How Cows Lie Down: a 3-D Kinematic Evaluation of the Lying Down Behaviour of Holstein Dairy Cows

by
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Abstract

Research in dairy cow (*Bos taurus*) housing and free-stall design has concentrated largely on the effects of the various types of stall configurations on parameters such as lying and ruminating times or on production parameters such as milk production or disease incidence. To date, no studies have examined the effects of free-stall design on specific movements of dairy cattle. Knowledge of how cows lie down in these environments may lead to a better understanding of these behaviors. I have used biomechanical techniques to measure the movement envelope of Holstein dairy cows when they lie down in an open pen, and in a free-stall, and in doing so have demonstrated that these techniques can provide useful information for the assessment of cow behavior. My study found that when lying down, cows use approximately 240 to 260 cm of longitudinal space, which is more space than current industry recommendations. Cows used approximately 70 to 100 cm of lateral space, an estimate that is within current industry recommendations for stall width. In addition, I found that the spatial pattern of lateral displacement could be used to improve the design of stall partitions. Further work is required to assess a wider range of cow sizes and stall configurations. Use of the techniques described in this study will allow for relatively efficient collection and analysis of this type of data.

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1.0 - Introduction

In the last forty years there has been growing concern over the care and handling of farm animals, initiated in part by the publication of Ruth Harrison's landmark book "Animal Machines" (1964) that described modern animal farming techniques. At that time, dairy farming in North America and elsewhere was relatively extensive and relied heavily on pasture grazing. Today's dairy industry is much more intensive with many cows spending the majority of their lives indoors, and now dairy industry practices are increasingly the subject of public concern. In an attempt to address some of these animal welfare concerns, scientists have begun research on understanding the effects of housing systems on the animals, and on ways of improving this housing.

Modern dairy farms normally house their animals in one of two ways: loose housed, or in tie stalls. In tie-stall operations, the cows are tethered to their stalls for most of the day. In contrast, loose housing systems allow the animals to move freely about within the barn. Loose-housed animals still require areas were they can lie down, ruminate and sleep. These areas can either be open, strawyard beds, or individual stalls referred to as free-stalls.

Recently a number of researchers have focused their attentions on evaluating how these various housing systems meet the needs of dairy cows. For example, Haley et al. (2000) compared "high comfort" pens (lots of space, free movement, mattress plus straw) with "low comfort" stalls (tie stall, concrete floor with little straw), and found that the cows in high comfort pens spent more time lying and less time standing idle than did the cows in the low comfort stalls. Similarly, Fregenosi and Leaver (2001) compared open, strawyard systems with free-stall systems, and found that cows in the strawyards had greater lying and ruminating times, but were more likely to lie down in their own feces. As well, there were indications that the decreased cow hygiene in the strawyard system led to a greater incidence of clinical mastitis, resulting in lower overall milk production.

Other researchers have looked more specifically at individual components within the free-stall, and have examined the effect of these components on the behaviour of cows. For example, Tucker et al. (2003) examined how free-stall width and length affected cow preference and stall usage. They determined that the cows spent more time lying down and had longer lying bouts in the wider stalls, but the length of the free-stall did not affect lying behaviour. While these approaches give us valuable information regarding the effects of housing systems and stall design on stall usage, they do not address the more basic issue of how stalls affect the movements of cows as they lie down and stand up in these stalls.

A few previous studies have attempted to measure the amount of longitudinal space used by cows when lying down and standing up (summarized by Lidfors, 1989, and described in greater detail below). Although these findings provide some basis for recommended stall length, they do not address other aspects of stall design. Unfortunately, the lack of objective research in this area has not prevented the publication of free-stall design recommendations for dairy farmers. Although these recommendations are evidently based on these earlier studies, the authors do not provide any justification for the measures they put forward (e.g. Irish and Martin, 1983, McFarland and Gamroth, 1994, Faull et al., 1996, Bickert, 2000).

There is some research indicating that inadequate stall design can lead directly to injuries to cows. For example, Blom et al. (1984) measured the pressure exerted by cows against structures in free-stalls, and found that they often contacted the partitions between stalls likely leading to contusions and inflammation at the costal arch. Cernak (1988) attributed specific inadequacies in stall design with various injuries sustained by cows. If we are to understand how these injuries occur, and how they might be prevented, it is clear that we must understand how the cow is moving within the free-stall environment.

The objective of this thesis was to use 3-D kinematics to define the movement envelope of mature Holstein dairy cattle in order to assess their spatial requirements for the purposes of free-stall design. In doing so, I will demonstrate that biomechanical methods can provide reliable and accurate data in field conditions. In this work, "movement envelope" refers to the total amount of longitudinal and lateral space used by cows during the lying down behaviour. Kinematic variables (displacement, velocity and time) of various body landmarks were measured using video cameras to capture the movements, followed by three dimensional movement reconstruction using a computerized motion capture and analysis system. This reconstruction allowed for accurate measurement of cow movement, and thus allowed me to understand how these animals were moving and reacting to their environments. Ultimately, this work should lead to free-stall designs that accommodate rather than restrict the movements of dairy cattle.

2.0 - Background

Lidfors (1989) provides a qualitative description of the lying down and standing up behaviours of bovids. Lying down occurs in three steps: 1) the animal bends its front legs, 2) it falls onto its front knees, and 3) it lets its abdomen and hind quarters fall backwards. The animal will then generally roll towards the side that corresponds with the first foreleg that was bent. Standing up consists firstly of a lunge forward and upward by the head during which the animal rises onto its knees and breastbone. It then extends its head and neck upward while at the same time rising up onto its hind legs. Lastly it extends one foreleg, followed immediately by the other.

