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Calculation of the Residual Error in Three-dimensional Videography Using Stationary, Panning and Mobile Video Capturing Techniques

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Calculation of the Residual Error in Three-dimensional Videography Using Stationary, Panning and Mobile Video Capturing Techniques

By

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School of Human Kinetics

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of the degree of Master of Arts

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ABSTRACT

Significant technological advancements have been made in the study of human motion over the past few decades. There are three known video capturing techniques for collecting three-dimensional kinematic data; stationary, panning and mobile camera set-ups. The panning and mobile camera techniques allow for the cameras to follow a subject throughout the entire length of the skill while maintain a close-range view of the subject, something the stationary camera set-up does not allow. Accuracy of the panning and mobile camera techniques has not yet been well documented. The main objective of this study is to determine root mean square (RMS) errors of three-dimensional coordinates in a 5.5-meter filming volume using stationary, panning and mobile camera techniques using three specific testing conditions. Three testing conditions were set-up in order to verify the accuracy of the 3 camera systems over a 5.5 metre field. The first testing condition involved the simple linear movement of a moving calibration frame with reflective markers (n=7). The second test condition involved angular movement using a pendulum, where three vectors were precisely measured from three markers placed on the pendulum and recorded by the three camera set-ups. The final test condition involved standard gait data collection. Reflective markers (n=9) on the subject were positioned in a fashion to create triads on each of the three segments on the right leg (thigh, shank and foot). Three segment lengths were precisely measured from the marker set on each segment for a total of nine segment lengths. All marker positions were tracked with cameras and reconstructed using the APAS system. Residual errors were calculated for the collected three-dimensional positions and vector lengths were compared to the reference measurements made with the microscribe or anthropometer. Although the three camera techniques showed acceptable residual errors throughout the three testing conditions, the mobile technique produced the lowest RMS error for the two out of the three test condition. For the panning and mobile camera set-ups, camera-to subject distance is much smaller than the static camera technique for a 5.5-meter field. Lamontagne et al reported that residual errors could be minimized when camera-to-subject distance is reduced. The mobile technique produced acceptable accuracy in video analysis (Lafontaine et al., 2000). This technique did reduce the residual errors, of positional coordinates of markers and the vectors length measurements; by 55% and 44% in the gait testing condition respectively from errors obtained using the stationary camera technique. This study allowed for a comparison of three video capturing techniques abilities to collect accurate data over a large filming area. The results show that, although all three camera set-ups produce low residual errors, the mobile camera set-up offers the best accuracy while maintaining a small camera-to-subject distance, allowing for close range studies to be performed successfully.

Keywords: RMS errors, stationary, panning, mobile, camera technique.

CHAPTER I

INTRODUCTION

Significant technological advancements have been made in the study of human motion over the past few decades. Two-dimensional video recording with a sampling speed from 30 to 60 frames per second was originally used for gait analysis; however, this approach poses some limits for kinematic analysis since even basic human movement involves some degree of segment rotation. Three-dimensional (3D) motion analysis was introduced to address this limitation. Using three-dimensional videography, researchers were able to study a greater variety of human movements, from simple gait to more complex activities such as ice hockey and the golf swing while choosing from a wider variety of sampling speeds (60 to 240 frames per second). To measure 3D rotations of rigid bodies, 3D motion analysis must be used. Significant efforts on technological advancements of 3D motion analysis using video cameras are underway.

In order to accurately capture motion, a marker set is fixed on bony landmarks. Marker capture is the crucial factor when analyzing angular displacement, velocities and acceleration; therefore, it is important to quantify the limits of three-dimensional motion analysis systems. Different approaches have been developed to perform three-dimensional video motion analysis in the field of biomechanics. Most studies use a stationary camera set-up. Such an approach limits the size of the field of view and thus limits the activities that can be accurately studied. For example in ice hockey, when focusing solely on the right leg (from the hip to the foot of the athlete), the stationary camera set-up restricts the number of consecutive strides that can be continuously recorded throughout each trial. Furthermore, by only wanting to focus on the leg of the subject, the area of which the cameras will be able to view becomes much smaller. A decision needs to be taken as to how to go about collecting data from the entire skill while focusing on the leg of the subject. The stationary camera set-up offers some alternatives in this situation; ask the subject to perform the skill at full speed in the original setting and have the cameras focus in on one area of the skill and hope that the desired skill is performed in that area or move the cameras further away from the subject to ensure that the entire skill is captured, thus sacrificing the camera's focus on the subjects leg. The area where a participant performs the skill should not in any way influence the outcome of the skill. If the area is too small, the participant may be unable to perform the skill as they would in non-experimental setting. Therefore, there is great importance to ensuring that the experimental setting is as close to reality as possible. Obvious techniques for obtaining consecutive strides have been used in the past, such as moving the cameras further away from the filming volume. However, this increases the camera-to-filming volume distance and consequently increases the residual errors of markers of known positional coordinates, as reported by Lamontagne et al (2000).

To address this problem, the panning camera methodology was introduced. This method involves pivoting the cameras about the vertical axis of their tripods to follow the subject through out the activity. This method allows for a more natural setting for the subject while enabling the researcher to maintain a relatively small camera-to-filming volume distance, thus possibly reducing RMS errors of subject segment markers. Errors obtained using three-dimensional videography in stationary camera set-ups have been documented. Furthermore, the panning camera technique evolved to a more complex approach, which was a combination of panning, tilting and zooming. For the purpose of this study, only the panning technique is used. Little work has been done on errors from the panning camera technique, specifically with close range cameras positioned for 3D data collection. Finally, a three-dimensional mobile capture system has just recently been introduced and used in an experimental setting by Lafontaine and Lamontagne (2003). This technique consists of measuring a small filming volume and following the subject for several strides by moving the cameras parallel to the subject's line of motion. This method has seldom been used and there is therefore no literature that reports levels of RMS errors associated with the technique.

Errors in 3D research have been reported for the stationary camera settings. Skin marker, digitizing and videography related errors have been well documented. Stationary camera settings are limited for the study of a skill or movement requiring a large filming volume. Again, Lamontagne, Kendall and Murphy (2000) reported increased residual errors with an increase in the cameras-to-filming volume distance. Analysis of residual errors in the panning and mobile camera set-up is not well documented. As such, determining if residual errors resulting from a panning and mobile camera set-up are less than for the static set-up would confirm the validity of the approaches and provide two means of obtaining more realistic experimental kinematic data. These methods would allow participants to perform specific skills more naturally and also allow for the researcher to follow a particular skill through-out its entirety while maintaining the same or lower levels of residual errors as the static camera set-up.

Stationary camera set-ups are the norm for the study of 2D or 3D human movement. Size of the filming volume is determined based on the space required to perform one cycle or a certain aspect of the studied skill. This has shown limited effectiveness in describing skill kinematics. However, for skills that require a bigger filming volume, the stationary camera set-up has been shown to report higher errors, thus reducing the accuracy in reporting kinematic data. Since a panning and mobile camera set-up allows the researcher to follow the subject through out the whole skill, the cameras can be placed much closer to the filming volume, thus, possibly minimizing the cameras to filming volume distance problem. These two methods would also provide a more realistic acquisition of data since it would make it possible to collect many cycles of a particular movement, net advantages compared to one or two cycles obtained in a static camera setting.

1.1 STATEMENT OF THE PROBLEM

Very little research has been documented with regards to video residual errors in panning and mobile camera set-ups. It has already been shown that the size of the filming volume directly affects the amount residual error one could expect to have when filming human movement in a static setting. A panning and mobile camera set-up allow for filming at close range over a greater filming area.

1.2 PURPOSE

The purpose of this study is to determine the root mean square (RMS) error in three-dimensional videography using stationary, panning and mobile video capturing techniques by means of three specific experiments.

1.3 OBJECTIVES

The objective of this study is to determine RMS errors of measured distances using a close range stationary, panning and mobile camera set-up. Three simple experiments are used to verify the errors associated with the measuring approaches.

The first experiment consists of measuring distances between markers of known three-dimensional coordinates moving linearly through the filming volume of 5.5m. Residual error will be determined by calculating the root mean square (RMS) of the measured distance between markers in all three-camera set-ups (stationary, panning and mobile methods).

The second experiment is achieved in much the same fashion as the first experiment. Once again, distances between markers of known three-dimensional coordinates were measured, however, this time having an angular movement through the filming volume of 5.5m by means of a pendulum. Residual error was determined by calculating the RMS of the measured distance between markers in all three-camera set-ups (stationary, panning and mobile methods).

The third experiment, the validation of the three systems, consists of calculating residual error of measured marker distances and gait using all three-camera methods.

It is further verified if the panning and mobile camera techniques can be used in actual motion analysis while producing kinematic data within the acceptable scientific limits of a normal distribution (alpha < 0.05).

1.4 RESEARCH HYPOTHESIS

It is hypothesized that acceptable operational errors can be achieved using the panning and mobile techniques. Operational error can be defined as the percentage of error relative to the size of the filming volume. Acceptable operational errors of 5% have been reported in scientific literature (Lafontaine et Lamontagne, 2002). The fact that the cameras, in both the panning and mobile camera settings, are positioned much closer to the filming volume should ensure equal or lower marker residual errors for all three testing conditions.

1.5 LIMITATIONS AND DELIMITATIONS

Segment lengths were compared rather than joint angles throughout this study. In traditional gait analysis, joint angles tend to be reported. Segment length measurements were used in this study in order to have definite "real" measurements to compare to those captured with the three camera set-ups.

It was assumed that the two cameras used in each camera set-up were perfectly synchronized. A flash was used to synchronize the two cameras since a Genlock system was not available.

The 3D digitizer also had some limiting factors, such as its workspace size of 1.27m. In a perfect setting, the 3D digitizer would have been used to measure all the devices used in the study, however due to its limited workspace, it was unable to measure the 1.5m and 3.0m calibration frame, which we measured using a theodolite.

Prior to the study, tests we done to determine the ideal length required to view three complete right footed steps during gait. A volume, with a length of 5.5m, was deemed sufficient to complete the task. The large calibration frame (3.0m) was a limiting factor since it did not cover the entire length of the filming volume. Though it has been reported that reconstruction of markers outside of the calibrated area can be done, at the expense of additional errors (1-2mm) for markers more than approximately 20% outside the filming volume (Chen et al, 1994), it would have been ideal to have a calibration frame that could cover the entire 5.5m.

The reference measurements

The reference measurements in this study were taken with a theodolite and an anthropometer and also the three-dimensional digitizer (Microscribe 3DL, Immersion Corporate, San Jose, USA). These reference measurements are accurate to 0.5mm and 0.23mm respectively in determining the precise coordinate of a markers' three-dimensional position. The results of this study can only be as accurate as the least accurate measurement tool used in the study therefore all errors below 0.5mm cannot be explained since the theodolite was the least precise of the two measurement tools.

Delimitations

The delimitation of this study is therefore limited to reproducing three-dimensional marker positions, vector lengths and segment lengths for slow movements, such as gait. It can also be said that this study can only report data for movements in one direction. The mobile camera set-up could accurately follow the pendulums' forward motion however it was difficult to accurately reverse the motion of the mobile device in order to capture the pendulums' backward motion. In consequence, all the collected data was motion moving from the left side of the filming volume, to the right.

CHAPTER II

REVIEW OF LITERATURE

In this chapter, several topics related to video capture technologies are discussed. First, three-dimensional versus two-dimensional research and the advantages and disadvantages of both approaches is discussed. In a subsequent section, the types of errors related to video capture and data acquisitions, such as skin marker movement and lens distortion errors reported during human movement analysis. The third section reports on direct linear transformation (DLT). The final section looks at three camera set-ups: stationary, panning and mobile.

2.1 TWO-DIMENSIONAL (2D) VERSUS THREE-DIMENSIONAL (3D) VIDEO ANALYSIS

Early research focused on two-dimensional (2D) video analysis of human movement because of its simplicity, set-up and usage. Technological advancements have made it possible to use three-dimensional (3D) video analysis for nearly every type of kinematic study with the same simplicity as the 2D method.

There are many differences between 3D and 2D motion analysis. One aspect that differs between both approaches is the camera set-up. Three-dimensional motion analysis requires at least two cameras to record each marker on the subject, and calibration, at all times, whereas 2D motion analysis requires a single camera. Looking at the advantages of the two methods, it is clear that three-dimensional analysis offers much more to researchers than the traditional 2D method. Three-dimensional analysis offers the possibility to study linear and angular kinematics comprising of rotations around the three main axes; whereas, 2D analysis is limited to movements in two directions forming a single plane. Conversely, for the 2D set-up, only one camera is used and therefore relays merely the X and Y coordinates of each marker on the subject. Nike Inc. (1991) presented a 3D kinematics protocol which described the steps required to successfully perform 3D data analysis. They compared 2D analysis with 3D analysis, and have deduced that while 2D analysis could determine position, displacement, velocity and acceleration, it could not determine other movements, such as rotation around the three main axes. More complex skills demand the use of a 3D set-up since human movement likely would happen in three dimensions. For this reason, a three-dimensional approach will be investigated for this thesis.

Table 2-1: Applicability of 2D and 3D motion analysis

Characteristic	2D	3D
Minimum # of cameras needed	1	2 or more
Measure rigid body rotation – out of plane	No	Yes
Number of axis of motion that can be studied at a time	2	3
Measure linear motion	Yes	Yes
Measure Complex skills	Yes, but in one plane only where rotations out of plane cannot be measured	Yes, in all three planes where rotations in all planes can be quantified.
Measure angular motion	Yes, in plane	Yes, In all planes

2.2 ERRORS RELATED TO VIDEO CAPTURE

In the literature, investigators have reported a number of errors inherent to video motion data analysis. Two types of errors are applicable to biomechanics, systematic errors and residual errors. Some examples of systematic errors are errors that remain constant for the most part; such marker vibration, skin marker movement etc. Residual errors are detectable through repeated measures, a function of the system being used to collect the data. Moreover, it is the error the system being used has made in locating the position coordinate of a landmark.

Residual errors are also common occurrences that result from the difference between the measured (known values) markers and average measurements of reconstructed digitized markers. The causes of such errors are numerous. The number of cameras used can have a significant effect on the level of residual errors. Lamontagne, Kendall and Murphy (2000) determined that an increase of the number of cameras used during motion analysis caused less residual errors that were unrelated to the size of the filming volume. Giakas (2001) reported that the use of many cameras (8) might not produce the lowest residual error in comparison to fewer cameras (2). The eight camera set-up produced residual errors as low as 0.66mm and as high as 0.68mm whereas the two camera set-up produced residual errors as low as 0.51mm but as a high as 2.7mm. He concluded that though the two-camera set-up produced the lowest level of residual error, more cameras produced consistent levels of residual error. In the two-camera set-up, camera placement largely influenced level of residual errors; thus increasing the number of control variables. Also, with a greater number of cameras, camera positioning had a less significant effect. In other words, two cameras set-up with proper projection angle, and optimized view is better than an eight camera set-up with no optimized projection angle at all.

Skin markers are often used to capture joint motion during a given skill. Skin marker movement is one common source of RMS error. It is well known that human skin is a visco-elastic material, which stretches and moves when limbs are in motion. Luchetti, Capozzo, Cappello et al (1998) reported root mean square (RMS) errors of up to 14 mm from marker movement on the skin. They corrected this error with a rigid movement artefact compensator and reduced the skin movement errors to less than 4 mm. They found that relative errors of the knee joint are approximately 21% in flexion, 63% for internal/external rotation and 70% for abduction/ adduction. They concluded that substantial errors could be found with knee rotation when using skin markers. With regards to surface markers, another source of error can be found with regards to finding the centroid (center of mass) of a marker. When using the digitizing process, it is important to find the centroid of a particular marker. This is done to ensure that there is uniformity when digitizing. Manual digitizing would no doubt cause problems since determining the centroid of a marker can differ from person to person. Though investigator have not agreed on exactly how much error can be attributed to digitizing error, 5% seems to be the acceptable estimation (Triano, 2000).

Another common source of error in 3D video analysis is video synchronization. When using multiple cameras to study an event, it is imperative to ensure that the cameras are synchronized. One camera synchronizing technique is to use a flash of light prior to performing the event (Miller et al, 1980). A similar technique was used by Degueurce et al (1996), where a light bulb inside the field of view was turned on prior to the subject performing the event. Although these are fundamental methods, they do not account for the relative offset of time between the cameras (Yeadon, 1989 & 1990). In order to reduce this offset between the cameras, a Genlock system would be necessary. This system simultaneously starts multi-camera recording set-ups; to ensure that the cameras begin recording at exactly the same time and are focused on the exact same field on the videotape. Genlocked video cameras or phase-locked cinecameras are required for the DLT method using two or more cameras (Yeadon et al, 1998). For this work, a simple flash will be used since a Genlock system was unavailable and relatively expensive to purchase.

