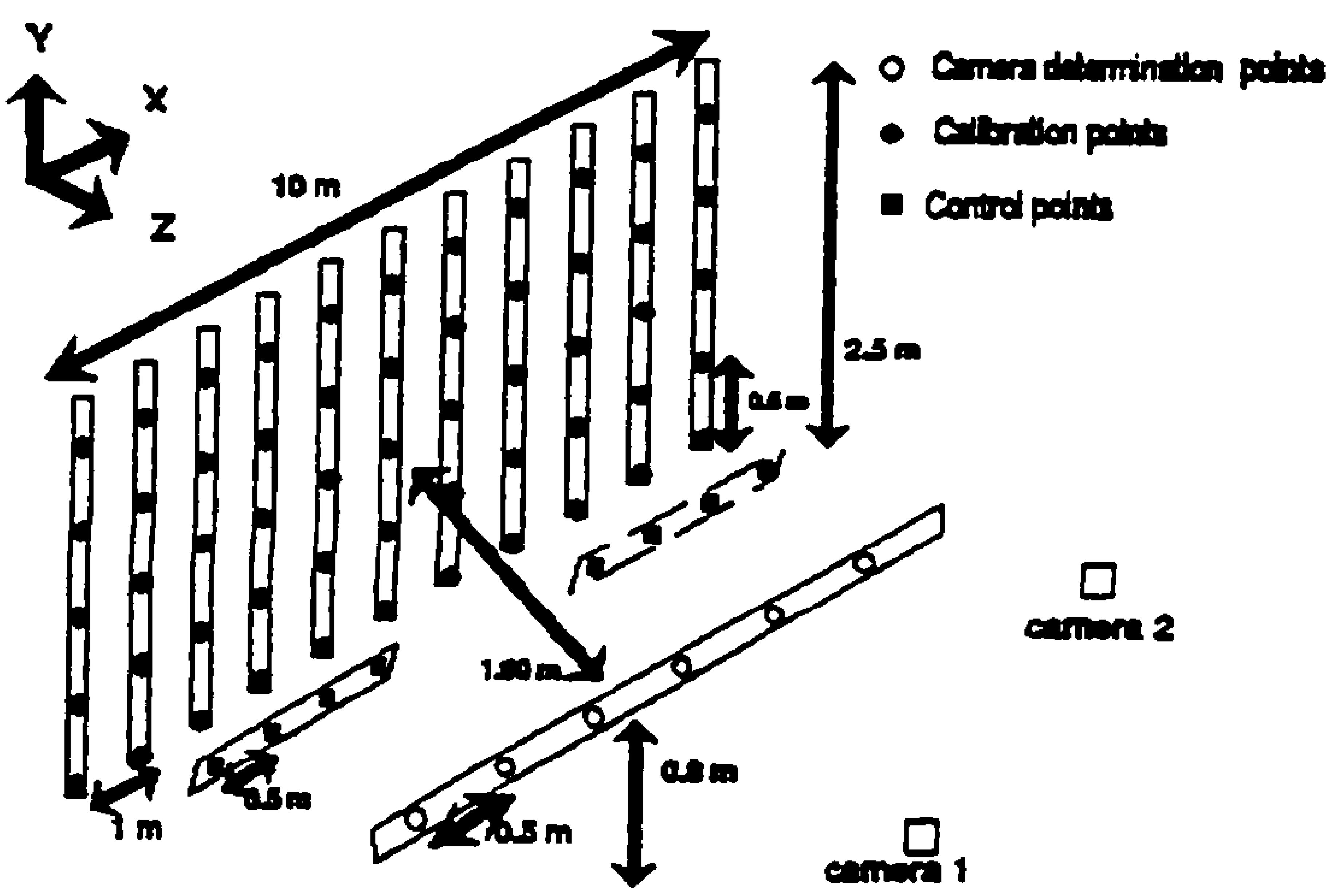

Figure 2 The calibration plane and the camera positions

CALIBRATION PROCEDURE

A calibration plane (10 m wide x 2.5 m high) was formed using eleven survey poles, with five markers on each. A survey pole was fixed in a parallel and horizontal position, with its markers (camera determination points) in known 3-D coordinates relative to the fixed calibration origin. Four control points on a pole, fixed in five random and non parallel (relative to the calibration plane) positions between the cameras's optical view and the calibration plane, were used to determine the reconstruction error, forming two distances of 0.5 m in random positions in the field of view. The two S-VHS Panasonic F-15 cameras used, were free to rotate around the vertical axis, in order to record the control points simultaneously in different (panning) positions (Figure 2). The orientation of the cameras was determined in every panning angle.