There have been previous attempts to quantify the lying down and standing up behaviours of cattle. Faull et al. (1996) reported observations of dairy cattle lying down and standing, but failed to describe the methods they used to generate their measures of displacement. Hoffman and Rist (1975) filmed cattle standing up behind a wire grid of known dimensions. They measured the movements of markers placed on the body, relative to the grid, and used these to estimate the amount of longitudinal and vertical space used by the cow during this movement. As well, they determined the "movement curves" of individual body parts, such as the muzzle (which could be used as a measure of lunge space) and the pelvis. Lidfors (1989) cites a number of other studies, with similar findings. However, due to the technology available at the time of those studies, these studies had weaknesses that now can be addressed with modern methods. Appendix 1 provides a more detailed discussion of these techniques and some of the errors inherent in them, as well as a general discussion of biomechanics. Although these types of errors can be mathematically compensated for, Hoffman and Rist (1975) failed to do so, and state their findings as being approximate. Additionally, these authors used techniques that measured only kinematic variables in two dimensions, both of which were parallel to the film planes of their cameras. The present study made use of techniques that allowed me to obtain three-dimensional movement reconstructions.

Most kinematic research has been done on human subjects, although there is a significant body of work on animal athletes, most commonly horses and greyhound dogs, and one study investigating locomotion in dairy cows. The majority of this work has involved gait analysis, using both video-derived kinematic data, as well as force-plate measures to obtain kinetic data (see: Decamp et al., 1993, Allen, K, 1994, Hottinger et al., 1996, Herlin and Devremo, 1997, Clayton et al., 1998). Of this work, most was conducted on treadmills under laboratory conditions, although there was least one attempt to use gait analysis in non-laboratory conditions to evaluate horse locomotion (Degeurce et al, 1996). These studies largely address lameness. To date, there is no work available using computer-aided kinematic evaluations of dairy cattle motion for the purposes of improving free-stall design.

3.0 Objectives

The primary objective of this thesis was to determine the amount of lateral and longitudinal space used by mature Holstein dairy cows when lying down in open, unrestricted environments, and in restricted, free-stall environments. These measures can have a direct impact on free-stall design. In addition, a number of other measures of movement were reported. These additional measures will help to further quantify and understand the lying movement, and may have further implications for free-stall design. Lastly, in achieving the primary objectives, I will demonstrate that modern biomechanical methods are a valuable tool for the study of cow movement in field situations.

Given the effort required to modify these techniques to this application, and the time consuming nature of the analysis, this study considered a sample intended for descriptive analyses only. Further work will be required to draw statistical inferences regarding differences in behaviour in the free-stall compared to the open pen.

4.0 – Materials and Methods

All animal related portions of this experiment were conducted at the UBC Faculty of Agricultural Science's South Campus Large Animal Research Facility. The motion analysis was conducted at the UBC Biomechanics Laboratory in the School of Human Kinetics.

4.1 – Cows

The animals (Table 1) used were non-lactating Holstein cows from the UBC Dairy Education and Research Center herd in Agassiz, BC. A total of five cows were used, with each cow being filmed in each of two conditions: a large open pen, and the same pen containing a free-stall. Cows were in the last trimester of pregnancy, showed no signs of impaired movement, and were healthy. All cows were fed ad libitum hay and had free access to water at all times. Animals were cared for according to the guidelines outlined by the Canadian Council on Animal Care (1993).

4.2 – Pen and Free-stall

The indoor housing consisted of a pen measuring 513 cm X 359 cm, bounded on three sides by a rope fence, and a concrete feed bunk on the fourth side. The floor of the pen was dirt covered with approximately 20 cm of sawdust.

The first condition of filming involved video-recording the cows in the above pen, where they were free to lie down anywhere in the pen.

The second condition of filming required that a free-stall (Figure 1) be placed in the pen and secured at the end opposite the feed bunk, such that it became the only place for the cow to lie down. Dimensions of the free-stall were within the size limits used by the dairy industry (see Cernak 1988, Irish and Martin, 1983, McFarland and Gamroth, 1994, Schoonmaker, 1999). However, it should be noted that the bed length was at the upper limit of current industry recommendations, and the width was at the lower limit. Sawdust was added daily to the free-stall to maintain a depth of approximately 5 cm.

4.3 – Control Object and Calibration

Before filming the cows, the volume of space available for movement was calibrated, thus giving the motion analysis system a point of reference from which to reconstruct the positions of markers on the cows (subject markers) and their displacements. For a full discussion and description of the calibration and filming procedures see Appendix 1.

Accuracy of the calibration was determined, in part, by filming a model (Figure 2) with known segment lengths, and comparing the predicted segment lengths to the actual lengths. A complete discussion of calibration accuracy is presented in section 5.1.

4.4 – Subject Markers and Filming Procedures

I attached subject markers to the cows at nine anatomical locations (see Appendix 2 for specific anatomical locations of all real subject markers). Five other subject markers were also attached (on the forehead and above each hoof), but were not digitized and thus will not be discussed. In addition to the real markers that were placed on the cows, I created two virtual markers during the analysis phase, in order to define a dorsal midline on the cows (Figure 3). Virtual markers are locations on the subjects that are defined within the analysis system, and thus are not "real", but are based on real subject markers. The "front virtual marker" was defined as being on the midpoint of a straight line joining the two shoulder markers. Based on the actual locations of the two shoulder markers, the system is able to calculate the position of this virtual marker. The straight line formed between the two shoulder markers created a segment that will be referred to as "shoulder width". The second virtual marker ("back virtual marker") was defined as the midpoint of a straight line joining the two hip markers. This straight line formed a segment that will be referred to as "hip width". The straight line joining the front and back virtual markers formed a segment that will be referred to as "back length".

Cows were allowed 24 h to habituate to each of the filming conditions before video-recording began. Continuous video-recording was undertaken for 6 h each evening until I had recorded a minimum of two lying events for each cow in each condition in full view of all cameras. The actual number of days that were required to successfully capture these events varied considerably for each cow (see Table 1).

4.5 Video Analysis Procedures

Lying events were digitized and analyzed on the PEAK Motus 2000 Version motion analysis system (Peak Performance Technologies, Inc., 7388 South Revere Parkway Suite 603, Englewood, CO, USA 80112). For each event recorded, 4 files of two-dimensional image data were reduced to one file of three-dimensional co-ordinate data. Data obtained from this system consisted of 3-D co-ordinates (cm) for each real marker, as well as 3-D linear velocities (cm/s).