The size of the filming volume also has an effect on residual errors. When large filming volumes are required, greater camera to filming volume distance is needed to fit the filming volume into the cameras field of view. With a greater distance between camera and the filming volume, the image in the cameras is smaller resulting in the appearance that the markers on the subject are smaller, thus, decreasing the resolution of the markers and consequently more susceptible to digitizing errors. Lamontagne et al (2000), in addition to looking at the effect of the number cameras on RMS errors, also evaluated the effects of different camera-to-filming volume distances. They reported an increase in residual errors as the distance between the cameras and the calibration frame increased; therefore, close range filming is advantageous for motion analysis. To minimize residual errors, it is necessary to ensure that the subject markers are large and visible through the camera lenses. In contrast to a static camera setting, the panning and mobile methods are capable of following a movement throughout several cycles at very close range. This is a result of the camera to filming volume distance being reduced and maintained in comparison to a static camera set-up filming the same volume. This concept will be thoroughly addressed in chapter 3.

2.3 DIRECT LINEAR TRANSFORMATION (DLT)

Three-dimensional reconstruction requires combining two-dimensional coordinates from at least two cameras to form three-dimensional coordinates (Murphy, 1988). A common technique for three-dimensional reconstruction of planar images is the direct linear transformation technique (DLT) (Abdel-Azziz, 1971). It has been shown that the DLT approach yields very good results for both video and film systems in the control region (Hatze, 1988; Kennedy et al 1989; Shapiro, 1978; Wood and Marshall, 1986). Abdel-Azziz (1971) developed a series of equations, based on 11 to 16 parameters, to reconstruct the three-dimensional coordinates of the objects being collected by 2 or more cameras. The additional parameters correct camera lens distortion (Murphy, 1989). At least six calibration points are needed to solve the 11 DLT parameters. However, it has also been shown that improved accuracy of 3D reconstruction can be obtained by using more than 8 calibration points. No significant improvement in accuracy is gained by using more than 32 calibration markers (Chen, Armstrong and Raftopoulos, 1994). To ensure high accuracy while using the DLT, position and number of calibration points should be optimized. Adding more calibration points to the calibration frame allows for a greater scatter of calibrating point in the field of view thus giving a better estimate of the filming volume. These points should also be placed in an orderly fashion within the calibration space. Calibration points that are not placed uniformly tend to produce less accurate results (Chen et al, 1994). Based on this information, the calibration frame in this study has 20 markers.

Inter-camera distance is an important aspect that must be considered when setting up cameras for three-dimensional video acquisition. Optimum camera distance and angle can greatly enhance video accuracy. Studies by Marzan (1975) and Lamontagne et al (2000) reported significant differences in accuracy when altering the inter-camera distance and angle of projection while maintaining the camera to subject distance to a minimum. Optimum camera angle is found when the camera optical axes converge within the desired filming volume. A small intersection angle between the optical axes can produce substantial variation in digitized marker coordinate positions (Nigg and Cole, 1995; Chen et al, 1994). Thus a proper convergence of the optical axes enhances accuracy and ensures that the cameras are focused on the same filming volume.

2.4 FILMING TECHNIQUES

Creating realistic settings to perform a skill while controlling as many parameters as possible, it has been a continual source of concerns. Currently, much of the three-dimensional motion analysis is done in a controlled laboratory. This environment is not ideal conditions for skills such as skating or golf that require greater space to perform repetitive skills. Furthermore, previous studies used static cameras settings when filming a skill. Again, this technique has many limitations. Close range research is limited to recording a small portion of a skill since the cameras, in the static set-up, focus on one area. For example, skating is a skill for which a static camera set-up would not allow the whole movement to be viewed without sacrificing camera-subject distance, thus reducing accuracy.

Techniques were developed to address the problem of large filming volumes. One technique, the panning camera technique, involves following the subjects with the cameras by means of pivoting and turning it on a tripod (pan and tilt). This method requires a time-consuming calibration procedure, followed by a long digitizing procedure. Many reference points are required to maintain a calibrated field of view (Yu, Koh and Hay, 1993). Few researchers have used a panning camera technique. Those that have, focused on complete body movement. Yeadon (1989) used a 3D pan and tilt technique to study ski jumping by using two reference markers in each film frame. High digitizing errors of 0.05m for the location of the centre of mass and one degree in orientation angles were reported. It should be noted that the filming volume was quite large and markers were likely very small and hard to capture with good accuracy. Dapena, J. (1978) evaluated errors of 3D cinematography with horizontal panning cameras. It was reported that systematic errors could likely be attributed to lens distortion and improper rotating about the vertical axis. Dapena believes that constructing a proper tripod could rectify this problem. The systematic errors observed were still within acceptable limits for most activities. This is believed to be the earliest use of the panning camera method. Again, only whole subjects were studied, demonstrating a lack of literature for close range panning studies. A study by Yu et al (1993) attempted to develop a method of 3D videography using panning cameras for analysis of human motion that did not require on-site measurements to be taken for determination of camera position. The filming speed was 60 Hz and their methodology was validated. They did report a limitation to this method, stating that there was a large amount of digitizing required. Recommendations included reducing the number of control points to six, which is the minimum required for the DLT. It is clear that there is little research done on close range three-dimensional motion analysis using a panning camera technique.

Finally, the latest and not yet validated technique is the tracking camera technique. The cameras glide on tracks and can follow the subject during their movements. Literature reporting accuracy or use of this system in research is quite scarce. The only two studies found where the mobile system was used were Lafontaine and Lamontagne (2003) and Fournials, Lambert and Cantin (2002). They reported valid and consistent results, stating that their results are considered as being near the accepted baseline of validity (i.e. 5% error).

2.5 SUMMARY

Three methods will be evaluated for the level of the residual errors they produce. The static camera technique is an accepted method used by most researchers, which produces acceptable levels of operational errors (approx. 5% of the size of the filming volume).

The panning method has not been well tested and therefore is not readily accepted. Theoretically, this method would improve human motion analysis by following the subject throughout the complete sequence of a movement. The most significant drawbacks with the panning technique are the level of errors and the time consuming process required. Limited sources have reported on the level of accuracy for the panning process, causing doubt to the efficiency of panning as an accurate tool in data acquisition.

Finally, the mobile camera approach has not been evaluated for research in the field of biomechanics. The advantages of this approach are its abilities to follow the subject for many cycles throughout the entire movement while having the capability to maintain a short camera-to-filming volume distance in order to enhance the resolution of the markers and consequently maximizing the digitizing process accuracy.

Measuring the residual errors of the three different motion analysis approaches will permit the evaluation and ranking of their accuracy during data collection. This will help determine which method yields the lowest errors for a given type of movement studied.

CHAPTER III

METHODOLOGY

The main purpose of this study is to determine the accuracy of video capture of three different camera set-ups by measuring the residual errors obtained in three specific testing conditions: linear motion condition, angular motion condition and gait condition.

3.1 MATERIALS

A brief description of the equipment used for each of the three camera set-ups in all three testing condition will follow.

3.1.1 Calibration Frames

A custom-made three-dimensional grid (3DG) was designed by Jason Carey, P. Eng., Ph.D and built by Spero Manufacturing Inc. The 3DG was very versatile, in the sense that the filming volume could easily be modified depending on the size of filming volume needed. The 3DG consisted of a base with dimension of 3.0m in length, 1.5m in depth, 1.5m in height and modular at every 25 cm (to allow variable configurations). Two calibration settings of the 3DG were used; the first setting was a 3.0 m by 1.5 m by 1.0 m where the X-axis rods were set at 100 cm apart whereas Y and Z-axes remain at 50 cm apart. The second 3DG was smaller in the X-axis with dimensions of 1.5 m by 1.5 m by 1.0m where the rods in X-axis were 50 cm apart whereas Y and Z-axes remain at 50 cm apart and each rod had 3 markers (Figure 3.1 and 3.2). Each marker has been covered by reflective tape in order to ensure good reflection of each marker during video camera recording.

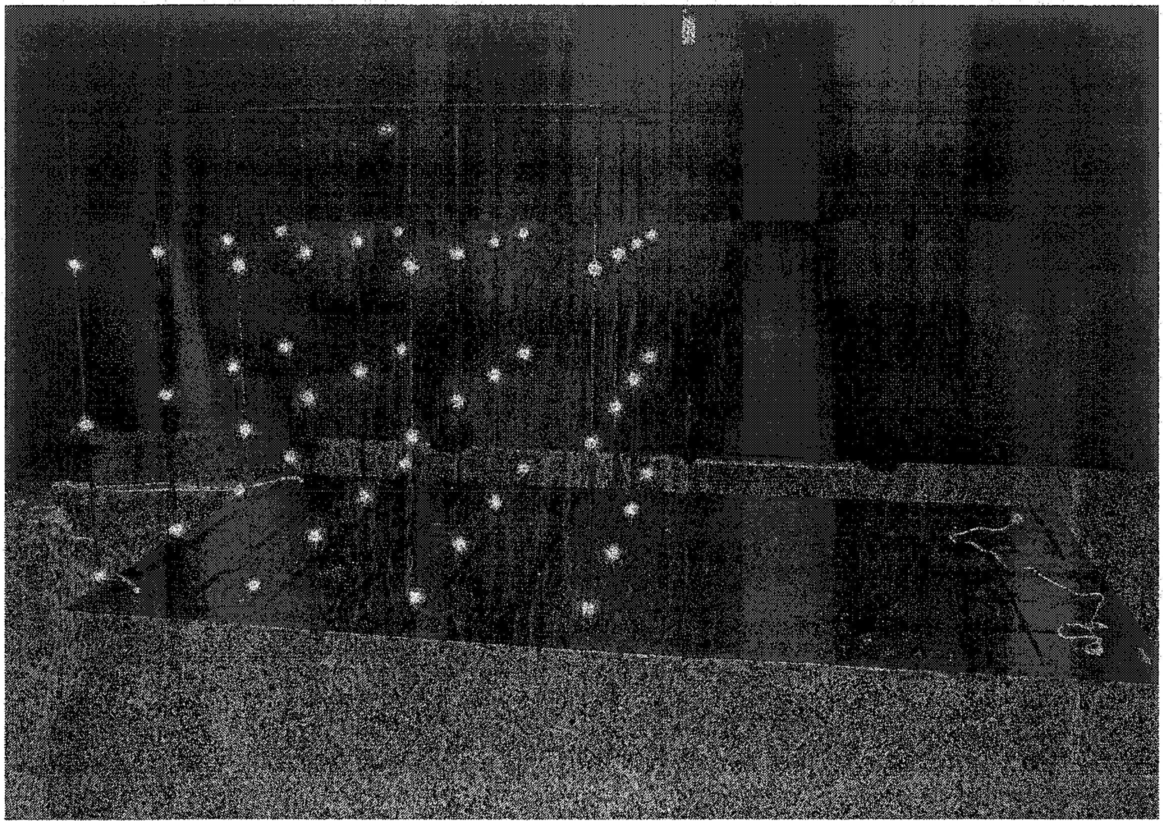

Figure 3.1 The small calibration frame used for the panning and mobile camera techniques. Dimensions for this calibration frame are 1.5m in length, 1.5m in depth and 1.0m in height

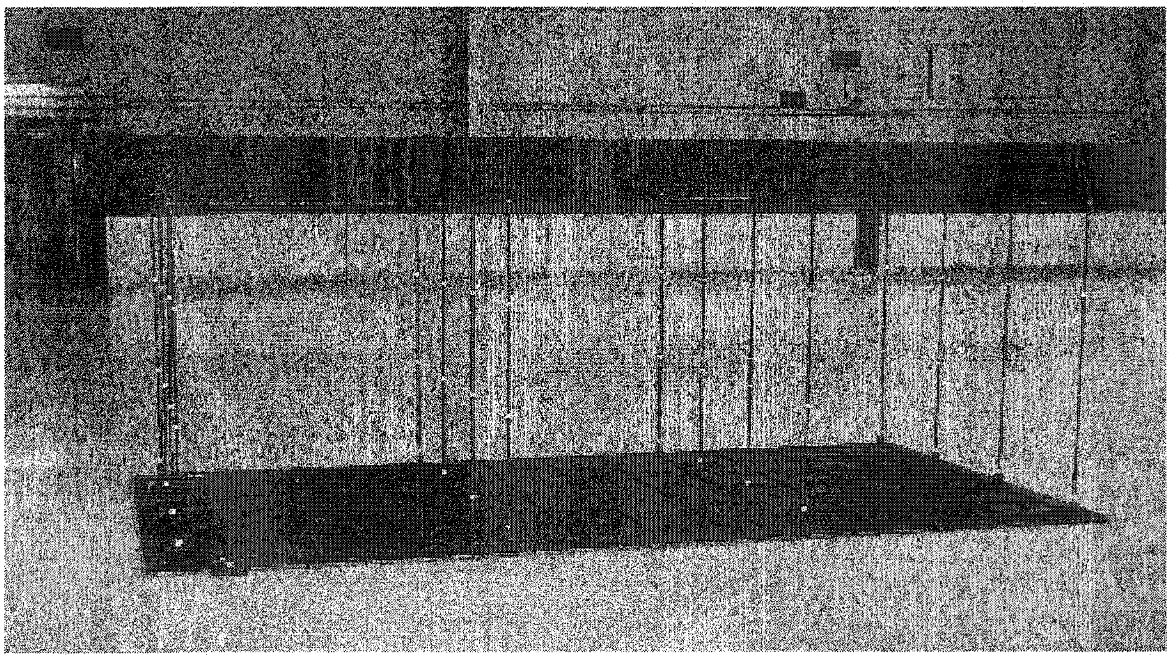

Figure 3.2 Large calibration frame used for the static camera set-up. The dimensions of this frame are 3.0m in length, 1.5m in depth and 1.0m in height.

Balancing and aligning the 3DG was accomplished, using pre-determined alignment markings on the base of the 3DG. Lead weights were hung from the top of the calibration 3DG and alignment was achieved once the weights lined up were aligned with the predetermined markings. This step was repeated each time the 3DG was reconstructed and was verified regularly.

Each 3DG contained 48 markers accurately measured (see Appendix A.1 and A.2). The marker positions on the 3DG were accurately measured using a theodolite. The theodolite was placed in a fashion to properly measure all three dimensions (X, Y and Z components) of each marker components of each marker. Measurements of each point were taken for each of the two filming volumes.

3.1.2 Video Cameras

The filming of all the trials was made easy with the use of two high-speed digital video (HSDV) cameras (JVC camera: model GR-DVL9800, City, Country) (Figure 3.3). These two HSDV cameras could record at three speed settings, 60, 120 or 240 fields/s. For the purposes of this study, the HSDV cameras were set at 60 fields/s, which was sufficient. Other advantages associated with these cameras are their small size and because they are lightweight. These factors made them easier to handle during the mobile camera phase of the study. Their small size made them less cumbersome to attach to the mobile device; larger cameras could have posed some balance and vibration related problems.

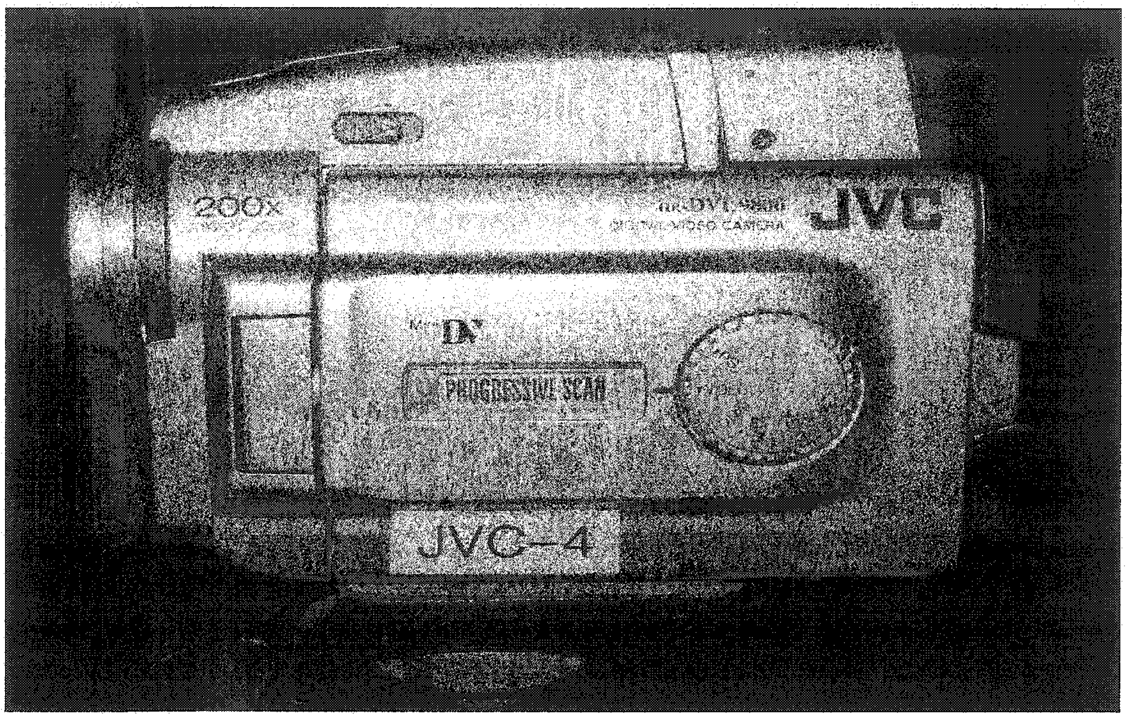

Figure 3.3 JVC GR-DVL9800 high-speed digital video camera used to collect data for the three camera set-ups.