RESULTS

Sixteen calibration and four control points were digitized in each of 2 reference frames from both cameras. This procedure was repeated in five different camera positions during panning with the angles between camera optical axes and the normal to the calibration plane ranging from approximately -30^0 to 60^0. Mean error and the standard error of the mean ranged from 1.856 ± 0.640 mm (0.053% of field of view) to 3.334 ± 0.210 mm (0.095%) for the five different panning positions. The statistical results indicate that the measurement error at the different panning positions are not significant ($p>0.05$).

DISCUSSION -CONCLUSION

Different techniques have been implemented in order to film a large area and to provide better observation and consequently reconstruction accuracy of the markers. The panning method is the most effective technique, when a large field of view is required, because it can be implemented easily and therefore has been applied for two (Chow, 1987; Gervais and Wronko, 1988; Hay and Koh, 1988; Gervais *et al.*, 1989; Chow, 1993) and three dimensional analysis (Dapena, 1978; Yeadon, 1989; Yu *et al.*, 1993). Dapena (1978) and Yeadon (1989) used metric cinematography cameras for the 3-D analysis of high jump and ski jumping respectively. However, in Dapena (1978) and Yeadon (1989) studies the metric cameras used, must be in known positions (relative to the global origin) and furthermore, a large number of accurately measured control points placed in the field of view of each camera are required. Yu *et al.* (1993) develop a method for panning technique, using video systems, based on the DLT procedure. Although, this method is applicable in large areas, the major shortcomings are the large number of calibration points which must be digitized in each frame (time-consuming and error prone digitization), and the large measurement error.

The planar calibration procedure used in the present study, not only simplifies the calibration structure, but is also adequate and easily implemented for large filming areas. Furthermore the calibrated volume is not restricted in the area formed by calibration plane-camera, but expands beyond the calibration plane. The measurement error in the 3-D reconstruction was considerably reduced compared to previous 2-D and 3-D studies, using panning film or video systems.

Gervais *et al.* (1989) and Chow (1993) reported that the measurement error was related to the recording angle (the angle formed by the camera optical axis and the calibration target). In the present study, although the measurement error in the first and fifth panning angles (the extreme left and right panning angles), is slightly higher than the others, there is no significant difference in the accuracy between the panning angles. Furtermore, the sorting method used in the present study corrects the image distortion, and produces accurate results in every screen location.

In conclusion, the developed three dimensional polynomial method, for panning video systems, is an accurate and easily implemented technique that is suitable for large filming areas.

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3-D KINEMATIC ANALYSIS USING PANNING VIDEO SYSTEMS

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INTRODUCTION

The accurate measurement of kinematic parameters is of fundamental importance in the evaluation of human movement performance. The data collection process in biomechanics is highly dependent on rapid advances in technology. According to recent studies (Shapiro *et al.*, 1987; Kennedy *et al.*, 1989; Angulo and Dapena, 1992) video systems offer an accurate and less expensive alternative to cine-photographic systems. Although the relatively low sampling rate (compared to cinematography systems) and limited resolution affect measurement accuracy, coordinate reconstruction error can be improved using appropriate correction algorithms. Higher sample rates and resolution video systems can further improve kinematic measurement accuracy.