4.6 - Measures

The maximum lateral displacement from their original locations, in the X-Y plane, for each hip and shoulder marker was calculated in order to determine the lateral space used when the cow lay down (Figure 3). These displacements were then added to the mean shoulder and hip widths obtained for each cow to obtain the total lateral space used in the movements. For example, if the left shoulder marker reached a maximum lateral displacement (from it's original position, away from the midline, parallel to the X-Y plane) of 20 cm during the lying down movement, and the right shoulder reached a maximum lateral displacement of 15 cm, these displacements were added to the mean shoulder width of that animal to obtain the maximum lateral space used in that particular movement. In this example, if the shoulder width was 50 cm, then the lateral space used would be: 20 cm +15 cm+ 50 cm = 85 cm. Thus for each cow in each movement, there were two measures of lateral space usage, one at the shoulder and one at the hips.

Since the stall was of equal width at the front and back, I only reported the greater of the hip or shoulder space usage, because the goal was to identify the greatest amount of lateral space used by the cows during the lying down movement. For example, if in the same movement for which the lateral space usage for the shoulders and hips was 85 cm and 100 cm, respectively, only the hip measurement was reported. In all but one of the events that were digitized (27 of 28 events), the lateral space usage at the hips was the greater of the two.

For the nose marker, the maximum displacement parallel to the longitudinal axis, in the X – Y plane, was obtained. I reported this displacement in two ways. Firstly, the furthest forward displacement of the nose marker was reported, as a measure of the amount of space used in the forward lunge during the lying down movement. For example, if the nose marker was displaced a total of 80 cm longitudinally (from it's starting position, parallel to the longitudinal axis of the cow and parallel to the X-Y plane), then this displacement was recorded as the amount of space used in the forward lunge. Secondly, I determined a measure of the total longitudinal space used by the cow by calculating the distance between the back virtual marker at the start of the movement, and the nose marker at it's point of furthest forward travel during the movement. This measure was only an approximation of the total longitudinal space used by the cow because the back virtual marker was defined as the midpoint between the two hip markers, and was therefore not the most caudal point of the animal.

I reported all lateral and longitudinal displacements as the mean (maximum and minimum values are also included) for each cow in each condition.

Additionally, for each of the nose, hip and shoulder markers, the vertical distance (Z – direction) above the ground at the point of furthest displacement was also recorded. Rather than report means for each cow in each condition, I reported the actual values for all movements. This was done because these observations formed bi-modal distributions with implications for stall design, a full discussion of which is found in section 5.3.

Lastly, the maximum linear velocities of each of the nose, shoulder and hip markers, during the lying event, were obtained, as well as the time taken to complete each movement. Again, these were reported as means ($\pm$ max and min) for each cow in each condition.

Derived Measures

I normalized the displacement measures described above by reporting them relative to body measurements for each cow. For the lateral hip and shoulder displacements, the actual lateral space usage was normalized to the mean hip and shoulder widths, respectively. Similarly, the nose marker displacements and total longitudinal space usage were normalized to the mean back length of each cow. In the example given above for a lateral shoulder displacement, the normalized value is calculated by dividing the lateral space usage at the shoulders by the mean shoulder width of that cow: (80 cm/50 cm) x 100 = 160 %. This figure can be interpreted as indicating that the amount of lateral space used by the cow at the shoulder is 160% of the shoulder width of that cow. As with the displacements described above, I reported the normalized displacements as means ($\pm$ max and min) for each cow in each condition.

4.7 – Definition and Calculation of Measures

Initiation of the lying movement began when the first front knee marker to eventually touch the ground began to move, and ended when the final rear knee marker touched the ground. A marker was deemed to have initiated movement when it's instantaneous resultant linear velocity exceeded 10 cm/s, and was deemed to have stopped moving when it's instantaneous resultant linear velocity dropped below 10 cm/s. The value of 10 cm/s was chosen because it corresponded well with visual observations of when the markers began to move and terminated movement. In situations when the marker was obscured at the time of impact (for example, in deep sawdust) I estimated stopping times by manually viewing the images. Starting and stopping times were recorded as frame numbers, and as frames were recorded at a rate of 60 Hz, time taken to complete the movement was calculated by dividing the difference in frame numbers by 60. For example, if the first front knee marker to touch the ground began to move at frame number 50, and the final knee marker touched the ground at frame 500, the time taken to complete the movement was calculated as: [(500 – 50)frames] / [60(frames/s)] = 7.5 s.

At the start of the lying event, the co-ordinates of the two virtual markers (front and back) were recorded, and the vector formed by these points was defined as the longitudinal axis of the cow at the time she began to lie down. Ignoring the vertical (Z) component, the angle of this vector, with respect to the global co-ordinate system that was defined in the calibration phase, was calculated. See Appendix 3 for an example of this calculation. I used this angle as the reference angle (longitudinal axis) in all further calculations.

The calculations for the nose, hip and shoulder markers were made relative to the longitudinal axis. For the nose marker, the start position was taken as its position at the beginning of the lying movement, while the endpoint was defined as the furthest forward displacement parallel to the longitudinal axis during the lying movement. The displacement of the nose marker was the length of the horizontal (X – Y plane) vector formed by the co-ordinates of these two points. For the hip and shoulder markers, the start position was taken as the beginning of the lying movement, while the endpoint was defined as the furthest lateral displacement (away from the midline) of each of the hip and shoulder markers. Their displacements were thus the length of the horizontal vectors formed by the co-ordinates of these points.

In order to report longitudinal and lateral components for all of these displacements, I resolved the vectors into parallel and perpendicular components, relative to the longitudinal axis. Appendix 3 provides an example of this calculation.

As was mentioned in section 4.6, I calculated total longitudinal space usage and used the same endpoint described above for the nose marker, with the back virtual marker as the start point. This vector was also resolved into parallel and perpendicular components.