3.1.3 APAS System

The Ariel™ dynamics software was used to perform all the digitizing of the trials recorded during the three testing conditions. The APAS™ system has its own DLT built-in software, thus easing data processing. The APAS™ system also offers a "Trimmer" feature that enhances the synchronization of all cameras involved in the data collection process. During the digitizing process, which can usually be long and tedious, the APAS system offers the option of automatic marker digitizing. An advantage of this option is an increase in the accuracy since the software determines the centroid of each reflective marker based on its number of pixels. Another advantage of this system is that it was developed to perform panning camera research, which was crucial for this study.

3.1.4 3D Digitizer (3DD)

All standard coordinates were measured with an accurate three-dimensional digitizer (3DD) (Microscribe 3DL, Immersion Corporate, San Jose, USA). The 3DD can precisely measure virtually any object (Figure 3.4). It has an accuracy of 0.23mm and a workspace size of 1.27m. A tip extension was developed to enhance its workspace size in order to expand the objects it can measure. The 3DD was used in this study to measure the moving calibration frame, the markers on the pendulum and the markers on the subjects' leg.

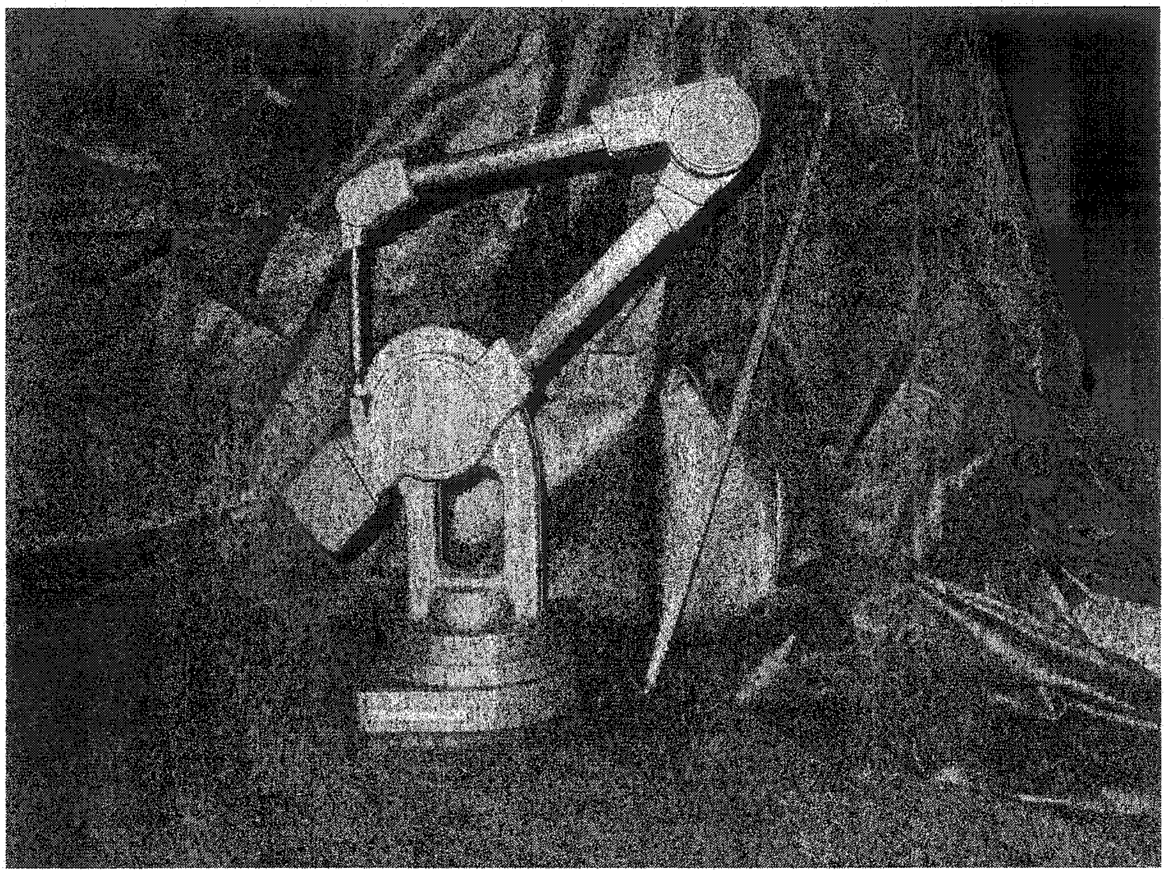

Figure 3.4 The 3D digitizer was used to measure the moving calibration frame, the pendulum and the segment markers. The long silver rod is an extension tip made to enhance its the workspace capabilities.

3.2 TEST CONDITIONS

3.2.1. Linear Motion Condition

The basis for this test condition is to verify that all camera set-ups can accurately reconstruct an object of known coordinates and vector lengths during one directional movement (linear). This is a simple motion, with minimal variability since only one dimension of the three dimensional coordinate should be subject to change. In this case, since the object was moving from the left side of the filming volume to the right, the X component should be the only coordinate to be subject to change. To accomplish this task, a cart (Figure 3-5), with 8 markers of known coordinates, was used. The three-dimensional coordinates of the 8 markers were measured using the 3D digitizer. The marker on the bottom left corner of the cart was considered as the origin (0,0,0) and all the other markers were measured with reference to the origin. Nine vectors lengths (see Appendix B.1), shown in Figure 3.5, were calculated from the obtained three-dimensional coordinates by means of the vector length equation (1). The markers on the cart were covered with reflective tape to facilitate the video capture and digitizing process.

The video data from all three trials were then trimmed in APAS to ensure good synchronization. The trials were then individually digitized in APAS and transformed to produce three-dimensional coordinates of the markers placed on the cart. Vector lengths were calculated from the 3D positional coordinates using the vector length formula.

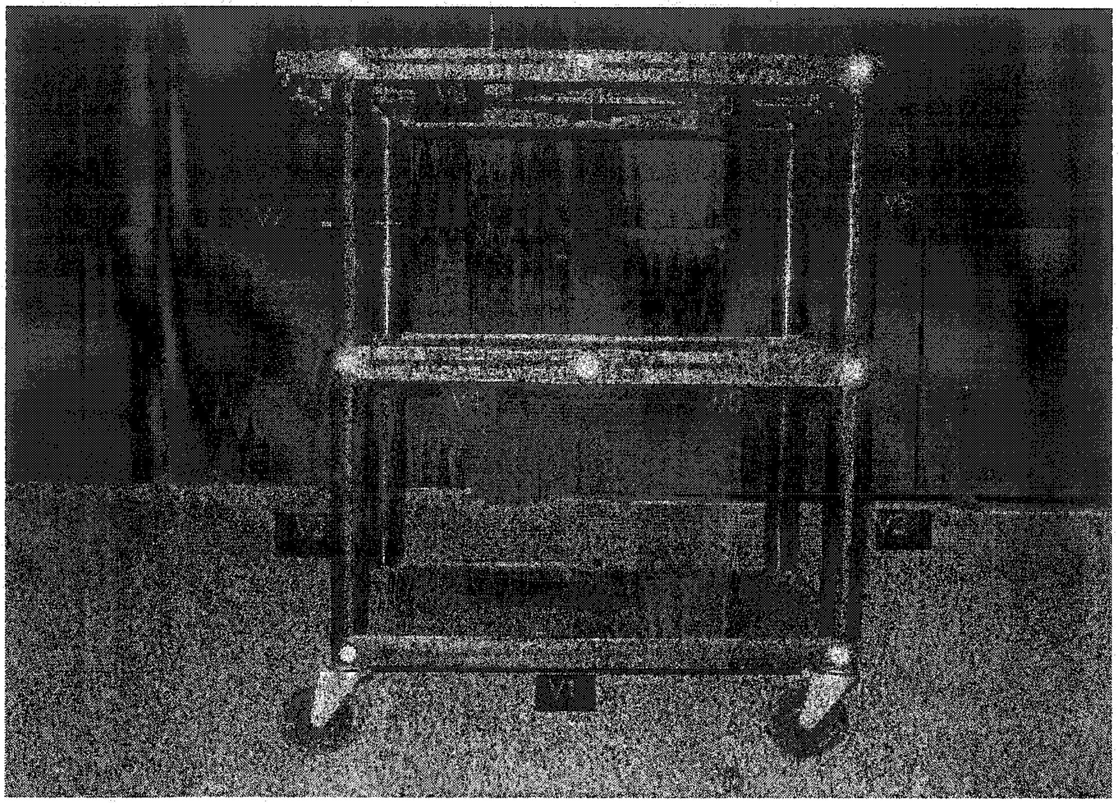

Figure 3.5 Marker placement and vector identification on the cart. The three dimensional coordinates of each marker were precisely measured with the 3D digitizer and vector lengths were calculated.

3.2.2 Angular Motion Condition

With the linear validation, only one component of the three-dimensional coordinates was subject to change. The angular motion condition looked at reconstructing positional coordinates of a moving object while being subjected to changes to multiple components of the three-dimensional coordinates. To verify the reliability of the three camera set-ups for angular motion a pendulum movement was selected, since it involves relative angular motion. With the pendulum, two axes are subject to constant change, the X-axis (through forward motion) and the Z-axis (through vertical displacement). Three reflective markers were placed on the pendulum and their positional coordinates were precisely measured using the 3D digitizer). Three vectors (see Figure 3.6) were then calculated from the coordinates of the markers using the vector length formula (see Appendix B.2). The purpose of this test was to ensure that the vector length between two markers on a moving pendulum did not change during one angular cycle.

Three trials were recorded for this test condition. A trial was defined by collecting three complete cycles of the pendulum. A complete cycle was defined as full forward and full backward motion. As was done in the linear motion validation, the video data from all three trials were then trimmed. The trials were then individually digitized in APAS and transformed to produce three-dimensional coordinates of the markers placed on the cart. Again, vector lengths were calculated from the 3D positional coordinates using the vector length formula.

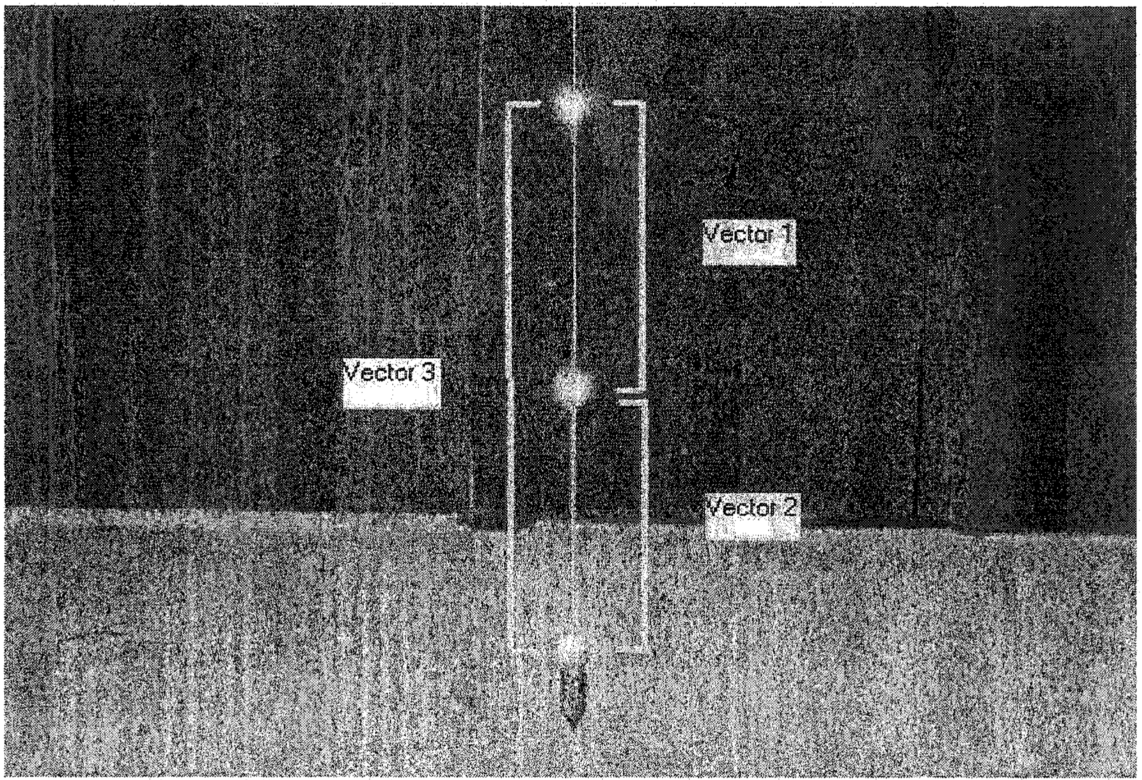

Figure 3.6 The pendulum used during the three camera set-ups is illustrated. Three markers were positioned on the string at precisely measured distances. Three vectors were measured before and after digitizing, and compared to obtain RMS error.

3.2.3 Gait Condition

The previous two testing conditions (linear and angular motion validation) are good testing experiments however, not realistic experimental settings since many variables are controlled. For example, during the linear motion condition, only the X component of the 3D coordinates of the markers is changed, the other two components always remain in the same position throughout the trials. In the case of the angular motion validation is basically a two-dimensional controlled angular movement. Certain aspects of three-dimensional motion, such as combined linear motion and three-dimensional rotations, are not analyzed. In addition to validating the three camera systems, this work hopes to determine which produces the most accurate results in a realistic experimental setting. Gait trials were used to achieve this objective.

Nine reflective markers were placed on the subjects' right leg. Conventional triangular marker placement was used on each segment of the subject's right leg to determine rigid body motion (Figure 3.7). Distances between the three markers were calculated from their 3D coordinates measured using the 3D digitizer. Measurements of the rigid body segments are shown in (see Appendix B.3). The thigh segment was defined by vector 1 (v1), vector 2 (v2) and vector 3 (v3). The shank was defined by vector 4 (v4), vector 5 (v5) and vector 6 (v6). Finally, the foot segment was defined by vector 7, (v7), vector 8, (v8) and vector 9 (v9).

The subject was asked to walk normally within the filming volume from the left side to the right. Three trials were recorded for this test condition. A good trial was defined as containing three right-footed steps within the 5.5m filming volume. As was done in the linear and angular motion validation, the video data from all three trials were trimmed, digitized and transformed in APAS to produce three-dimensional coordinates of the markers placed on the subjects' right leg. Again, vector lengths were calculated from the 3D positional coordinates using the vector length formula.

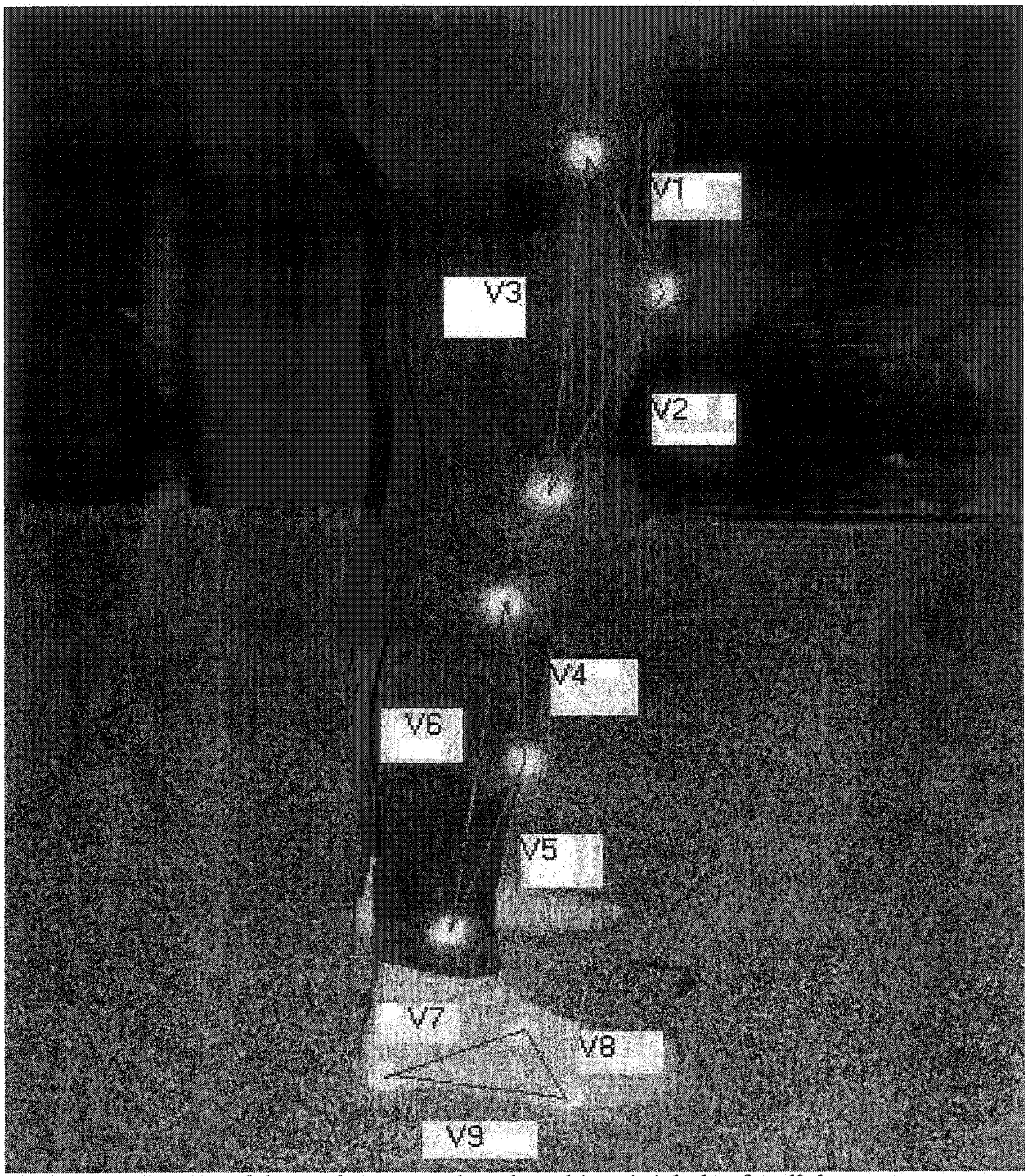

Figure 3.7 Diagram of the marker set used on the subjects' right leg for all three cameras set-ups. Distances between all three markers on each segment of the subjects' leg were precisely measured using the 3D digitizer. Vectors a numbered accordingly (v1 through v9).