The usual practice in 3-D filming is to set up two or more stationary cameras that simultaneously record the filming area. This procedure is not appropriate for the reduction of measurement error when a large field of view is required, due to the small image size and limited resolution. In previous studies for two and three-dimensional analysis, different techniques have been developed in order to minimize this measurement error. This was accomplished using different camera placements (Fredricson *et al.*, 1970; Whittle, 1982; Wood and Marshall, 1986) or multiple cameras (Noble and Kelley, 1966; Huntington *et al.*, 1979; Williams and Cavanagh, 1983; Dillman *et al.*, 1985; Cappozzo and Gazzani, 1990). The limitations in kinematic analysis using cinematography, optoelectronic or video systems, when a wide field of view is required, can be overcome with camera panning. In this technique the camera is free to rotate about the vertical axis (Dapena, 1978; Chow, 1987; Gervais and Wronko, 1988; Hay and Koh, 1988; Gervais *et al.*, 1989; Yeadon, 1989; Chow, 1993; Yu *et al.*, 1993). However, the limitations in previous panning studies relate to the recording systems (metric cameras in Dapena (1978) and Yeadon (1989)), the large measurement error and the time-comsuming digitizing procedures. The purpose of this study was to develop and evaluate a polynomial method for image distortion correction and coordinate reconstruction, in order to improve the 3-D reconstruction accuracy of spatial coordinates, using panning video techniques.

METHODS

COORDINATE RECONSTRUCTION MODEL

The three dimensional coordinates of any point are determined as the intersection of two lines formed by the position of the cameras and the projection of the point on a calibration plane viewed from the two cameras respectively. These projections are determined using a first degree polynomial model:

$$X_p = a_1 + a_2 x + a_3 y \qquad (1)$$

$$Y_p = b_1 + b_2 x + b_3 y \qquad (2)$$

where X_p, Y_p are the coordinates of the projection of any 3-D digitized point on a calibration plane mapped from the 2-dimensional x, y camera image coordinates. The polynomial coefficients $a_1..a_3$ and $b_1..b_3$ are determined from three calibration points. The 3-D camera position (coordinates relative to the calibration plane) is determined as the intersection point of (at least) two lines formed by two points (camera determination points) with known 3-D coordinates and their projections on the calibration plane using the following equation:

$$_{cam}X = {}^{P}{}_{cd}X_1 + t\,({}_{cd}X_1 - {}^{P}{}_{cd}X_1) = {}^{P}{}_{cd}X_2 + s\,({}_{cd}X_2 - {}^{P}{}_{cd}X_2) \qquad (3)$$

where t,s : scalar factors

${}^{P}{}_{cd}X_1$, ${}^{P}{}_{cd}X_2$: the projections of the two camera determination points on the calibration plane in the X axis.

${}_{cd}X_1$, ${}_{cd}X_2$: the known coordinates of the two camera determination points in the X axis.

${}_{cam}X$: the coordinate of the camera in the X axis.

The same equation is used to calculate the ${}_{cam}Y$ and ${}_{cam}Z$ coordinates of the camera. Consequently, the 3-D coordinates of any point, can be determined by solving the overdetermined system of equations for t_j and s_j:

$${}^{R}{}_{cp}X_j = {}_{cam}X_1 + t_j\,({}^{P}{}_{cp}X_j - {}_{cam}X_1) = {}_{cam}X_2 + s_j\,({}^{P}{}_{cp}X_j - {}_{cam}X_2) \qquad (4)$$

where ${}^{R}{}_{cp}X_j$: the X coordinate of any digitized $j=1...N$ point.

The same equation is used to calculate the ${}^{R}{}_{cp}Y_j$ and ${}^{R}{}_{cp}Z_j$ coordinates of any point.

In order to reduce the measurement error the polynomial model was used in combination with a sorting procedure for the calibration points. This sorting technique was used for the selection of the three closer calibration points (according to their distance(in video coordinates) from the projection of any digitized point) from a total of 16 available, in order to form a local plane and determine the polynomial coefficients. Consequently, the projection of any digitized point on the calibration plane was calculated from a local plane (and not a global plane fitted to all calibration points), in order to accomplish the correction of the different degrees of optical distortion produced by the video lenses at different screen locations and the effects of acute recording angle-perspective error (Figure 1). Image distortion and coordinate reconstruction is therefore based on calibration points from a confined area with uniform distortion during panning.