The vertical displacement (Z-direction) for each of the nose, hip and shoulder markers was also recorded. The endpoints of these for each of the nose, hip and shoulder marker displacements were the same as described above. For the vertical measure, the height above the ground at the endpoint is reported, rather than the vertical displacement. For example, if the height of the nose marker at the point of furthest forward displacement is calculated to be 35 cm, but the level of the ground is at - 10 cm then I reported the height above the ground at the point of furthest forward displacement as: 35 cm – (- 10 cm) = 45 cm. Note that the level of 0 cm is defined by the control object (the control object is used to calibrate the motion analysis system, and is fully described in Appendix 1), therefore the actual level of the ground was not at 0 cm, but very often had a negative value, i.e.: was below the level of the lowest control markers,

It should be noted that with the vertical measures, there was some error that was not possible to quantify. The level of the ground was estimated by calculating the level of the knee markers when they were on the ground. However, when in the no stall condition, the depth of the sawdust pack made this measurement difficult to obtain. In this situation, the position of the knee markers was estimated and digitized visually.

I obtained maximum instantaneous velocities attained by each of the hip, shoulder and nose markers during the lying movement directly from the PEAK system.

5.0 - Results

5.1 – Calibration

The initial step in the calibration procedure required that the positions of all 45 control markers, relative to marker #1 be determined. These values were then entered into the system. The PEAK motion analysis system automatically calculated the positional error of each control marker by using the surveyed positions of the other markers to arrive at a predicted position for the marker in question. This predicted position was then compared to the surveyed position, with the difference being reported in terms of errors in the X, Y and Z directions, as well as an overall root mean square (RMS) positional error for each marker and for all markers together ($RMS = (X^2 + Y^2 + Z^2)^{1/2}$, where (X,Y,Z) represents the positional error in the (X,Y,Z) direction).

The minimum number of control points needed in a control object when using DLT is six, however, the greater the number of control markers the smaller the resulting error (Challis and Kerwin, 1992). Since the control object used in the present study contained 45 control markers, there were a large number of redundant markers that could be removed. After initial digitization of the control object, I eliminated 11 markers with large positional errors in an iterative fashion, until an overall RMS error of 0.896 cm was obtained. See Appendix 4 for positional errors for all remaining control markers.

Challis and Kerwin (1992) demonstrated the need for an independent assessment of accuracy, which was achieved by constructing a model with segment lengths that could be physically surveyed (Figure 2). The predicted segment lengths were compared to the actual segment lengths. These results are shown in Table 2. The difference in actual and predicted segment lengths varied from 0.2 to 1.2 cm, (mean = 0.54, S.D. = 0.42), providing an estimate of the measurement error in the findings reported below.

5.2 – Cow Data

Table 3 contains the number of successful recorded lying movement observations (2 to 4) in both conditions obtained for each cow. All but one of the cows was successfully recorded in both conditions. Cow # 5, when in the no-stall condition, refused to lie down in view of one of the cameras, and as well was outside of the volume encompassed by the control object. She was therefore excluded from all analysis in this condition. Mean hip width, shoulder width and back length (measured as described above) for all five cows varied from 56.5 to 64.1 cm, 46.4 to 51.4 and 99.6 to 109.9 cm, respectively.

5.3 - Measures

Mean longitudinal nose marker displacement ranged from 36.9 cm to 55.8 cm and 35.1 cm to 63.4 cm for the no stall and stall condition, respectively (Figure 4 a). The mean total longitudinal displacement ranged from 197.6 cm to 223.7 cm in the no stall condition and ranged from 199.6 cm to 216.1 cm when the stall was present (Figure 4 b). Mean lateral space usage by the cows ranged from 84.1 cm to 97.5 cm in the no stall condition and ranged from 70.2 cm to 98.9 cm when the stall was present (Figure 4 c).

Vertical height at the point of furthest displacement for both hip markers and the nose marker are plotted in Figure 5. In both the stall and no stall conditions the vertical displacements of the hip markers occurred largely in one of two clusters. Of 22 (11 events X 2 hips for each event) observations in the no stall condition, 11 (50 %) occurred between approximately 100 – 130 cm above the ground, while 5 (23 %) occurred between approximately 30 – 45 cm above the ground. Of the remainder, 5 (23%) were recorded as 0 cm because there was no lateral displacement away from the starting point for that particular hip marker on that event, and one occurred at 78.7 cm. In the stall condition, 17 of 34 (50%) observations occurred between approximately 95 – 135 cm above the stall bed and 15 (44 %) occurred between approximately 10 – 50 cm above the stall bed (2 observations were recorded as 0).

The nose markers showed clustering around only one zone. In the no stall condition, all 11 observations occurred between approximately 17 – 25 cm above the ground. In the stall condition, all 17 observations occurred between approximately 10 – 30 cm above the stall bed.

Figure 6 presents the velocity data. In the no stall condition, the greatest instantaneous velocities reached were 210.8 cm/s (nose), 182.1 cm/s (hip) and 129.8 cm/s (shoulder). In the stall condition, these values were 199.4 cm/s (nose), 218.8 cm/s (hip) and 141.6 cm/s (shoulder).

Figure 7 presents the mean of the time (s) taken by each cow in each condition to complete the lying movement. Note that these times represent the time to complete the movement once the cow has commenced it, and does not account for time taken standing in the stall prior to the lying movement. Mean times varied from 3.2 to 5.6 s in the no-stall condition, and from 3.1 to 5.5 s in the stall condition.

Derived Measures

Normalized mean nose marker displacements ranged from 35.2% to 60.9% of mean back length in the stall condition, while in the no stall condition, the values ranged from 37.0% to 53.2% (Figure 8 a). Normalized overall longitudinal displacements ranged from 191.2% to 210.1% of mean back length in the stall condition, and from 189.9% to 211.4% in the no stall condition (Figure 8 b). Normalized mean hip marker displacements ranged from 124.2% to 154.3% of mean hip width in the stall condition, and from 136.2% to 152.1% in the no stall condition (Figure 8 c). Normalized mean shoulder marker displacements ranged from 106.0 % to 150.3 % of mean shoulder width in the stall condition, and from 111.3% to 141.4% in the no stall condition (Figure 8 d).