3.3 CAMERA SET-UPS

In order to minimize camera position variability, all three test conditions for each camera set-up were filmed sequentially. The following are descriptions of the methodology followed for each camera set-up during the three testing conditions.

3.3.1 Stationary Camera Set-up

For the purpose of this study, the filming volume needed to be sufficiently large to perform at least three strides of walking. The larger calibration frame (Figure 3.2), with dimensions of 3.0m x 1.5m x 1.0m, was used. The larger calibration frame was needed since the static camera set-up does not allow for the cameras to follow the subject throughout the filming volume. Both cameras must remain perfectly still during the data collection process. The calibration frame contained 48 precisely measured markers of which 20 were chosen in a uniform pattern with relatively large distances between them, as recommended by Chen (1994), to define the filming volume. Due to the inability of the stationary camera set-up to follow (pivoting and turning) the subject through-out three cycles of a walking trial, the cameras-to-filming volume distance needed to be large (approximately 6.0m away from the front of the filming volume) to ensure that both cameras were able to view the entire 5.5m filming volume (see Figure 3.8). For all three test conditions, the two cameras were synchronized using a camera flash prior to each trial. The calibration frame was filmed for five seconds in the center of the filming volume prior to the first trial of each test condition. Three trial test conditions were recorded sequentially in order to preserve the same camera positions throughout the entire data collection process.

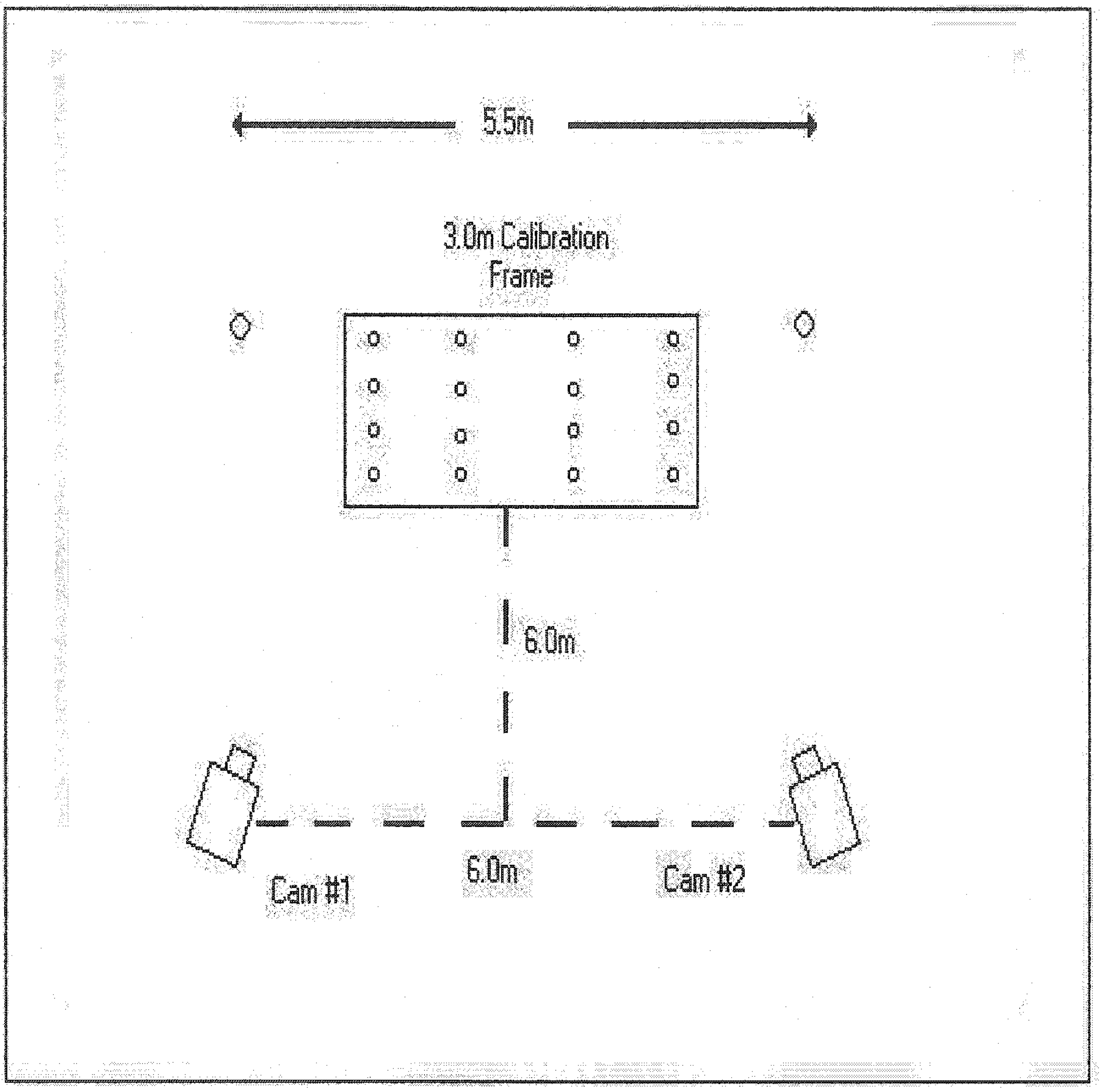

Figure 3.8 Arial view of the static camera set-up. The calibration frame (20 markers) is filmed first to define filming volume. For the stationary set-up, the line between the cameras was approximately 6.0m from the front of the filming volume. The distance between the two cameras was also approximately 6.0m to ensure that both cameras viewed the whole 5.5m filming volume.

3.3.2 Panning Camera Set-up

It was determined prior to the data collection process that at least three strides of walking would define the length of the filming volume. The smaller calibration frame configuration can be used for this camera set-up since the cameras are placed closer to the filming volume (approximately 3.0m). The dimensions of the smaller calibration frame configuration are 1.5m in length, 1.5m in depth and 1.0m in height (Figure 3.1). The size of the calibration frame coincided with the length of the walking trials, the focus of which will be the subject's leg (from hip to foot). The cameras were set-up in a fashion to ensure that the calibration frame filled the video cameras' entire view screen. The difference between the stationary and panning procedure is that it was necessary to ensure, for the stationary camera set-up, that each camera could capture the entire 5.5 meter filming volume while the panning technique, capable of following the subject, therefore could focus on the subject rather than the entire filming volume. Inter-camera distance was determined based on the size of the filming volume and, as aforementioned, on maintaining a relatively large distance to ensure constant view of all markers throughout the movement. However, when using the panning method it was important to ensure that no markers are lost as the camera-subject distance decrease. If the distance between the two cameras is too big, marker loss becomes a significant issue. As the subject-camera distance increases, there is a higher possibility of marker loss. Tests were performed prior to the actual collection of data to ensure that all markers were visible throughout the entire trial. It was determined that by placing the cameras at equidistance relative to the center of the filming volume, marker loss would be minimal. This procedure also ensures equal camera-subject distance for both cameras throughout all the trials.

The first step of the panning process is to define reference markers within the field of view. The measurements of these markers are known and used by the APAS as reference markers during the panning process. Also, these markers are necessary to enable the APAS system to locate where the subject is positioned inside the filming volume. A rod with markers, similar to the one used by Yu et al (1993), was built and placed in front of the filming volume. Five markers placed a meter from on another on the rod were used as the reference markers for the APAS system during the digitizing process. It is important to note that with APAS, there is no limit to the amount of reference markers used during the collection process.

The procedure to define the filming volume for the panning camera set-up differs from the stationary set-up. APAS has developed a simple procedure for calibrating such a filming volume. The calibration frame was filmed in two different positions in the filming volume (see Figure 3.9). The first position is described as the "Pan Left" position and the second as the "Pan Right" position. These two positions define the beginning and the end of the filming volume. The distance between the two calibration trials (Pan-Right and Left) must be known since that distance will be added to the X-axis of the positional coordinates of each marker on the Pan Left to define the Pan Right frame. For instance, (see Figure 3.10) if the coordinates of point#1 on the calibration frame found using the Pan Left frame is (0,0,0) and the distance between the two calibration frames is one meter, then the positional coordinate of the same marker on the Pan Right calibration frame will be (100,0,0). APAS, when using the panning procedure, identifies both calibration frames as one large calibration frame. The reference markers placed between the two frames, also known as "Pan Points", are also precisely measured relative to the origin found at the rear- bottom-left corner of the left calibration frame. The positional coordinates of all the control markers can be found in appendix A.3; the "Pan Point" coordinates are in italic at the bottom of the table. The calibration rod with known points was placed in the front of the filming volume in order to ensure that the points are never blocked or covered by the subject during the trials. During the data collection phase, the cameras did not need to move in a synchronized fashion; however it was important to ensure that the tripod was locked into a "pivoting only" setting. Any tilting of the cameras could skew the data collection.

To reiterate what was stated in section 3.3.1, both cameras for each testing condition collected three trials. Synchronization, again, was achieved with a camera flash prior to each trial. The calibration frame, in both the "Pan Left" and "Pan Right" positions, were filmed for five seconds in their respective positions defining the filming volume prior to the first trial of each test condition. Three trial of each test condition were recorded sequentially in order to preserve the same camera positions throughout the entire data collection process. Finally, the digitizing process followed the instruction offered by APAS.

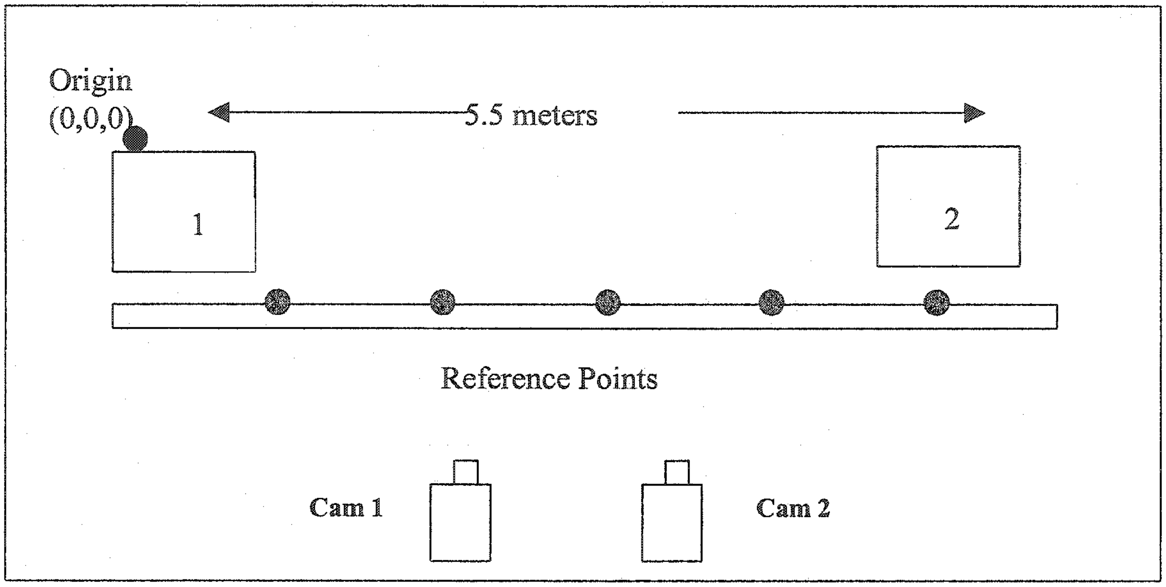

Figure 3.9 "Pan Left" (position 1) and "Pan Right" (position 2) define the filming volume space. Reference markers between the two calibration frames are precisely measured with reference to the origin on frame #1. These reference markers are very important during the digitizing process with APAS.

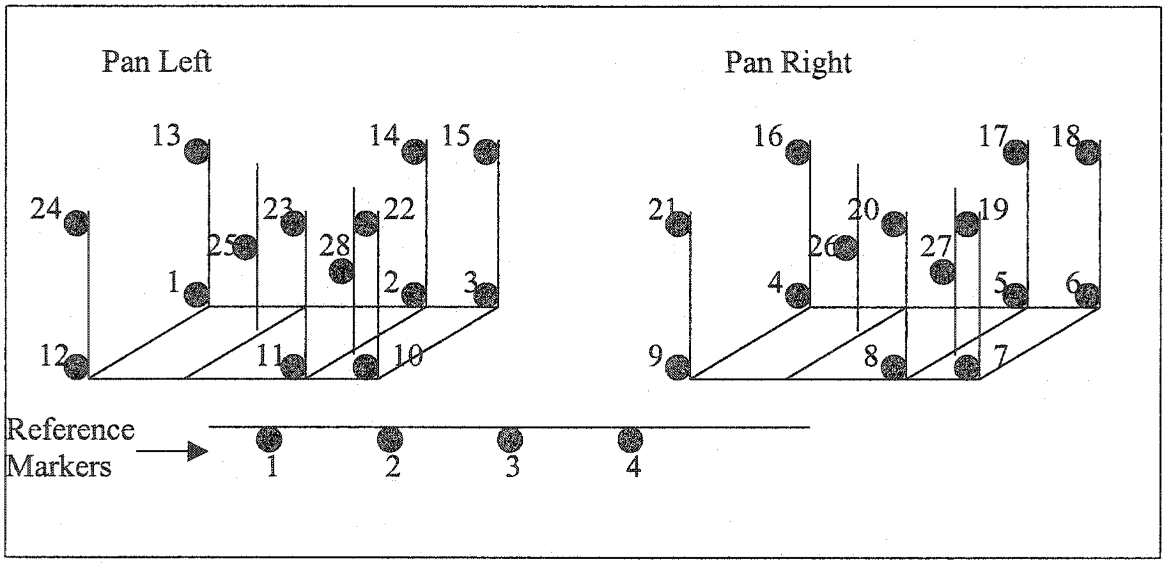

Figure 3.10 The control points used to define the filming volume. The number beside each marker represents the order these points were digitized in based on APAS's described methodology.

3.3.3 Mobile Camera Set-up

As was done with the panning camera set-up, the 1.5m calibration frame was used. This mobile camera set-up allowed for the smallest camera-to-filming volume distance of the three camera set-ups with a distance of approximately 2.0m. This also allowed for the cameras to focus on the close range aspect of the study (focusing on the subjects' hip to foot).

The two cameras were fixed to a wheeled mobile platform (Figure 3.11). A rail system was built to accommodate the mobile device and ensure that the cameras moved perfectly parallel to the filming volume during data collection (Figure 3.12). Polyvinyl Chloride (PVC) tubes were cut in half to construct the track. Two wheels of the mobile platform were placed in a track that ran parallel to the filming volume in order to ensure proper alignment and reduce variability. This produced a smooth surface with little freedom of movement for the wheels. The PVC tracks were aligned and anchored to wooden planks on the floor. Vibration of the mobile device during the trials was a concern. The mobile platform was fitted with rubber wheels to minimize frame vibration.

The APAS system was used to treat the video data even though it is technically not supposed to be able handle data from a mobile camera set-up. The APAS system uses fixed points to determine the camera positions. With the mobile camera set-up, it would not be possible to have a fixed point in the filming volume since the cameras are always moving and the fixed point would never be in the same place. In Lafontaine et al (2003) study, a rod with many reflective markers was placed in front of the filming volume along the X-axis. This allowed them to "fool" the APAS digitizing system into believing the cameras were set-up in a static setting. The basis of their idea was that as the image advanced and the fixed point moved out of APAS' allotted fixed-point box, another marker would come into the box to be digitized. This turned out to be quite successful, although involved a very long digitizing process. To alleviate this problem, a rod with a single reference marker was attached to the mobile device and was used as the fixed point required for the APAS software during digitizing. Both cameras needed to be adjusted to ensure that they were able to see this fixed point.