CALIBRATION PROCEDURE

A calibration plane (10 m wide x 2.5 m high) was formed using eleven survey poles, with five markers on each. The distances between the points in each pole and between the survey poles were 0.5 m and 1 m respectively (measurement error ≤0.5 mm). For reasons of analytical convenience, the origin of the system was selected to coincide with the first lower-left marker of the calibration plane. A survey pole was fixed in a parallel and horizontal position, 1.90 m in front of the calibration plane, and 0.80 m from the ground, with its markers (camera determination points) in known 3-D coordinates relative to the fixed calibration origin. The points on this external pole were used for the determination of the 3-D camera position. A second pole with markers (control points) was fixed in five random and non parallel (relative to the calibration plane) positions between the cameras's optical view and the calibration plane. Four control points on the pole were used to determine the reconstruction error, forming two distances of 0.5 m in random positions in the field of view. Horizontal and vertical linear alignment of survey poles was achieved using a Wild N20 level instrument. The distances between the points on every pole (0.5 m) were measured using a Rabone Chesterman Digi-Rod 4000, electronic digital measuring rod (measurement error ≤0.5 mm). The two S-VHS Panasonic F-15 cameras (fitted with WV-LZ14/15E lenses) that were used to videotape the calibration and control points, were positioned approximately 1.20 m and 1.50 m (left and right camera respectively) from the ground and 5 m from the calibration plane and were free to rotate around the vertical axis, in order to record the control points simultaneously in different (panning) positions. A S-VHS Panasonic AG-7330-B video recorder interfaced to an Intel 82386 based-computer with a coded Turbo Pascal program was used to review and analyze the recorded data. The calibration plane of the test and the camera positions are illustrated in Figure 2.