6.0 – Discussion

The main objective of this study was to determine the movement envelope of mature Holstein dairy cows during the lying down movement, for the purposes of improving free-stall design. As well, some additional objective measures were reported that can be used to further quantify these movements. This study also demonstrates that modern biomechanical methods can be a valuable tool in examining the motion of dairy cows in field conditions.

6.1 – Movement Envelope

Of the studies that have been published to date dealing with the dimensional needs of cattle, most have dealt specifically with the standing up behaviour, which makes comparison with my work on lying behaviour difficult. Furthermore, these previous studies failed to provide detailed methodology, which also makes it difficult to compare with my work. However, in reviewing the previous literature there are some interesting points to note. For example, Cernak (1988) reported that a large (up to 800 kg) Friesian cow requires between 70 and 100 cm of forward space during the rising movement. It appears, however that this author measured the distance from the forward-most forelimb at the start of the movement to the point of furthest advance of the tip of the nose. Faull et al. (1996) reported that a distance of 60 cm was needed for the length of the head lunge taken by a rising Holstein.

Lidfors (1989) cites Tschanz and Kammer as reporting that during the lying down movement, the body moves forward a minimum of 150 cm. This finding was very different to my findings that indicated forward space usage by cows was generally between 30–70 cm, with no single movement exceeding 90 cm. Unfortunately Tschanz and Kammer's manuscript was not available for review and thus the differences between the two studies can not be discussed.

Lidfors (1989) also cite Tschanz and Kammer as reporting that standing behaviour requires approximately one third more space than the overall length of the cow lying on the ground (e.g.: 290 cm for a cow with a length of 220 cm). Although Hoffman and Rist (1975) report that during the standing movement the muzzle moves forward about 45–60 cm, they found that the total amount of longitudinal space required was about 300 cm. Both of these measures of overall space usage are larger than my findings that indicated that cows utilized between 190-220 cm of longitudinal space. However, when the distance between the back virtual marker and the most caudal point of the cow (approximately 50–60 cm) is considered and added to the requirement of longitudinal space, these findings correspond much better. It should be noted that my measurements were all taken on mature Holstein cows, one of the largest dairy breeds. Earlier papers do not specify the breed of animal used, further complicating comparisons. In general we can expect that larger cows will take up more space than smaller ones.

Industry recommendations for overall stall bed length range from 200 – 240 cm, although head-to-head designs often call for overall bed lengths much shorter than these recommendations. As well, if there is space for a lateral head lunge, bed length recommendations can be as little as 185 cm (Irish and Martin, 1983, McFarland and Gamroth, 1994, Faull et al, 1996, Bickert, 2000). Based on my findings and the results of previous studies, these industry recommendations may not be sufficient to accommodate the amount of longitudinal space used by cows during the lying movement.

No published studies have examined the lateral space requirements of cattle. My findings indicate that lateral space usage ranged from approximately 60-110 cm, with the vast majority of the maximum displacements occurring at the hips (27 of 28 events). Current recommendations for stall width are equivalent to about twice the hip width (Irish and Martin, 1983, McFarland and Gamroth, 1994, Faull et al., 1996, Bickert, 2000). When the lateral hip displacements are normalized to hip width, they ranged from approximately 120 and 180 % of mean hip width, so a stall width that is 200 % of hip width would appear to be appropriate.

The height above the ground at which the maximum displacements occurred is relevant to stall partition design. The data from this trial indicates that there are two zones within which most lateral hip excursions occur: a high zone at 90 – 140 cm above the ground, with low zone at 10 – 50 cm above the ground. The nose marker displacements clustered within one zone between 10 – 30 cm above the ground or stall bed. Although no previously published work describes data of this type, diagrams of movement curves of specific body parts suggest similar results for the vertical position of the muzzle at maximum forward displacement (Hoffman and Rist, 1975). This data suggests that there are heights at which stall partitions can be located so as to minimally interfere with the displacements of the cow's hips and nose. Most modern stall side partitions are similar to the one used in my study (see Figure 1), consisting of a lower and an upper bar. Clearly, these results indicate that these bars should be positioned between these clusters. For example, the lower bar positioned at 70 cm and the upper bar at 140 cm would allow lateral excursions without contacting the bars, at least for the cows used in the present study. Similarly, placing the forward side bar below 10 cm would allow sufficient space for a side lunge.

The timing and velocity data were presented in this study as a way of further quantifying the lying movement, and may be of use in examining differences between individuals or environments. The velocity data also may be useful in understanding how stall design affects the force of impact of hips or shoulders on stall partitions, which may aid in reducing injuries during lying. Additionally, measuring the speed at which limbs hit the ground, in combination with force plate data, may help in the design of mattresses or stall beds.

This study also allowed for some comparison of lying down movements in the open, unrestricted pen and the free-stall. Interestingly, the measures I recorded were very similar in the two conditions, suggesting that lying behaviour need not be compromised when using a large free stall. This study was not designed to provide for inferential statistical comparisons between the two conditions, but the lack of any obvious condition effect indicates that a much larger sample size would be required to statistically detect such differences. Future work should consider the effects of alternative stall designs, including those more representative of the types used in the dairy industry, as well as how design affects standing behaviour.

6.2 – Biomechanics

This study demonstrated that modern biomechanical methods can be used in non-laboratory conditions to study the movements of dairy cattle in free-stall and open pen environments. The errors associated with these measurements can be minimized through the use of careful calibration and the use of the techniques described below.

Errors associated with the technique used in my study fall into one of two categories; those errors that were quantified, and those that were not quantified. Quantified errors are those associated with calibration of the control object. These errors can be determined by the tests described in section 5.1. As shown in Table 2, the differences between the measured and predicted segment lengths of the model ranged from 0.2 cm to 1.2 cm (mean = 0.54, S.D. = 0.42). These errors, along with the total RMS error of the control markers of 0.896 cm, allow me to confidently report the movements of these animals. These results are similar to those reported by Deguerce et al. (1996) in a field experiment designed to evaluate the kinematics of horse locomotion. The planar techniques described in Appendix 1 do not allow for the measurement of these displacement errors.