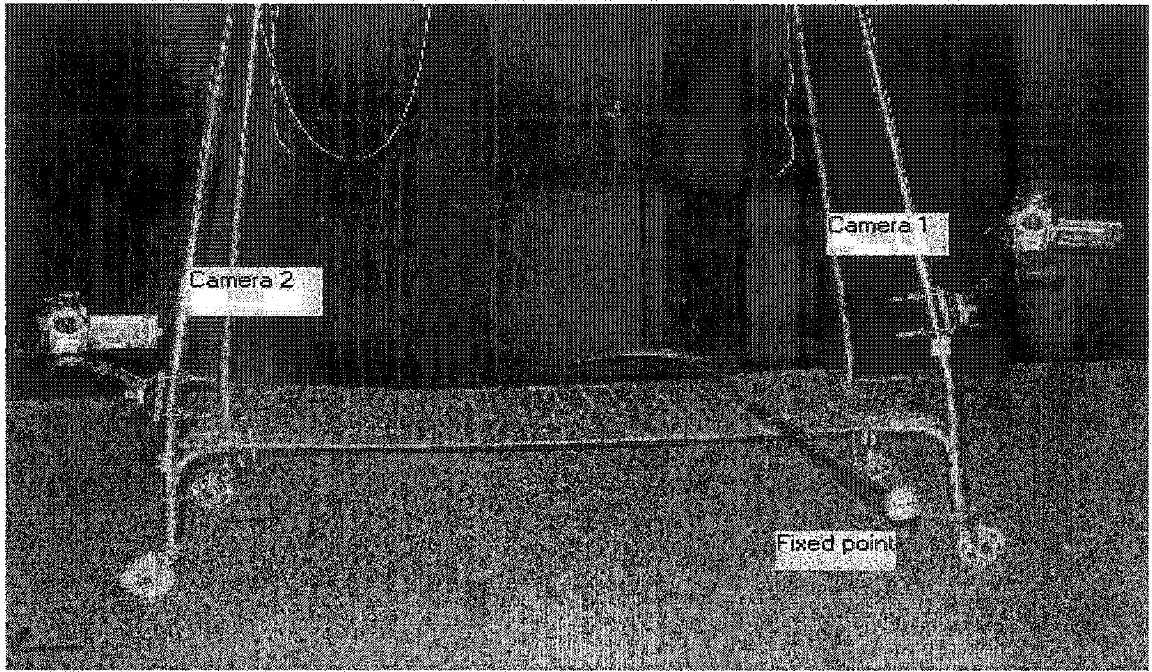

Figure 3.11 Mobile platform used to mount the cameras. The wheels on the device are rubberized and therefore minimize vibration during movement. The fixed point is attached to the device and is clearly viewed by both cameras at all times.

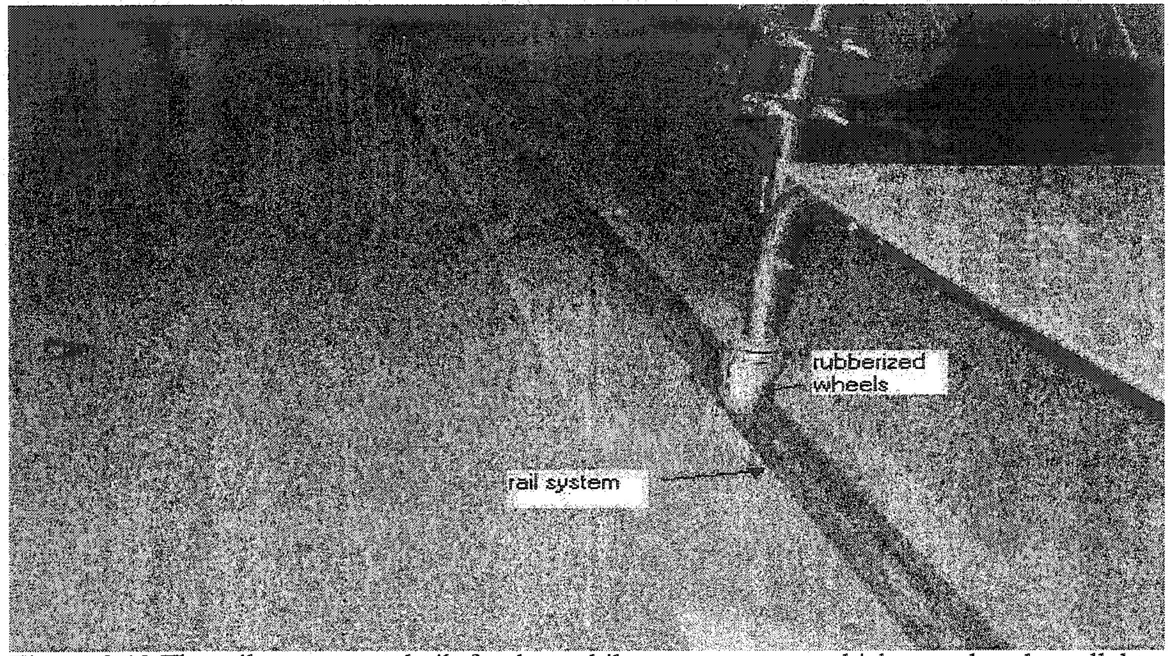

Figure 3.12 The rail system was built for the mobile camera set-up, which was placed parallel to the filming volume. The rail is made of PVC material, which was fastened to the floor and stretched along the full length of the 5.5 m filming volume. The rubber wheels were used to help dampen the possible vibration during movement of the mobile device.

During the data collection process for all three testing conditions, the calibration frame was placed and filmed at 60 Hz in the far left edge of the 5.5m filming volume (Figure 3.13) to define the filming volume. The video cameras were synchronized using a camera flash prior to each trial. All trials were trimmed and digitized using the APAS system.

It was determined while collecting the data for the angular motion validation, that the mobile camera technique would only collect one forward swing of the pendulum. Due to the momentum of the mobile camera platform when following the forward motion of the pendulum, it was deemed impossible to accurately stop the platform and change its direction without inducing errors. Only the forward phase (left to right) of the pendulum's motion was digitized for all the camera set-ups in order to ensure consistency.

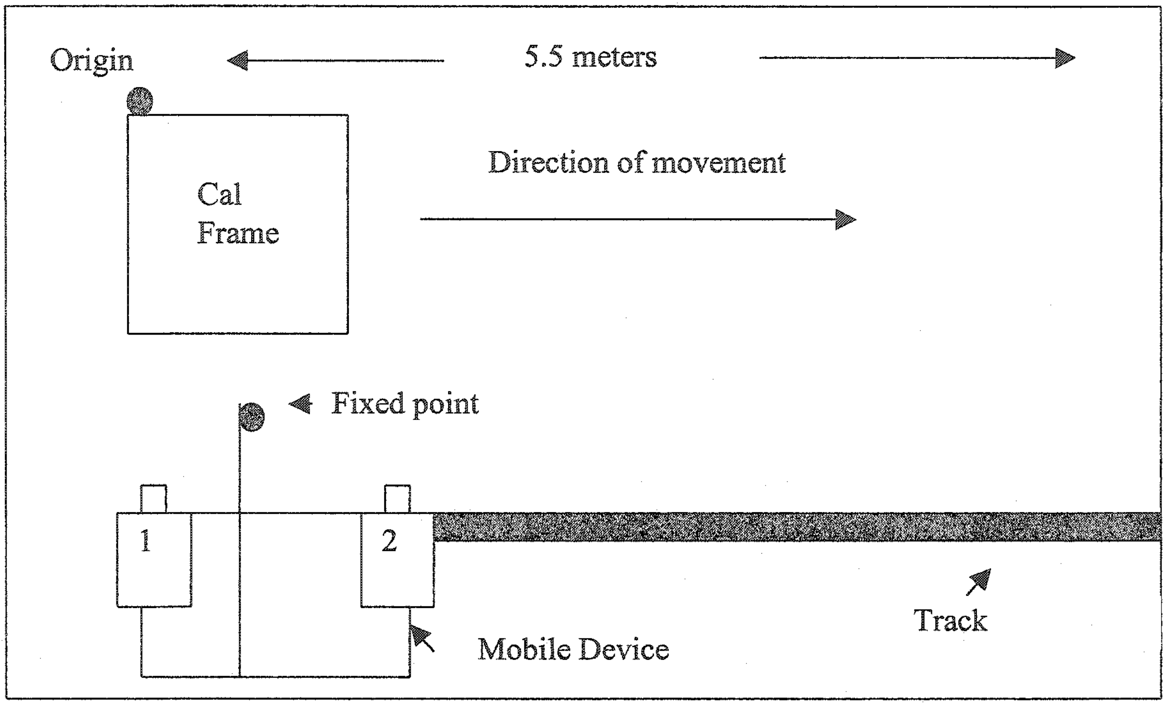

Figure 3.13 Mobile set-up: cameras are mounted on a trolley, which has its two front wheels in a track parallel to the filming volume. A moving fixed point is also mounted on the trolley in order to move with the cameras.

3.4 TREATMENT OF THE DATA

The three camera set-ups were evaluated with the linear, angular displacement and gait testing conditions. The reference system used was as shown in Figure 3.14

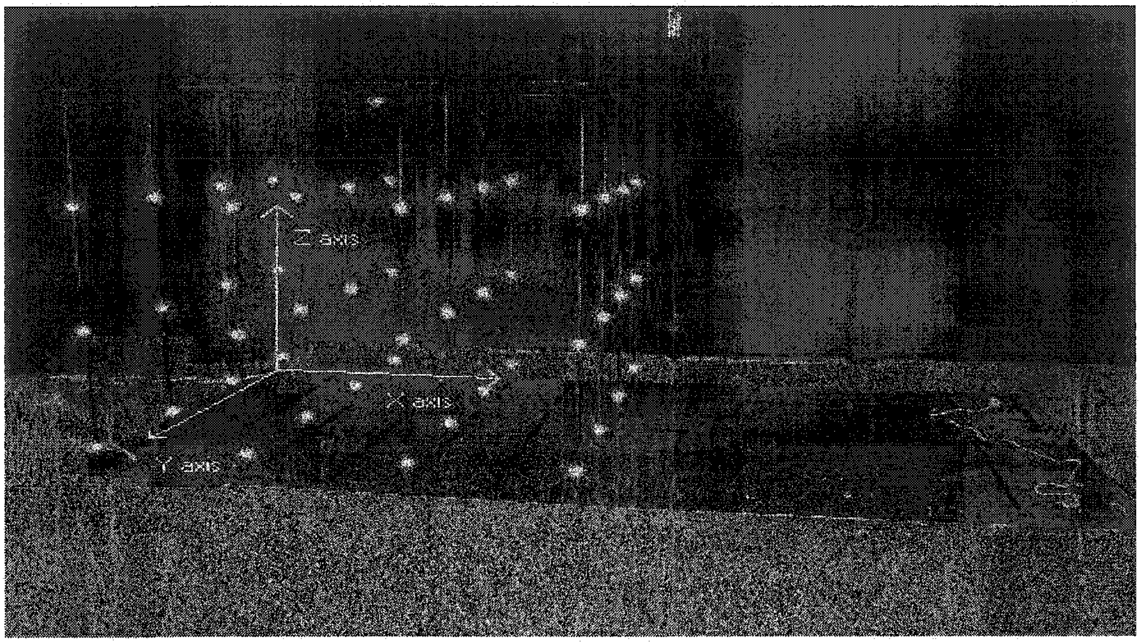

Figure 3.14 Illustration of the orientation of the three axes. Positive X going from the origin in the bottom back left corner of the calibration frame towards the right. Positive Y is actually going from the origin towards the wall in this figure. Y-axis values are measured towards the front of the calibration frame showing negative values. Finally, the positive Z-axis goes from the origin and up towards the ceiling.

3.4.1 Calculation of Residual Error

The first step for the calculation of residual errors was to take the video data and convert it to text files. APAS produces .3d files after the digitizing is complete. APAS also has a converter, which takes the .3d files and converts them into readable text files. These text files were then placed into Excel where a macro was created to calculate vector length (equation 3.1). The vector length values obtained from this macro are then inserted into an excel template where residual errors of the vector length measurements are calculated by means of equation (3.2). This was done for every vector in all three testing conditions for each camera set-up.

$$Vectorlength = \sqrt{(\Delta X)^2 + (\Delta Y)^2 + (\Delta Z)^2} \qquad \textbf{(3.1)}$$

Where Δ = difference between two points

3.4.2 Data Analysis

Descriptive analysis of the data will include determination of RMS error for all vectors in each camera set-up for the three testing conditions. Calculating the sum of RMS error of each vector and dividing it by the number of reconstructed vectors or measurements determined a mean RMS error (Equation 3.2) for each camera set-up in the three testing conditions. Standard deviation was also calculated for each camera set-up and for each setting. Comparison of the three camera set-ups for each testing condition was done by means of percentage of difference. In order to calculate the percentage of difference between two camera set-ups, the equation (3) below was used.

$$V_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} V_i^2} = \sqrt{\frac{V_1^2 + V_2^2 + \ldots + V_N^2}{N}} \qquad \textbf{(3.2)}$$

Where $V_i = (V_r - V_e)$; V_r and V_e are real vector measurements and experimental vector measurements respectively

$$\%RMS = \frac{(V_{RMS_S} - V_{RMS\,x})}{V_{RMS\,s}} * 100 \tag{3.3}$$

Where s = RMS error of stationary camera set-up and x = RMS error of panning or mobile camera set-up.

CHAPTER IV

RESULTS AND DISCUSSION

This chapter will report the post analysis results. The results will be presented in the same order as the previous chapter.

4.1 TESTING CONDITIONS

4.1.1 Linear Motion Test Condition

Tables 4.1 to 4.3 show residual errors of each reconstructed vector for the linear motion test condition. The mean RMS error in the static camera set-up for the linear motion validation was found to be 0.4±0.4cm. Conversely, for the mobile and panning camera set-up, where the cameras are capable of being place much closer to the subject, the mean RMS errors were noticeably lower at 0.2±0.2cm. Table 4.4 shows the percentage of difference between the three camera set-ups.

Table 4.1 Vector length measurement of markers on the moving cart for the stationary camera set-up. (n=3)

Static Cameras	**Linear Motion Validation**			
Segment#	**Actual measured length (cm)**	**Measured length (cm)**	**SD of measured length (cm)**	**RMS (cm)**
1	56.7	55.6	0.8	1.1
2	34.8	34.7	0.2	0.1
3	34.2	34.1	0.2	0.1
4	26.6	26.1	0.4	0.5
5	30.0	29.2	0.5	0.8
6	34.9	34.9	0.3	0.0
7	34.8	35.1	0.3	0.3
8	26.0	25.4	0.3	0.6
9	31.0	30.5	0.4	0.5
Mean				**0.4**
Mean SD				**0.4**

Where n = number of trials averaged

Table 4.2 Vector length measurement of markers on the moving cart for the panning camera set-up. (n=3)

Panning Cameras	**Linear Motion Validation**			
Segment#	**Actual measured length (cm)**	**Measured length (cm)**	**SD of measured length (cm)**	**RMS (cm)**
1	56.7	57.0	0.8	0.3
2	34.8	34.6	0.2	0.2
3	34.2	33.9	0.2	0.3
4	26.6	27.0	0.3	0.4
5	30.0	30.0	0.5	0.0
6	34.9	34.8	0.2	0.1
7	34.8	35.2	0.2	0.4
8	26.0	26.1	0.3	0.1
9	31.0	31.2	0.4	0.2
Mean				**0.2**
Mean SD				**0.2**

Table 4.3 Vector length measurement of markers on the moving cart for the mobile camera set-up. (n=3)

Mobile Cameras	**Linear Motion Validation**			
Segment#	**Actual measured length (cm)**	**Measured length (cm)**	**SD of measured length (cm)**	**RMS (cm)**
1	56.7	56.8	0.2	0.1
2	34.8	34.5	0.1	0.3
3	34.2	34.1	0.1	0.1
4	26.6	26.8	0.2	0.2
5	30.0	30.1	0.1	0.1
6	34.9	35.1	0.1	0.2
7	34.8	35.2	0.1	0.4
8	26.0	25.9	0.2	0.1
9	31.0	31.4	0.1	0.4
Mean				**0.2**
Mean SD				**0.1**

The mobile and panning cameras cut the stationary camera residual error in by as much as 50% (see Table 4.4).

Table 4.4 Percentage of difference of RMS error between the three camera set-ups in the linear motion test. (n=3)

Camera Set-up	**RMS Error (cm)**	**% of Difference**
Stationary	0.4	0%
Panning	0.2	50%
Mobile	0.2	50%

The panning and mobile camera set-ups also produced lower standard deviation values, demonstrating low variability in the measurements of the vectors. This could be due to the rather large differences in camera-to-filming volume distance between the stationary camera set-up (approx. 6 meters) and the panning (approx. 3 meters) and mobile (approx. 2 meters) camera set-ups. It was reported that high residual errors could be expected if the distance between the cameras and the filming volume is too great (Lamontagne et al, 2000). It was thus expected that, for the most part, higher residual errors were found for the stationary camera set-up since these cameras were placed the furthest from the filming volume of the three camera set-ups in order the ensure that the entire 5.5 m filming area was captured. Looking at the camera-to-filming volume distance, the stationary cameras were approximately six meters from the front of the filming volume, while the panning and mobile cameras were able to get as close as three and two meters respectively. It has been indicated that if the distance between the cameras is approximately one-third of the distance from the object to line between the cameras and the convergence is kept to a minimum, acceptable data can be obtained (Shapiro, 1978). The static cameras were set-up in a fashion to ensure that the whole filming volume was in each camera's view. The consequences of doing this were two-fold. The first being that the camera to object distance was approximately six meters and the second was that the camera-to-camera distance was approximately six meters. This represents a camera-to-camera distance equal to the distance from the filming volume to the line between the two cameras. This is considerably greater than the maximum distance recommended by Shapiro. The mobile and panning techniques, on the other hand, had a much smaller camera-to-camera distance. Looking a little closer to the standard deviation (SD) of the measured vector lengths of the panning camera set-ups in comparison with the mobile camera set-up, it can be seen that the panning camera set-up demonstrates much more variability, with standard deviation as high as 0.8cm, than the mobile camera set-ups' highest SD value of 0.2cm. Figure 4.1 displays the mean RMS error of the three camera set-ups for the linear motion test condition. There is an obvious decrease in mean error from the stationary to the mobile camera set-up. There is also a rather high mean standard deviation (0.4cm) of the RMS error for the stationary camera set-up in comparison with the other two camera set-ups (panning 0.2cm and mobile 0.2cm).