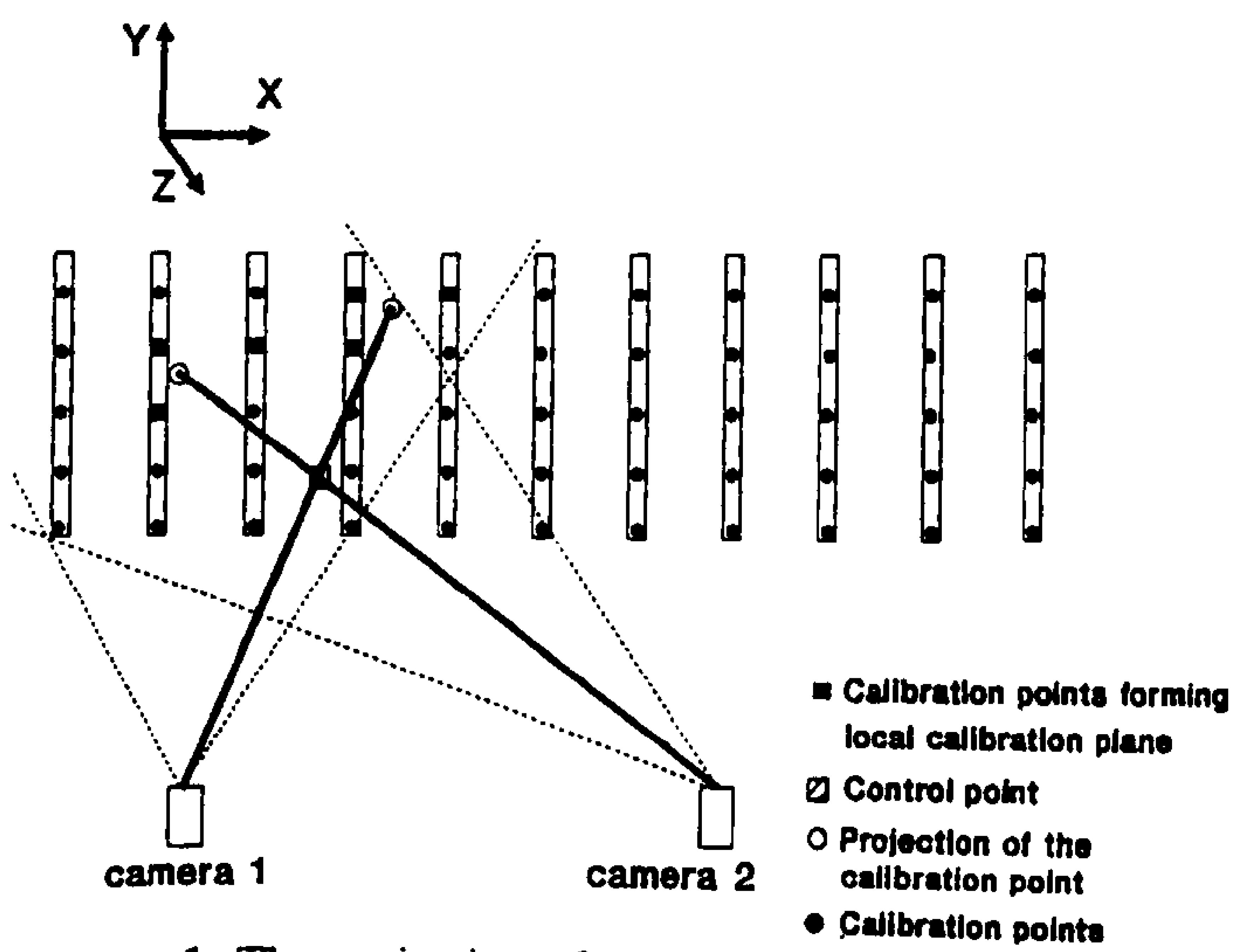

Figure 1 The projection of any digitized point and the formed local calibration plane.