Errors that were not quantified in this study include the accuracy and precision with which the markers are placed on the subjects. These errors can be mitigated by having the same trained person apply all markers to all subjects, as was done in this study. Another error that will be common to all techniques that use markers attached to a moving subject will be the soft-tissue movement of the markers. Van Weeren et al. (1990a, 1990b) demonstrated that skin movement in walking and trotting horses affected the displacement of markers placed on the skin, when compared to the movement of the bony anatomical locations under the skin. In my study, skin movement would be expected to be less when compared to gait analysis studies, due to reduced subject and marker speeds. As well, these skin movement errors may be reduced by using relatively light materials in marker construction and by applying the filtering algorithms used in the PEAK system to correct some of the small variations. However, until skin movement in the anatomical locations used in this study has been quantified, it must be assumed that some artifacts exist in the kinematic data presented. A last source of unquantified error was that discussed in the section describing the vertical measures (section 4.6.3), namely, that the location of markers that became obscured by sawdust were estimated and manually digitized.

6.3 –Recommendation for Future Biomechanical Work

Future researchers may be able to greatly improve the efficiency of gathering this type of data, facilitating future comparisons using larger samples of cows and testing alternative stall configurations by considering the following recommendations:

1) Use a dedicated black, light-proof room for all video recording of behaviour for biomechanical work. The use of the barn with its considerable background light in the present study prevented me from filming during daylight hours. Furthermore, despite painting pen dividers black and hanging black fabric around the pen, I was unable to eliminate all sources of background light. One of the advantages of modern motion analysis systems is that they have the ability to automatically track the movements of subject markers, vastly reducing the time spent digitizing. However, if the contrast between the markers and the background is reduced (as is the case when there is background light), the system is unable to track them, requiring the operator to manually track the markers. This greatly increases the time required to collect the data.

2) Carefully consider the camera locations when arranging the filming area. The cows escaped from the filming enclosure a number or times, requiring re-calibration of the cameras. This process took several days, therefore, each instance was a considerable set-back. Thus, in any future work I recommend housing the cameras behind an enclosure made of a clear material

such as Plexiglas so that cows cannot disturb their positions. Additionally, this would eliminate the need for a rope enclosure, which would also reduce the amount of clutter in the images, again speeding up the digitization process.

3) Do not use lights mounted directly above the cameras. Because the optimum angle between cameras is 90^{o}, having four cameras requires that each camera face another (see Appendix 6 for schematic diagram of camera locations) resulting it the light mounted above each camera becoming a major source of background light for the camera facing it. If the amount of background light is kept to a minimum, then less powerful lights mounted out of the cameras' line of view should suffice to illuminate the subject markers.

7.0 - Conclusion

The results of this study can be used to evaluate current stall recommendations and stall designs for cows having similar physical characteristics to those used in the present study. My results indicate that current recommendations for overall bed length may be too small to accommodate cow movements, but that width recommendations appear to be adequate. As well, the results from the vertical measures indicate that stall partitions can be designed to minimally interfere with cow movements. These results also indicate that a well designed stall has little effect on these behaviours. Future work should examine the effects of more typical designs on these same movements.

Additionally, my study demonstrated that biomechanical methods can be used to gather data useful in the assessment of dairy housing. Specifically, these methods provide an improved understanding how cows move naturally when lying down, and this understanding allows us to evaluate the design of cow stalls and how they may impede such movements.

Table 1: Parity, body weight and total number of days of filming required to obtain a minimum of two lying events in both conditions for each of the five cows.

Cow	Filming Days (days before calving)	Parity[1]	Mass [2] (kg)
1	40-47	2	599
2	20-23	7	679
3	51-63	2	549
4	39-48	3	619
5	28-32	2	589

[1] **Parity** refers to calving following filming.
[2] The cows were weighed twice approximately one month after calving, immediately after milking and before feeding.

Table 2: Predicted and **Measured** segment lengths from the model used to assess the accuracy of the calibration process. The PEAK Motus system automatically calculates the length of segments between any two markers, allowing an independent check of accuracy.

Segment #	Predicted length (cm)	Measured length (cm)
1	200.8	201.0
2	61.5	60.3
3	40.3	41.0
4	100.3	100.7
5	69.8	70.0

Table 3: Total number of successfully digitized events (**Observations**) for each cow in each condition, as well as the **Mean Body Lengths**, as defined in section 4.4. .

Cow	**Observations**		**Mean Body Lengths (SD) – (cm)**		
	No stall	**Stall**	**Hip**	**Shoulder**	**Back**
1	3	3	56.5(0.8)	49.9(0.6)	99.6(2.0)
2	3	3	64.1(0.8)	48.2(1.1)	104.0(1.6)
3	3	3	56.5(1.3)	46.4(1.0)	101.3(4.3)
4	2	4	60.3(1.5)	50.2(1.0)	109.9(1.4)
5	0	4	60.4(1.2)	51.4(0.5)	102.9(1.2)