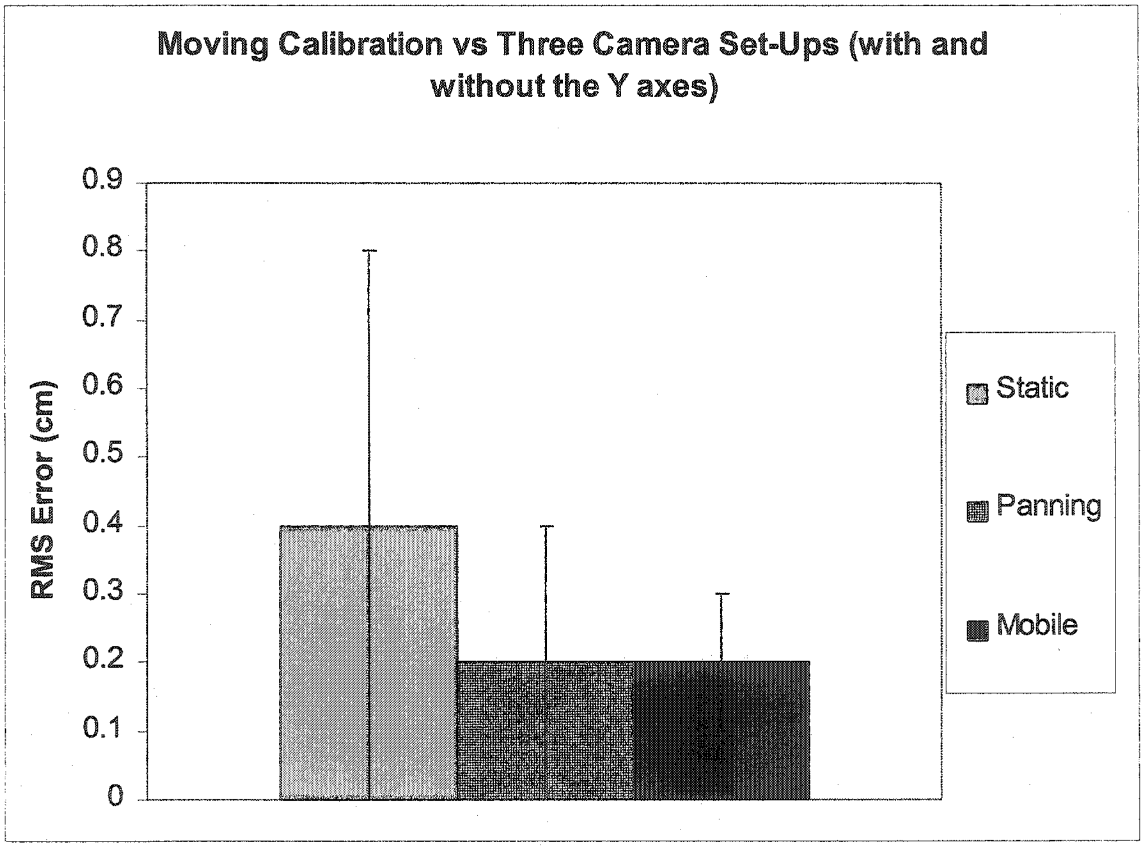

Figure 4.1 RMS errors of the three camera set-ups for the linear motion testing condition. Standard deviation is also displayed.

4.1.2 Angular Motion Testing Condition

Similar results as in the previous section were found for all three-camera set-ups using the angular motion test condition. Table 4.5 shows RMS values for each of the three vectors for the stationary camera set-up. A mean RMS error of 0.7±0.3 cm was found for this camera set-up. Table 4.6 contains the results for the panning camera set-up, which shows noticeably lower mean RMS errors than was found for the stationary camera set-up. Mean RMS error for the panning camera set-up was 0.2±0.1 cm. The mobile camera set-up (Table 4.7), a low mean RMS error value of 0.1±0.1 cm was found.

Table 4.5 Vector length measurement of three points during angular motion test for the stationary camera set-up. (n=3)

Stationary Cameras	**Angular Motion**			
Vector#	**Actual measured length (cm)**	**Measured length (cm)**	**SD of measured length (cm)**	**RMS (cm)**
1	34.0	34.6	0.1	0.6
2	32.2	32.6	0.2	0.5
3	66.2	67.3	0.1	1.1
Mean				**0.7**
Mean SD				**0.3**

Table 4.6 Vector length measurement of three points on a pendulum for the panning camera set-up. (n=3)

Panning Cameras	**Angular Motion**			
Vector#	**Actual measured length (cm)**	**Measured length (cm)**	**SD of measured length (cm)**	**RMS (cm)**
1	34.1	34.2	0.1	0.1
2	31.9	31.8	0.2	0.2
3	66.1	66.0	0.3	0.1
Mean				**0.2**
Mean SD				**0.1**

Table 4.7 Vector length measurement of three points on a pendulum for the mobile camera set-up. (n=3)

Mobile Cameras	**Angular Motion**			
Vector#	**Actual measured length (cm)**	**Measured length (cm)**	**SD of measured length (cm)**	**RMS (cm)**
1	34.0	34.2	0.2	0.2
2	32.0	32.2	0.2	0.1
3	66.2	66.4	0.3	0.2
Mean				**0.1**
Mean SD				**0.1**

Table 4.8 displays the percentage decrease of mean residual for the three camera set-ups. The panning camera set-up displayed much lower results than the stationary camera set-up, decreasing the error by 71%. Again, the mobile technique has the lowest mean RMS error decreasing the stationary camera set-ups error by 86%. Once again, this supports the expectations, stated earlier, of the mobile and panning camera set-ups producing the lowest RMS error.

Table 4.8 Percentage of difference of mean RMS error between the three camera set-ups in the angular motion test. (n=3)

Camera Set-up	RMS Error (cm)	% of Difference
Stationary	0.7	0%
Panning	0.2	71%
Mobile	0.1	86%

Figure 4.2 shows the mean RMS error of the digitized vector lengths for the three camera conditions. There is little difference between the panning and mobile camera set-ups, in contrast to the static camera set-up. The panning and mobile camera set-ups, once again, produce much smaller residual errors for vector length reconstruction than the stationary camera set-up. Minimal differences between the panning and mobile camera set-up were observed. Standard deviations of the three camera set-ups yield much the same results. The panning and mobile camera set-ups both demonstrated standard deviations of 0.1cm in reporting vector lengths while the static camera set-up displayed a larger value of 0.3cm.

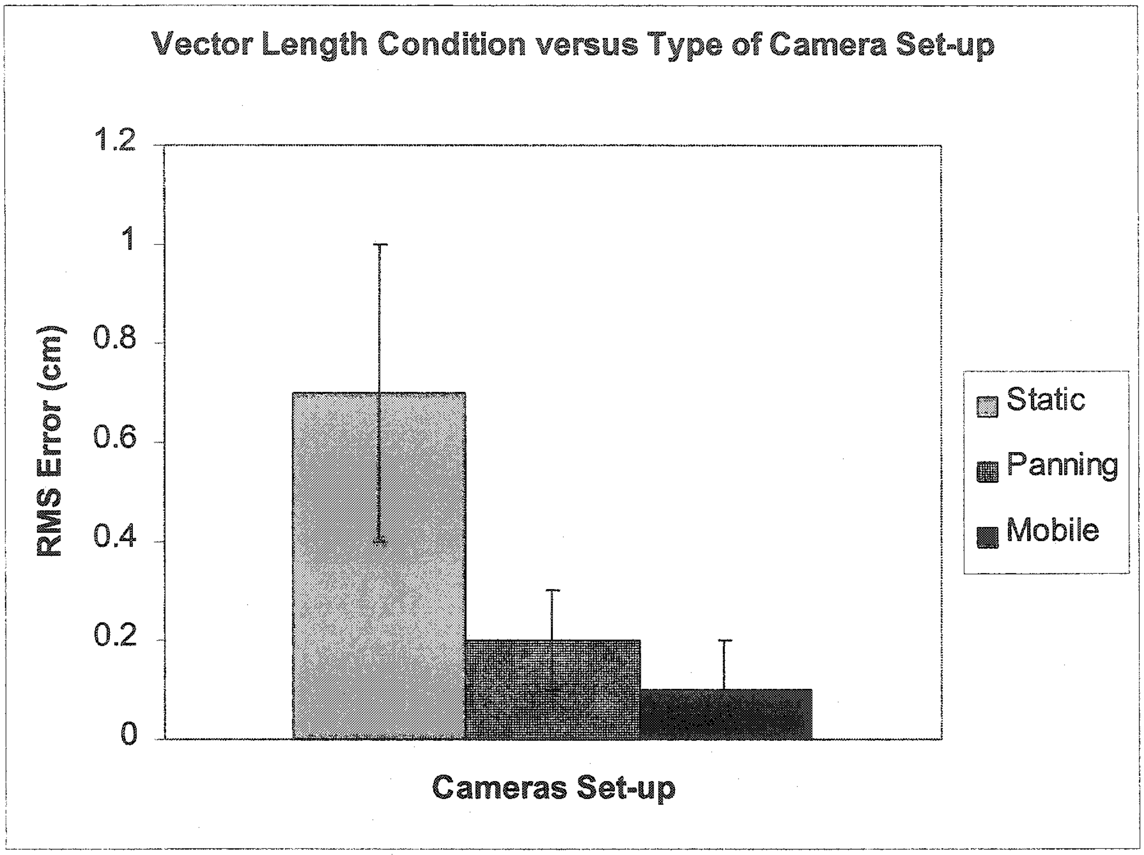

Figure 4.2 RMS error of the three camera set-ups for the angular motion test condition. Standard deviation is also displayed.

It was expected that the mobile and panning camera set-ups would produce the smallest mean RMS error. The errors reported for this testing condition were very similar to those seen in the linear motion test. A possible explanation for the higher stationary residual error could be, once again, due to the greater distance between the cameras and the filming volume. As the distance increases the markers become smaller in the camera view. When digitizing the collected video, the image is divided into two fields. The first field is made up of the horizontal odd lines of the original image while the second field is made up of the horizontal even lines. With the smaller markers in the stationary camera set-up, it could be easy for a positional markers' centroid be changed somewhat from field to field causing smaller, or larger vector lengths. In the linear motion test condition, movement was along one axis only (X-axis); therefore the odd and even fields would not effect marker position as much as in the angular motion condition. In this test condition, motion is happening along the X-axis and Z-axis. With the pendulum moving in a downward fashion and the images being divided into horizontal odd and even fields, there is a greater chance marker centroid movement. With the panning and mobile camera set-ups, the markers appeared much larger than in the stationary set-up. Any deviation of the centroid due to odd and even fields would be minimal since the size of the marker would never allow for a large percentage of the marker to change fields. This would likely explain why the static and mobile camera set-ups have very similar mean RMS values since they are approximately the same distance from the filming volume.

4.1.3 Gait Testing Condition

During the gait condition procedure, a subject was asked to walk normally wearing three sets of reflective markers placed in a triad defining the thigh, the shank and the foot of the right leg. These triads of points were precisely measured, creating three vectors per body segment (shown in Figure 3.7), for a total of 9 segment measurements. Table 4.9 shows mean RMS error for the stationary camera setting. A mean RMS error value of 0.9±0.6 cm was found. Both the panning and mobile camera set-ups showed a reduction in RMS error during this testing condition. Table 4.10 shows the mean RMS error for the panning procedure. A mean RMS error value of 0.5±0.3 cm was found. The mobile camera set-up produced a slightly lower mean RMS error of 0.4±0.4cm (Table 4.11). The three camera techniques show definite difference in RMS error. The static and mobile camera set-ups give the lowest standard deviations, 0.4 cm and 0.3 cm respectively. Though the panning camera set-up produces a lower RMS error than the static camera set-up, this method seems to yield a higher mean standard deviation for the nine digitized segment lengths.

Table 4.9 Mean RMS error of segment length measurements of markers placed on subject during the gait test condition for the stationary camera set-up. (n=3)

Stationary Cameras	**Gait Condition**			
Segment#	**Actual measured length (cm)**	**Measured length (cm)**	**SD of measured length (cm)**	**RMS (cm)**
1	18.4	18.0	0.4	0.4
2	16.2	16.9	0.4	0.7
3	31.5	32.2	0.5	0.7
4	16.5	16.6	0.4	0.1
5	16.0	17.3	0.3	1.3
6	30.1	31.9	0.5	1.8
7	13.8	12.1	0.3	1.7
8	7.8	7.2	0.4	0.6
9	15.0	14.6	0.4	0.4
Mean				**0.9**
Mean SD				**0.6**

Table 4.10 Mean RMS error of segment length measurements of markers placed on a subject during the gait test condition for the panning camera set-up. (n=3)

Panning Cameras	**Gait Condition**			
Segment#	**Actual measured length (cm)**	**Measured length (cm)**	**SD of measured length (cm)**	**RMS (cm)**
1	18.4	18.3	0.3	0.1
2	16.2	17.0	0.4	0.8
3	31.5	32.4	0.4	0.9
4	16.5	16.6	0.7	0.1
5	16.0	16.3	0.4	0.3
6	30.1	30.6	0.8	0.5
7	13.8	12.8	0.4	1.0
8	7.8	7.3	0.7	0.5
9	15.0	15.3	0.7	0.3
Mean				**0.5**
Mean SD				**0.3**

Table 4.11 Mean RMS error of segment length measurements of markers placed on a subject during the gait test condition for the mobile camera set-up. (n=3)

Mobile Cameras	**Gait Condition**			
Vector#	**Actual measured length (cm)**	**Measured length (cm)**	**SD of measured length (cm)**	**RMS (cm)**
1	18.4	17.9	0.3	0.5
2	16.2	16.6	0.3	0.4
3	31.5	31.8	0.2	0.3
4	16.5	16.3	0.3	0.2
5	16.0	16.1	0.2	0.1
6	30.1	29.9	0.4	0.2
7	13.8	12.6	0.4	1.2
8	7.8	7.2	0.3	0.6
9	15.0	15.0	0.4	0.0
Mean				**0.4**
Mean SD				**0.4**

Figure 4.3 shows mean RMS errors for the three camera set-ups, the mean RMS error and the mean standard deviation for the digitized segment lengths. The stationary camera set-up yields the highest RMS error for the walking trials with a mean value of 0.9±0.6cm. Though the mobile camera set-up yielded the lowest mean RMS error, the panning camera set-up had a lower standard deviation. All values are relatively higher than those obtained in the previous two tests. This is to be expected since the previous two tests were done in a somewhat controlled setting. With gait analysis, other variables come into play, such as skin and muscle movement.

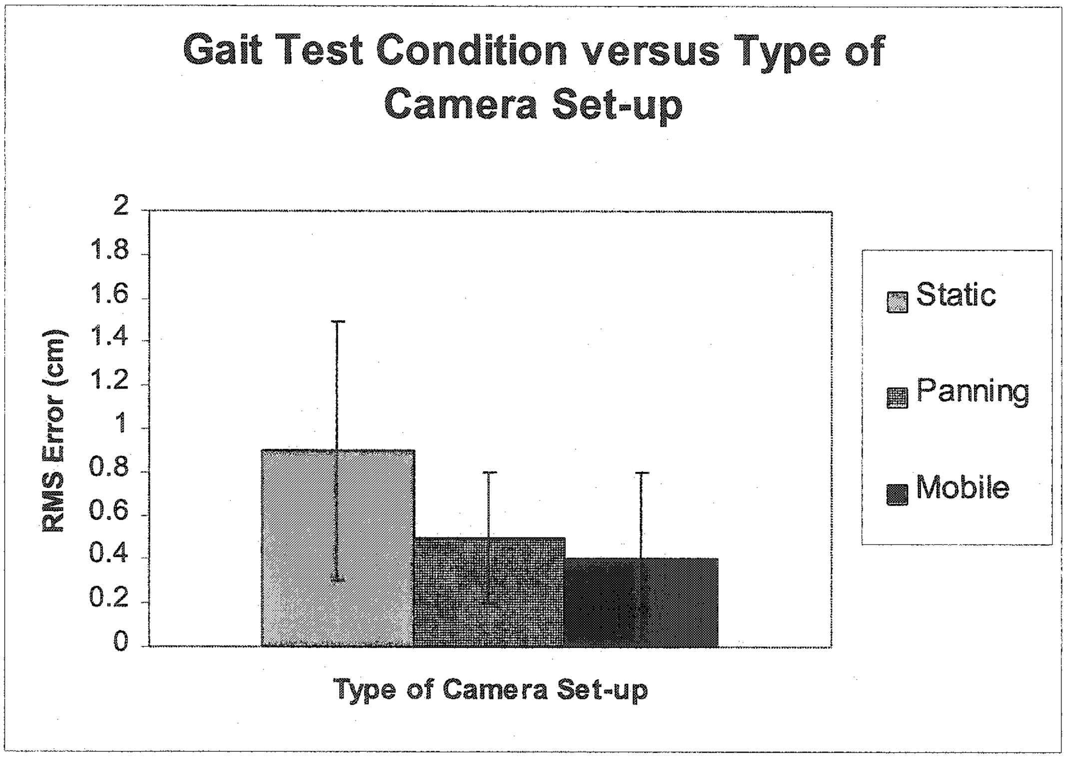

Figure 4.3 Mean RMS errors and standard deviation for the three types of camera set-ups using the gait test condition. It is shown that the mobile camera set-up offers the lowest mean RMS error of the three camera set-ups.