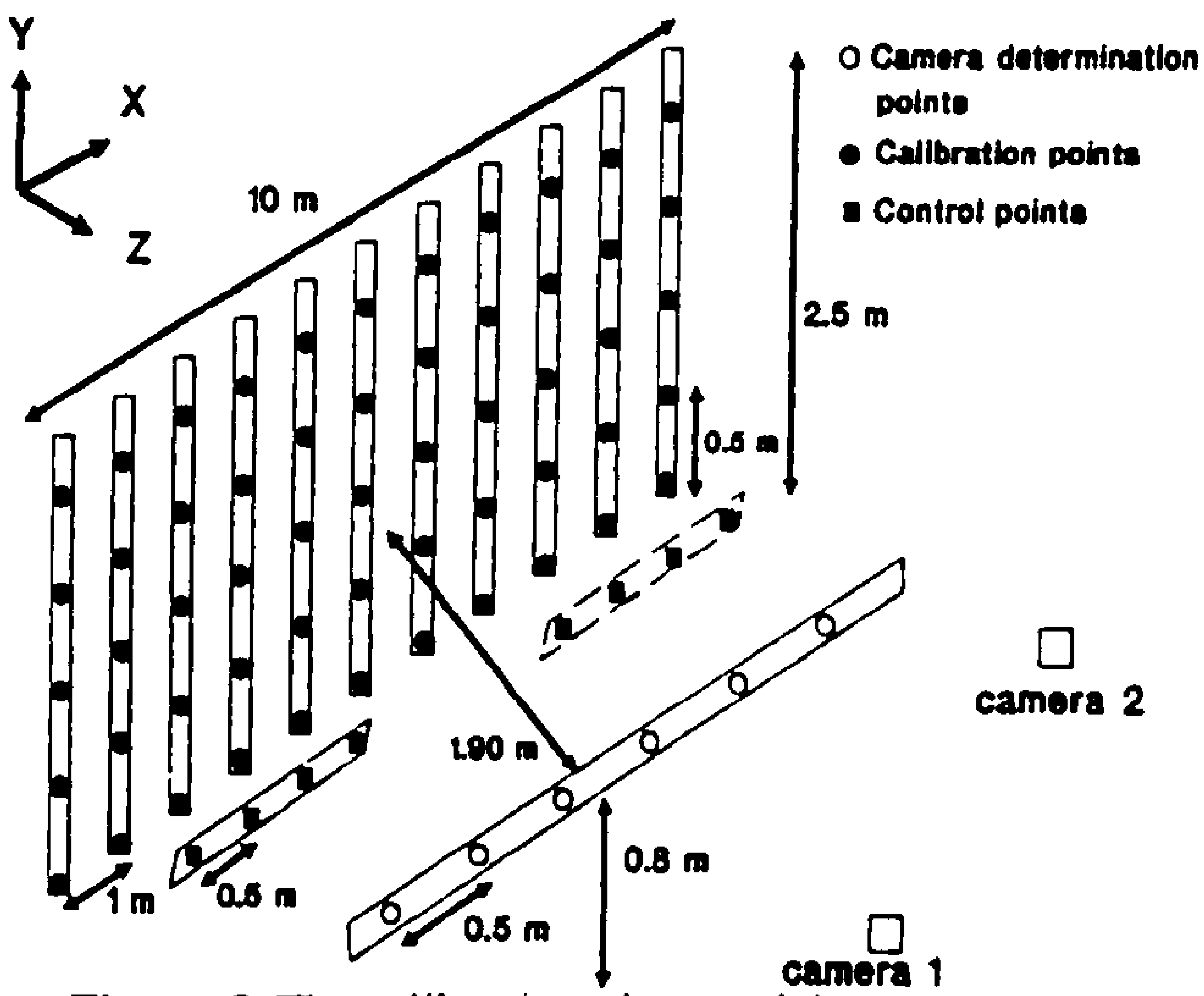

Figure 2 The calibration plane and the camera positions

RESULTS

Sixteen calibration and four control points were digitized in each of 2 reference frames from both cameras. This procedure was repeated in five different camera positions during panning with the angles between camera optical axes and the normal to the calibration plane ranging from approximately -30^0 to 60^0. The average field of view for every frame in the different panning positions was approximately 3.5 m wide x 3 m high. Mean error and the standard error of the mean ranged from 1.856 ± 0.640 mm (0.053% of field of view) to 3.334 ± 0.210 mm (0.095%) for the five different panning positions (Table 1). The measurement error (comparing the reconstructed with the actual 3-D distances between the control points) at the five different panning positions was analyzed using a Friedman's test. The statistical results indicate that the measurement error at the different panning positions are not significant ($p > 0.05$).

Table 1. Mean 3-D reconstruction error and standard error of the mean (mm) for two distances in five different camera angles.

	ANGLE 1	ANGLE 2	ANGLE 3	ANGLE 4	ANGLE 5
Distance 1	3.128±0.557	1.856±0.905	2.552±0.847	2.136±0.308	2.521±1.062
Distance 2	2.539±1.317	2.040±0.163	2.060±1.694	2.043±1.715	3.334±0.297

DISCUSSION

A 3-D panning technique was developed using video systems, in order to overcome the limitations of a small image size and a limited field of view, when fixed cameras are used in large filming areas.

Different techniques have been implemented in order to film a large area. Noble and Kelley (1969) used three cameras to determine the three dimensional coordinates of a moving ball, describing the path of a right circular helix. Fredricson *et al.* (1970) used a parallel (relative to subject motion) moving camera. In the study of Dillman *et al.* (1985), an increase of the phases of the movement and the conservation of a relatively large image size (compared to field of view), was achieved using three high-speed cine cameras. Williams and Cavanagh (1983) used four Locam cameras around the 3-D calibrated area. Similarly, Huntington *et al.* (1979) used three cameras, with the recording axis of the first (central) camera facing down the line of movement and two side cameras set at 45^0 to either side of movement. Cappozzo and Gazzani (1990), have used a COSTEL system equipped with three cameras which were mounted on a pole at three different positions. Whittle (1982) and Wood and Marshall (1986) used two television cameras at four different positions around the calibration area, in order to provide better observation and consequently reconstruction accuracy of the markers. The implementation of the above techniques can not be generalized for all human movement analysis, because the use of more than two cameras is not easily implemented,is time-consuming, expensive and usually only appropriate for indoor use or under specific conditions. The panning method is the most effective technique because it can be implemented easily and thus has widespread applications in the analysis of human movement, when a large field of view is required. The panning method has been applied for two (Chow, 1987; Gervais and Wronko, 1988; Hay and Koh, 1988; Gervais *et al.*, 1989; Chow, 1993) and three dimensional analysis (Dapena, 1978; Yeadon, 1989; Yu *et al.*, 1993). In order to film an object line of length 102 m Gervais et al. (1989) used a 2-D panning procedure with a single camera. The same technique was used by Chow (1987), Hay and Koh (1988) and Chow (1993), for the estimation of different kinematic parameters in athletic events. Chow (1993) specifically used video systems in the panning procedure. In this study there was no image distortion correction to compensate the effects of the acute recording angle during the panning procedure. In order to minimize this error the author suggested that the camera should be placed as far away from the plane of action and a telephoto lens be used in order to increase the image size. This method however, is not an appropriate correction for perspective error and image distortion. Dapena (1978) and Yeadon (1989) used metric cinematography cameras for the 3-D analysis of high jump and ski jumping respectively. However, in both the above studies the metric cameras must be in known positions (relative to the global origin) and furthermore, a large number of accurately measured control points placed in the field of view of each camera are required. Yu *et al.* (1993) develop a method for panning technique based on the DLT procedure. Small 3-D calibration structures were combined to form a large calibration volume. Although, this method is applicable in large areas, the major shortcomings are the large number of calibration points which must be digitized in each frame (time-consuming and error prone digitization), and the large measurement error.