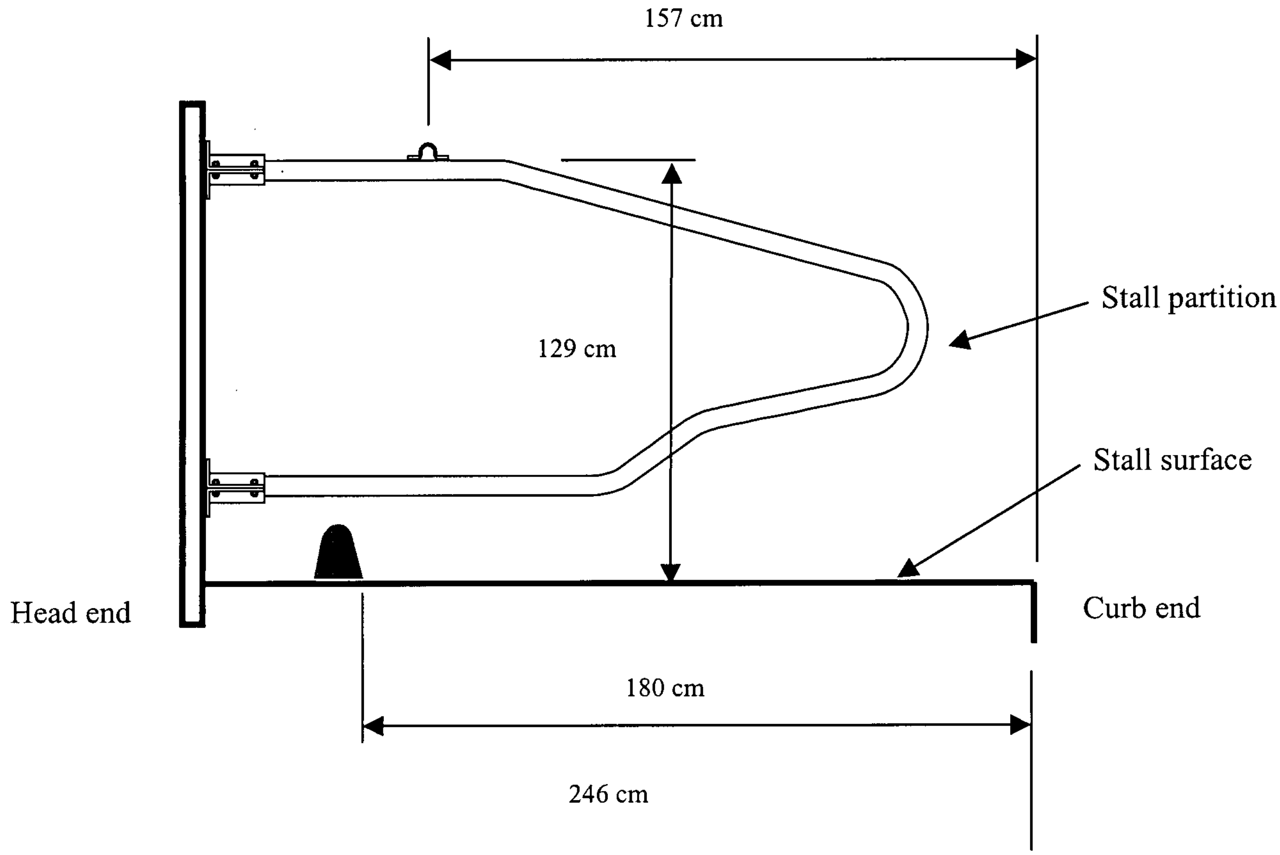

Figure 1: Diagram of free-stall used in this study (Artex Fabricators Y2K comfort stall with Promat cow mattress installed). When in the pen, the free-stall was secured to the rope fence opposite the feed bunk, with the open end facing the feed bunk. The head of the stall was roped off such that the cows could not lunge beyond the end of the bed. The overall stall width was 103 cm.

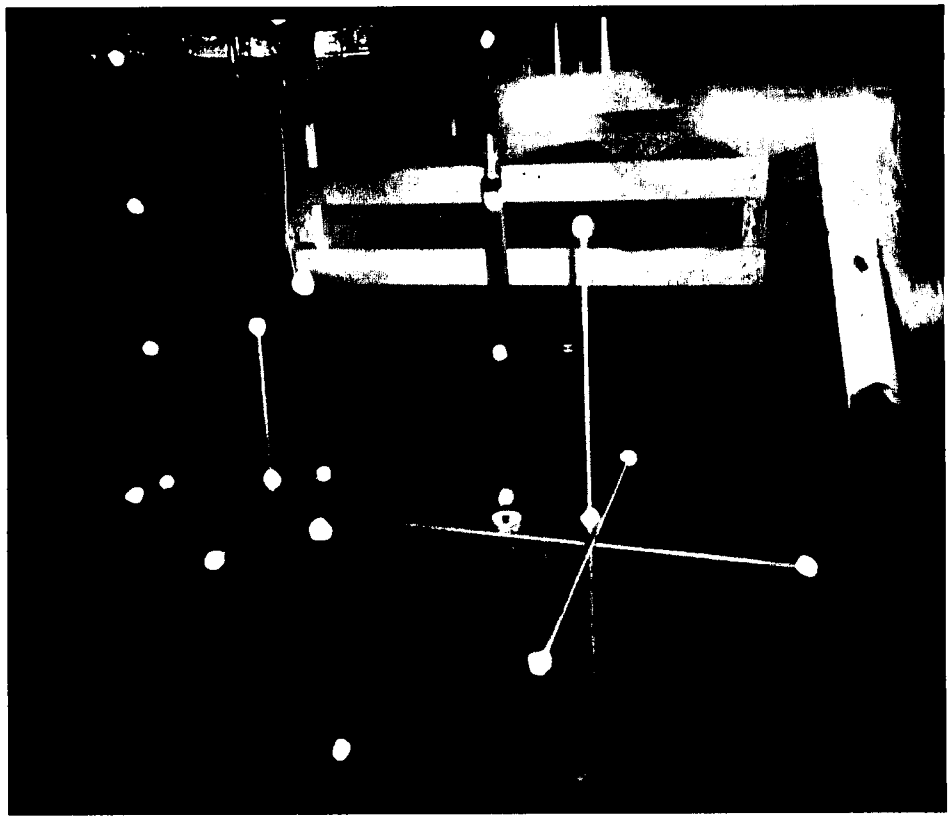

Figure 2: Photo of model used to determine the accuracy of the calibration. The model is made of wooden dowels with ten reflective markers. The other markers visible in this photo are from the control object.