The main purpose of the gait testing conditions is to determine which camera set-up produces the lowest residual error. This was achieved by measuring segment length on the right leg of a subject while performing normal gait through the filming volume. It was important to test in a realistic experimental setting, in order to confirm the accuracy of the three camera set-ups. Mean RMS error found for the static camera set-up was found to be 0.9± 0.6cm. The panning procedure produced a mean RMS error of 0.5± 0.3cm. This represents a reduction of 44% from the stationary set-up. The mobile camera system displayed even lower error values. The mean RMS error for the mobile camera system was 0.4±0.4cm. This represents a reduction of 55% in RMS error from the stationary camera set-up.

Table 4.12 Percentage of difference of RMS error between the three camera set-ups. (n=3)

Camera Set-up	RMS Error (cm)	% of Difference
Stationary	0.9	0%
Panning	0.5	44%
Mobile	0.4	55%

The results from the stationary camera set-up reflects the results of the study by Lamontagne et al (2000) where a two camera set-up, placed at a relatively great distance from the moving object, yields a rather high mean residual error. Their study showed that as the camera-to-object distance decreased, smaller residual errors were obtained which supports the current study since the static camera set-up involved two cameras placed at a greater distance from the subject than for other two camera set-ups.

Therefore, one could assume that smaller errors would be achieved using the panning and mobile methods. With the mobile method being so new in the field of biomechanics, it was uncertain how accurate this technique could be when collecting data. Lafontaine and Lamontagne (2003) reported the first results for the mobile technique.

The main difficulty with the mobile technique is the placement of the fixed point in the field of view and maintaining it in the view of the camera at all times. For moving cameras following a moving object it is a complex task to have a fixed point in the same position. To address this problem, Lafontaine and Lamontagne (2003) built a rod, long enough to stretch along the full length of the filming volume, with markers placed one next to the other, approximately 1cm apart, along its whole length. This rod was placed on the ground, in front of the subject. When digitizing each field, the APAS system would ask for a fixed point to be digitized. The digitizer would choose a marker on the rod as their fixed point. It becomes impossible to keep digitizing the same marker when the cameras begin to move, thus the reason for another marker to be placed approximately 1cm away. Once the marker moves out of range permitted by the APAS system, the digitizer would simply move to the next point on the rod. This technique is quite novel, however, it does make for a very long digitizing process, since the fixed point would need to be modified frequently. In this study, to circumvent this problem, a reflective marker was bonded to the end of a rod, which was anchored on the mobile camera device. Both cameras were set-up in a fashion that this point was in full view of each camera at all times. When using APAS to digitize the trials, this method worked very well. The APAS system had no problems finding the fixed throughout the entire digitizing process.

4.2 SUMMARY OF ALL TESTING CONDITIONS

To summarize the results, figure 4.4 shows the various testing conditions versus the mean RMS values of all three of the camera set-ups.

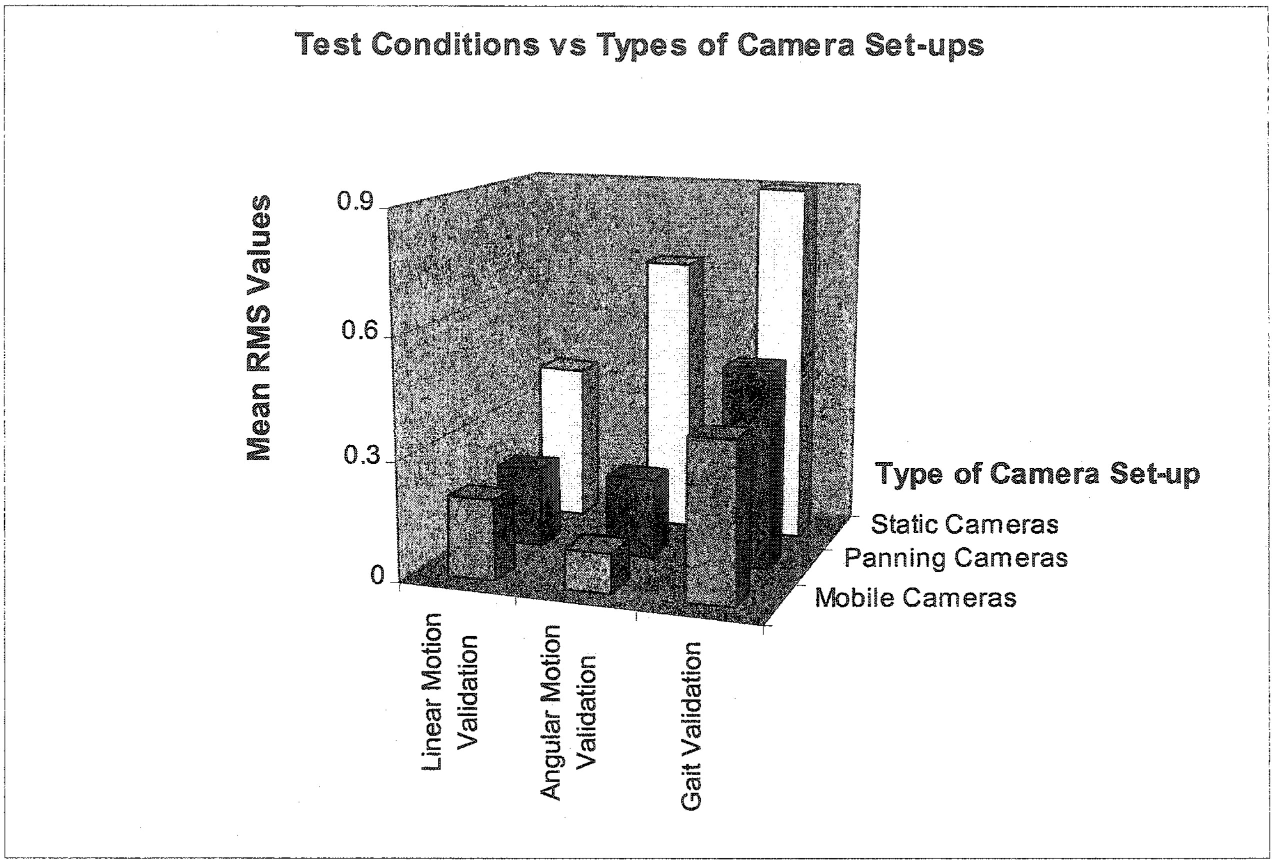

Figure 4.4 RMS errors obtained from all three of the camera set-ups during the three testing conditions.

The panning and mobile camera set-ups out-performed the stationary camera set-up in all test conditions. In all three test conditions, the stationary camera set-up had a much higher camera-to-filming volume distance than the panning and mobile camera set-ups. Though reporting of residual errors, using the panning camera set-up, has not been abundant, the results of this study seem to equal or better previous reported studies; such as Yeadon (1989) who reported panning errors of 5.0cm and 17 to 22mm in a study by Yu (1993). Those two studies focused on whole body movement; therefore cameras were likely further from the subject, thus being one of the sources of the resulted error. Looking at Figure 4.5, it can be seen that the mean residual error increases from the linear condition (the lowest error) to the gait condition (the highest). This can be attributed to the complexity of the movements in these tests. In the linear motion test, movement affects only one of the three major axes (X-axis). The angular motion condition on the other hand, involves the pendulum, which moves along two of the three major axes (X and Z axes) and yields slightly higher residual errors in all three camera set-ups. Finally, the gait condition involves movement in all three major axes (X,Y and Z) and consequently shows even higher residual errors for the three camera set-ups. This testing condition produced the highest residual errors of the three tests. This was to be expected since gait movement is not very controllable by the investigator as the previous two tests were. There are other variables that are involved in the gait condition, such as skin marker movement and marker vibration, however, there seems to be a trend towards obtaining higher residual error as the movement becomes more complex. This being said the mobile camera system still had the lowest mean residual error value of 0.4±0.4 cm. Once again the panning camera set-up was minutely higher than the mobile camera set-up. Overall, the mobile camera set-up produced the smallest mean residual error for all the testing conditions.

4.3 Comparison of the Three Camera Set-ups

As it was mentioned previously, it can be seen that the mobile camera set-up offers the lowest RMS error amongst the three camera techniques. During the gait condition, it had the best performance. The suggestion by Lafontaine and Lamontagne (2003) that the mobile technique shows great promise appears to be correct. There are some important aspects that need to be considered when using this technique. For instance, the track used to guide mobile platform must be straight and parallel to the filming volume or errors could occur. Such errors would be simple to identify during the data analysis since a gradual increase in error would be observable as the cameras move further down the track.

In the case of the panning camera technique, the mean RMS error was found to be 0.5cm, which is an acceptable level of error for biomechanical research. These results support the study done by J. Dapena (1978) and M. Yeadon (1989) where random errors were reported to be 0.5cm. A disadvantage of the panning procedure, found in this study, was that as the subject approached the limit of the 5.5 meter filming volume marker #5 on the subjects' leg was consistently lost for approximately 13 frames. Since only two cameras were used in this study, once this marker was lost, three-dimensional kinematic analysis was no longer possible. Though 13 frames is not a significant amount of time (approximately one sixth of a second for 60 Hz camera recording), those 13 frames could have been a very important for high-speed movement analysis.

In this experiment, gait is not a complicated movement and the loss occurred during the third gait cycle. However, this did not occur with the mobile method. The mobile camera method maintained visual contact with all markers at all times in both cameras for the duration of each trial. One of the biggest disadvantages of the panning method found by Yu et al (1993) was that there was a lot of digitizing necessary to calibrate each control volume. This was not the case with the APAS system. This system simplifies the process of digitizing the recorded trial by using a procedure that requires digitizing both "Pan Left" and "Pan Right" calibration frames. It is important that a precise measurement of the "Panning points" be done to minimize errors. It is also important to note that in the study done by Yu et al (1993), the markers were not coated with reflective material, therefore making it difficult to digitize. In this study, all markers were coated with reflective tape, simplifying the digitizing process with the APAS system.

The static camera set-up followed much the same set-up as was described by Lamontagne et al (2000). Although a two-camera set-up was known to produce higher RMS errors, it was the only option for comparison purposes in this current study since the mobile camera set-up was limited to the amount of cameras the mobile camera device could hold. A different number of cameras in for different set-ups would not have permitted an unbiased comparison of the methods. It is likely that lower RMS errors could be achieved using more cameras, however, this study looked only at a two-camera set-up. Based on the previous studies, it can be hypothesized that with the addition of more cameras, lower residual errors can be achieved, however, it is important to note that during the mobile set-up, it may become difficult to properly place the cameras, if there are too many cameras involved, while also ensuring that each camera views of the "fixed" point. Depending on the size of the trolley being used, the amount of cameras used for a particular study may be limited.

4.4 Estimated Sources of Errors

This study was subject to many error sources. Digitizing errors are an important factor. All the trials were digitized using the automatic digitizing function in the APAS system. This function searches for the centroid of each marker based on the number of pixels. Therefore if a particular marker is slightly hidden then the centroid of the marker could move based on the pixels available form the hidden marker. This being said, the digitizing of the control points is not done automatically as in the case of the trial marker digitizing, therefore some variance can be expected. This study is limited by the system used to digitize and transform the data.

As discussed in a study based on three-dimensional cinematography, many of the systematic errors are a result of the lack of modeling of lens/film distortion. This can affect the digitizing of the control object, the distance of the cross lens etc… (Kenefick, 1971). Lens distortion was also reported to be a problem in a study by Fournials et al. (2002), where they reported unstable and unreliable results with the panning camera technique when the subject was more than one meter away from the camera. They also reported that the mobile camera technique does not have this problem since the camera can follow and maintain that distance.

During the panning camera set-up, ensuring that the cameras did not tilt could not be positively assured. Also with reference to the panning procedure, the panning points need to be placed on a more precise device to ensure the utmost accuracy when measuring them. This study used separate rods placed on the ground in a straight line. Linearity could not be measured rigorously.

During the mobile camera procedure, it would be important to ensure that the track used for the cameras be precisely measured to restrict the motion to be parallel to the filming volume. Any minor deviation of the track could lead to progressively higher errors as the subject passes through the filming volume. A one-piece track would be ideal in ensuring that the track is straight and smooth to minimize unwanted vibrations. Such vibrations could be a source of error for the mobile camera set-up.

In the static camera set-up, the calibration frame was not big enough to cover the entire 5.5 m filming volume. As a result of this, the markers on the mobile device used in the linear movement test condition and on the subject during the gait condition, are filmed outside of the filming volume for 1.25m in front and behind the calibrated area. The following figures (4.5 and 4.6) show the vector length measurement (of vector 1 and 5) during the entire linear movement condition. Knowing that the calibration frame was placed in the center of the 5.5 m filming area, it can be said that there is an underestimation of the vector length but up to 2.0cm prior the device entering the calibrated area. Looking at all the vectors, all of them seem to report a maximum error of 1.0cm at its' furthest point from the calibrated area. Vector 1 reported a maximum error of 2.0cm at its furthest point from the calibrated area. The reason for this could be related to the length of that particular vector. Vector 1 is the longest (roughly twice as long as the others) vector in the study and therefore size it's length is double all the other vectors, its error could also expect to be doubled. This, when averaged for the entire 5.5m filming volume, can lead to higher than anticipated RMS error values. Looking at RMS error for the static camera set-up during the linear motion test condition when the mobile device is inside the 3.0m calibrated area, a significant reduction in error can be observed.

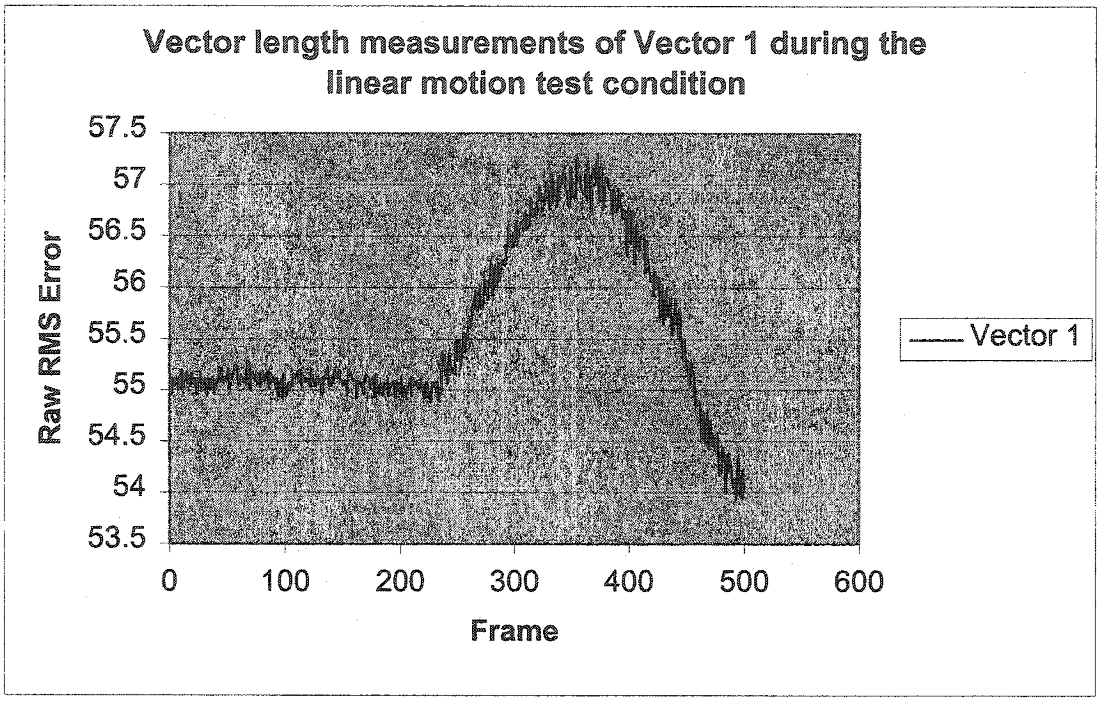

Figure 4.5 Calculated lengths of vector 1 for the linear motion condition throughout the entire linear motion data collection process.