The planar calibration procedure (a 3-D callibration structure not required) used in the present study, not only simplifies the calibration structure, but is also adequate and easily implemented for large filming areas. Furthermore the dimensions of the calibration plane can be considerably reduced relative to the calibrated volume. The calibrated volume is not restricted in the area formed by calibration plane-camera but expands beyond the calibration plane. Therefore any movement occurring between camera-calibration plane as well as beyond the calibration plane (assuming no refocusing is required) can be analyzed accurately.

The measurement error in the 3-D reconstruction was considerably reduced compared to previous 2-D and 3-D studies, using panning film or video systems. More specifically, Gervais *et al.* (1989) (using cinematography systems) reported mean measurement error ranging from ± 2.5 mm (approximately 0.13% of field of view) to ± 2.7 mm (approximately 0.38%). Chow (1993) using a similar technique but video systems for the recording and analysis process, defined 70 mm mean measurement error in a stride length (determined as the absolute error between the 2-D coordinates calculated from a stationary and the panning camera). The random measurement error reported by Dapena (1978) (using cinematography systems) was ± 5 mm in the X, Y and Z coordinates. The systematic measurement error in the same study, varied from - 20 mm to + 20 mm for the X and Y and -2 mm to +2 mm for the Z coordinates (horizontal field of view was approximately 10 m). The measurement error reported by Yeadon (1989) (using cinematography systems) was 0.05 m and 1^0, for the centre of mass location and orientation angles, respectively. Yu *et al.* (1993) (using video systems) reported a measurement error ranging from 14.4 mm to 44.7 mm.

Gervais *et al.* (1989) reported that the measurement error was related to the recording angle (the angle formed by the camera optical axis and the calibration target). The mean error was ± 7.5 mm for panning angle of 120^0, and ± 2.5 mm for panning angles of 75^0 and 40^0 respectively. Similarly, an increase of the measurement error with increasing recording angle was reported by Chow (1993). In the present study, although the measurement error in the first and fifth panning angles (the extreme left and right panning angles), is slightly higher than the others (Table 1), there is no significant difference in the accuracy between the panning angles.

In the study by Gervais *et al.* (1989) the control points were approximately in the centre of the screen (during the recording procedure) and there is no information indicating the error produced in the periphery of the screen. The sorting method used in the present study corrects the image distortion, and produces accurate results in every screen location. The measurement error depends on the area of the local calibration plane and therefore density of calibration points. Although the accuracy reported using 16 calibration points (for 3.5 m W X 3 m H field of view) is adequate for kinematic studies, an increase in the number of available calibration points will further reduce measurement error.

CONCLUSION

Static 3-D filming procedures can not be applied effectively for the recording of movements requiring large filming areas. The advantages of the panning method presented in this study is that a planar calibration structure is required. The dimensions of the calibration plane can be considerably reduced relative to the calibrated area. The effects of acute recording angle and lens distortion are corrected using a sorting technique, reducing significantly the measurement error compared to any other film or video method. In addition, the use of higher resolution video adaptors will be a significant factor for the improvement of digitization and reconstruction accuracy.

In conclusion, the developed three dimensional polynomial method, for panning video systems, is an accurate and easily implemented technique that is suitable for large filming areas.

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