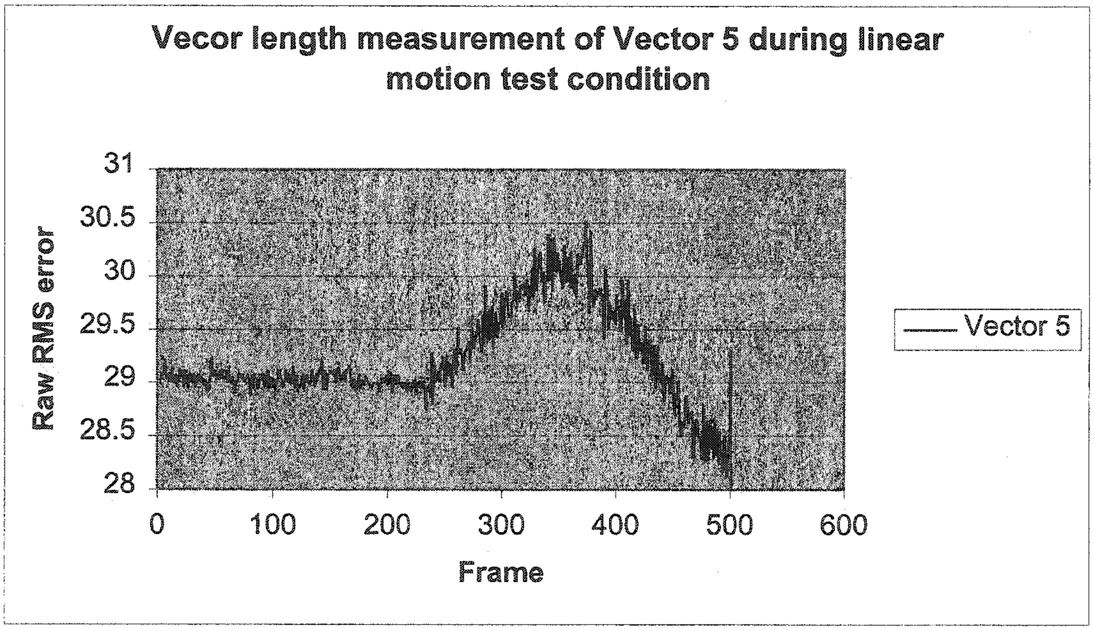

Figure 4.6 Calculated lengths of vector 1 for the linear motion condition throughout the entire linear motion data collection process.

Calculation of vector length for Vector 1 within the calibrated area during this trial reported mean RMS error of 0.3cm, whereas the RMS values of the entire data collection produced a mean RMS error of 0.4cm. This is still a larger mean error than the tracking and panning camera set-ups.

All the data used in this study is raw data. One set of measurements was filtered (6 Hz digital filter) and compared to the unfiltered measurements to verify that any unexpected sources of noise influenced the raw data. The data was taken from the static camera set-up, since this set-up produced the highest error values. The data was taken from the linear motion test condition since this condition allowed for minimal three-dimensional positional changes (movement along one axe only). Looking at Table 4.13, the measurement of the vectors for the non-filtered data was found to be exactly the same as the measurements calculated from the filtered data.

Table 4.13 Filtered versus non-filtered vector length measurements for the static camera set-up in the linear motion test condition.

Static Cameras	**Linear Motion Validation**				
Segment#	**Actual measured length (cm)**	**Measured lengths of non-filtered data (cm)**	**Measured lengths of filtered data (cm)**	**RMS of non-filtered vector lengths (cm)**	**RMS of filtered vector lengths (cm)**
1	56.7	55.56	55.56	1.14	1.14
2	34.8	34.69	34.69	0.11	0.11
3	34.2	34.12	34.12	0.08	0.08
4	26.6	26.12	26.12	0.48	0.48
5	30.0	29.22	29.22	0.78	0.78
6	34.9	34.91	34.90	0.01	0.00
7	34.8	35.10	35.10	0.30	0.30
8	26.0	25.36	25.35	0.64	0.65
9	31.0	30.50	30.50	0.50	0.50
Mean				**0.45**	**0.45**
Mean SD				**0.37**	**0.37**

Looking at the graphs of each vector (figures 4.7 and 4.8), there is a much smoother curve after filtering however; overall RMS error remains the same. There may be some benefit to filtering data from the gait testing condition since more variables are in play (X, Y and Z axis), however there seems to be no benefit to filtering the data for the linear motion test condition.

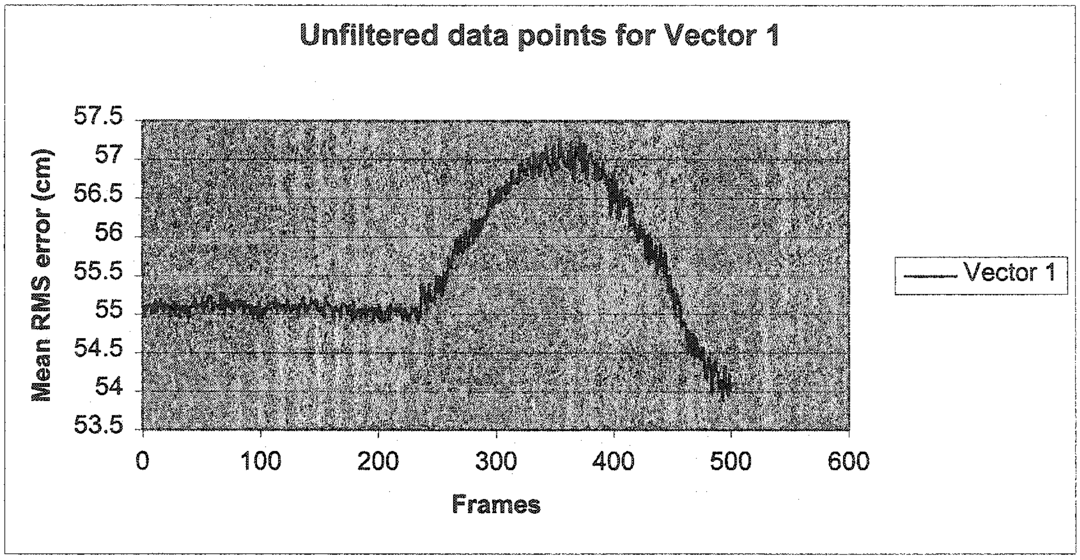

Figure 4.7 Unfiltered data points for vector 1 during the linear motion test condition

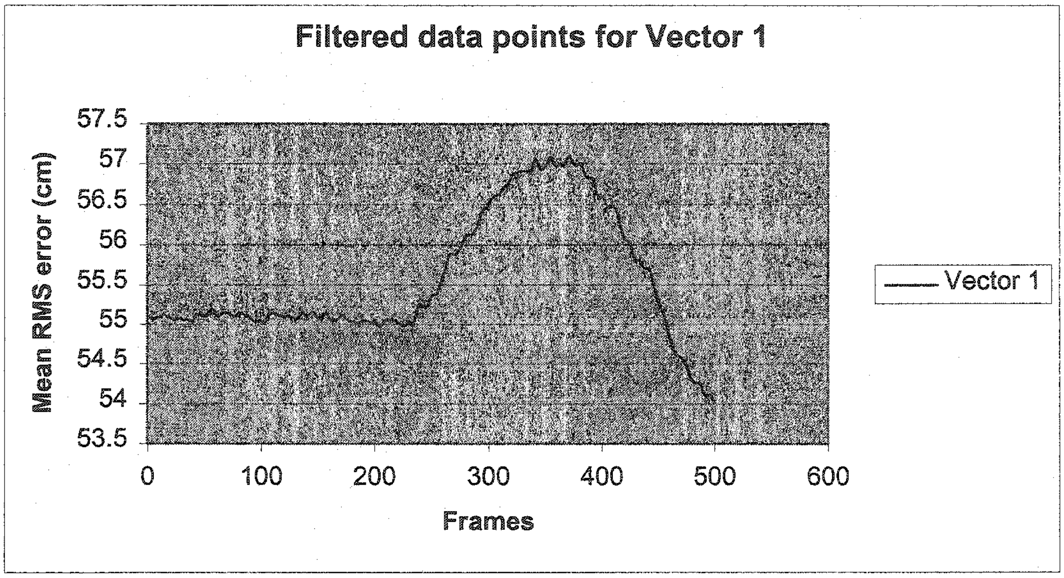

Figure 4.8 Filtered data points for vector 1 during the linear motion test condition.

4.5 Advantages and Disadvantages

After working with all three-camera systems during this study, it becomes simple to point out various advantages of using one system over another. The static camera set-up for instance, allows for a quick and easy set-up with minimal pre-data collection measurements. It's a very mobile system in the sense that there is little equipment needed to carry around. Some disadvantages of this system are: 1) Depending on the number of cameras used, the camera to subject distance can be quite large, therefore increasing residual errors. 2) The cameras are focusing in on one specific location in the filming volume and not on the subject performing the skill. 3) If you want to use this system for close range collection, you may not be able to collect the skill in its' entirety due to the immobility of the cameras.

The panning camera set-up offers many advantages. This camera system allows for the camera to follow, both horizontally and vertically, the subject throughout the entire skill. This can be done while maintain a relatively small camera to subject distance, thus minimizing residual error. The main problem with this camera system is found in the amount of time it takes to set-up the filming volume. Measuring the reference markers can be a very long and difficult process. Also, many more frames can be collected with this camera system, since it can follow the subject throughout the movement, therefore many more frames need to be digitized. This can result in greater time being spent on digitizing.

Finally, the mobile camera system provides the ability, like the panning process, to follow the subject throughout the entire movement. This system has an advantage over the panning process in the sense that the cameras move with the subject, whereas in the panning process, the cameras are fixed in a fashion to ensure that both camera can see the subject at all times. This means one camera is almost always further away from the subject than the other. With the mobile camera system, this problem is rectified. The camera to subject distance is even smaller than that found in the panning process. This is once again due to the fact that for the panning process, the cameras need to be placed in a fashion to ensure that all cameras can view the subject at all times. This may result in a greater camera to subject distance. Some disadvantages of the mobile camera system are: 1) Must build a rail or track system to ensure the camera move perpendicular to the subject. 2) Other sources of error, such as track vibration or camera movement due to vibrations.

Every camera system has its' advantages and disadvantages, however, for skills demanding larger filming volumes, the mobile camera system offers the best opportunity for minimal errors during data collection.

CHAPTER V

CONCLUSION AND RECOMMENDATIONS

The objective of this study was to determine which camera set-up would produce the smallest vector residual errors during 3D analysis. It was thought that the higher residual errors would be found in with the static camera set-up, while the lowest residual error would likely be found with the mobile set-up, simply due to the fact that the mobile set-up allowed for a smaller camera-to-subject distance than the static and panning procedure. It was shown in this study that with the mobile camera set-up, the residual error values did in fact tend to be lower than the static and panning camera systems.

The gait condition for all three-camera techniques proved to be a success. All three camera techniques displayed mean RMS errors within acceptable limits, based on previous studies. However, it can be said that the panning and mobile techniques offer a greater advantage when studying skills that take place over a large activity area, since they are able to follow the subject throughout the entire skill.

The stationary camera system is limited in its filming volume if accuracy is of the utmost importance. The use of a calibration frame covering the entire length of the filming volume would greatly enhance the accuracy of the static camera system. The panning technique yields high accuracy however the set-up is more demanding and can lead to some marker loss depending on their placement. The mobile technique offers the lowest mean RMS error of the three camera systems while showing an ability to follow the entire activity. This is also done with minimal set-up and minimal marker loss opportunities.

Further research on this subject would be important. It would be significant to assess the influence of using an increased number of cameras during the mobile camera system. The APAS system can use at least a five-camera combination. The mobile camera set-up could have used a three-camera set-up, however, for more cameras, a bigger mobile camera device would be required. This could show if perhaps an enhanced accuracy of the camera system could be obtained or if the system would reach a saturation number of cameras for data collection.

Finally, for future use of the mobile system, it would be of interest to evaluate the effect of track induced vibrations on the amount of residual error in a given filming volume.

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APPENDIX A

CALIBRATION FRAME MEASUREMENTS

Table A.1 Actual 3D positional coordinates of the 20 control markers used from the 1.5m filming volume.

Control Markers	X (cm)	Y (cm)	Z (cm)
1	0.2	0.6	61.4
2	-0.2	-49.9	11.8
3	0.8	-48.6	111.4
4	-0.1	-99.9	61.9
5	-0.4	-149.9	12.2
6	0.3	-148.4	112.6
7	49.9	1.9	111.5
8	50.1	-48.7	61.5
9	50.1	-98.7	61.4
10	49.7	-149.3	12.5
11	100.0	1.1	11.2
12	100.5	-48.0	61.5
13	100.3	-98.3	62.0
14	100.9	-147.8	111.9
15	150.1	2.0	61.2
16	149.9	-48.6	11.1
17	150.6	-47.5	111.4
18	150.2	-98.1	61.8
19	149.8	-148.6	11.8
20	150.9	-147.6	111.9

Table A.2 Actual 3D positional coordinates of the 20 control markers used from the 3.0m filming volume.

Control Markers	X (cm)	Y (cm)	Z (cm)
1	0.3	0.5	61.4
2	-0.1	-50.0	11.8
3	0.2	-48.9	111.6
4	-0.2	-99.8	61.9
5	-0.3	-149.9	12.5
6	0.4	-149.1	112.8
7	100.0	1.5	111.5
8	99.9	-48.5	61.5
9	100.1	-98.7	62.0
10	99.8	-148.8	12.2
11	199.9	1.3	11.1
12	200.2	-48.8	61.3
13	199.9	-99.0	61.7
14	199.9	-148.3	111.6
15	300.1	0.6	61.0
16	299.8	-49.7	11.0
17	299.3	-49.4	111.1
18	299.6	-99.4	61.5
19	299.6	-149.7	11.6
20	299.7	-149.2	111.7

Table A.3 Positional coordinates of the control markers defining the filming volume for the panning camera set-up

Panning Calibration Markers	Stationary Calibration Marker	X (cm)	Y (cm)	Z (cm)
Pan Left 1	1 (origin)	0.0	0.0	11.8
Pan Left 2	2	50.0	0.7	11.5
Pan Left 3	3	150.0	1.4	11.5
Pan Right 1	4	550.0	0.0	11.8
Pan Right 2	5	600.0	0.7	11.5
Pan Right 3	6	700.0	1.4	11.5
Pan Right 4	7	699.8	-148.6	11.8
Pan Right 5	8	599.7	-149.3	12.5
Pan Right 6	9	549.6	-149.9	12.2
Pan Left 4	10	149.8	-148.6	11.8
Pan Left 5	11	49.7	-149.3	12.5
Pan Left 6	12	-0.4	-149.9	12.2
Pan Left 7	13	0.4	1.3	111.5
Pan Left 8	14	49.9	1.9	111.5
Pan Left 9	15	150.2	2.6	111.5
Pan Right 7	16	550.4	1.3	111.5
Pan Right 8	17	599.9	1.9	111.5
Pan Right 9	18	700.2	2.6	111.5
Pan Right 10	19	700.9	-147.6	111.9
Pan Right 11	20	600.9	-148.0	112.1
Pan Right 12	21	550.3	-148.4	112.6
Pan Left 10	22	150.9	-147.6	111.9
Pan Left 11	23	50.9	-148.0	112.1
Pan Left 12	24	0.3	-148.4	112.6
Pan Left 13	25	50.1	-48.7	61.5
Pan Right 13	26	600.1	-48.7	61.5
Pan Right 14	27	650.3	-98.3	62.0
Pan Left 14	28	100.3	-98.3	62.0
Ref Marker	1	150.0	-158.6	2.0
Ref Marker	2	250.0	-158.6	2.0
Ref Marker	3	350.0	-158.6	2.0
Ref Marker	4	450.0	-158.6	2.0
Ref Marker	5	550.0	-158.6	2.0

APPENDIX B

LINEAR MOTION TEST CONDITION MEASUREMENTS

Table B.1 Measured three-dimensional coordinates of the markers with the 3DD placed on the cart for the linear motion test condition calibration

Markers	X (cm)	Y (cm)	Z (cm)
1	0.0	0.0	0.0
2	56.6	3.2	0.0
3	-0.1	0.1	34.1
4	26.5	1.4	34.2
5	56.8	3.0	34.3
6	0.0	0.6	69.3
7	26.6	1.8	69.5
8	56.9	3.5	68.8

Table B.2 Calculated lengths from the measured coordinates of the nine vectors from the linear motion cart

Vector#	Actual measured length (cm)
1	56.7
2	34.8
3	34.2
4	26.6
5	30.0
6	34.9
7	34.8
8	26.0
9	31.0

APPENDIX C

ANGULAR MOTION TEST CONDITION MEASUREMENTS

Table C.1 Three dimension positional coordinates of the three markers measured with the 3DD on the pendulum for the angular motion test condition.

Markers	X (cm)	Y (cm)	Z (cm)
1	0.0	0.0	0.0
2	0.1	0.3	34.0
3	0.1	0.3	66.2

Table C.2: Calculated lengths of the three vectors from the measured three-dimensional coordinates of the three markers on the pendulum.

Vectors#	Actual measured length (cm)
1	34.01
2	32.17
3	66.18

APPENDIX D

GAIT MOTION TEST CONDITION MEASUREMENTS

Table D.1 Measured vector lengths with the 3DD of markers during gait motion test condition.

Vector#	Actual measured length (cm)
1	18.4
2	16.2
3	31.5
4	16.5
5	16.0
6	30.1
7	13.8
8	7.8
9	15.0