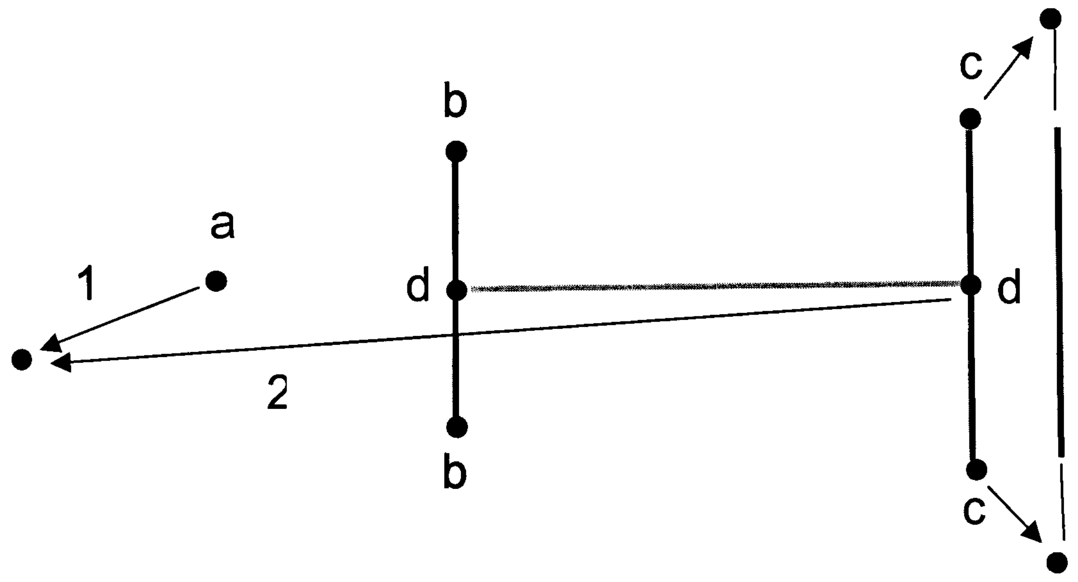

Figure 3: Schematic overhead view of: a) nose marker, b) shoulder markers, c) hip markers and d) virtual markers. The numbers indicate representations of: 1) nose marker displacement, 2) total longitudinal displacement and 3) total lateral displacement.

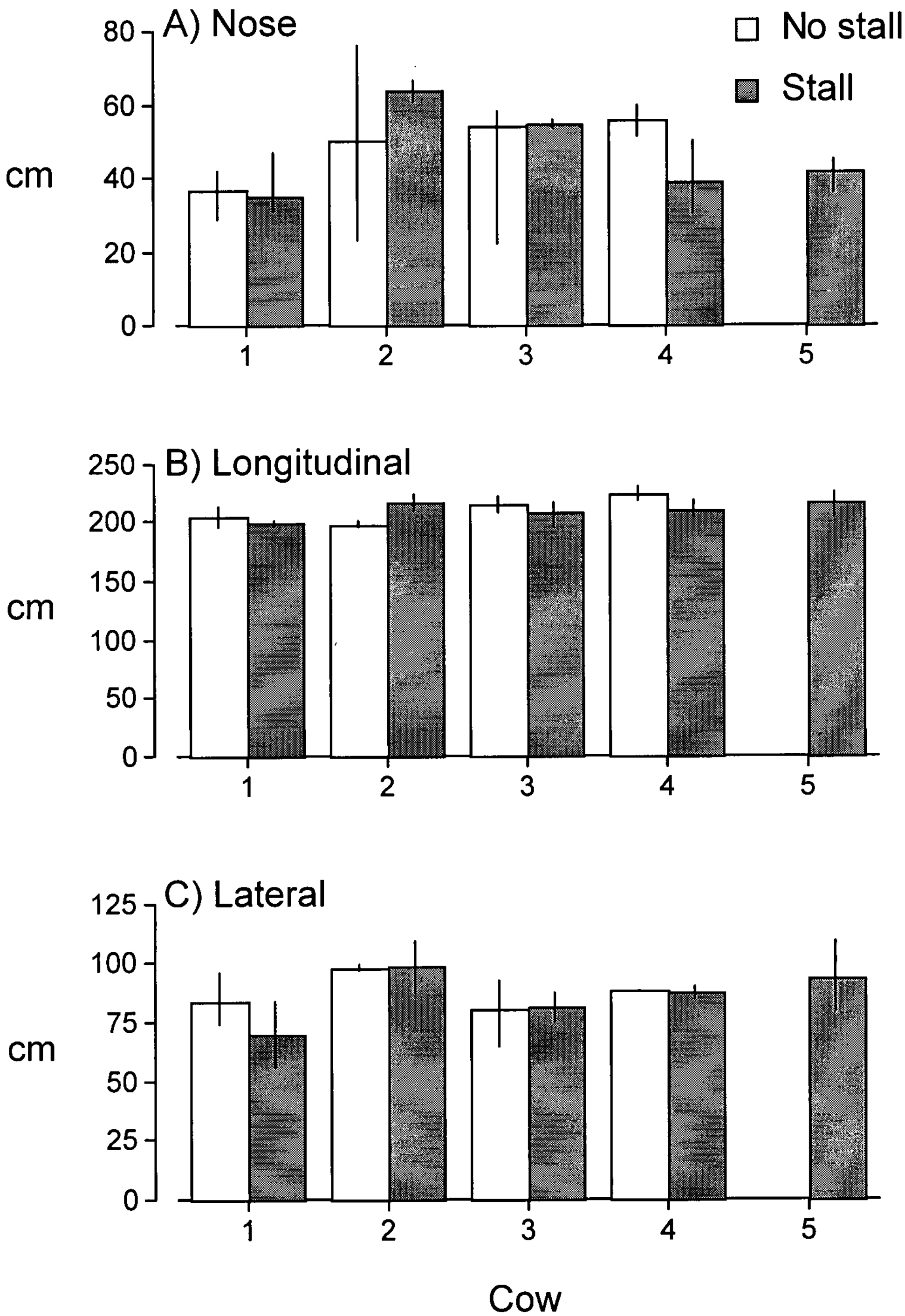

Figure 4: Means of a) nose marker displacements, b) total longitudinal displacements, and c) maximum lateral displacements. Error bars show maximum and minimum values.

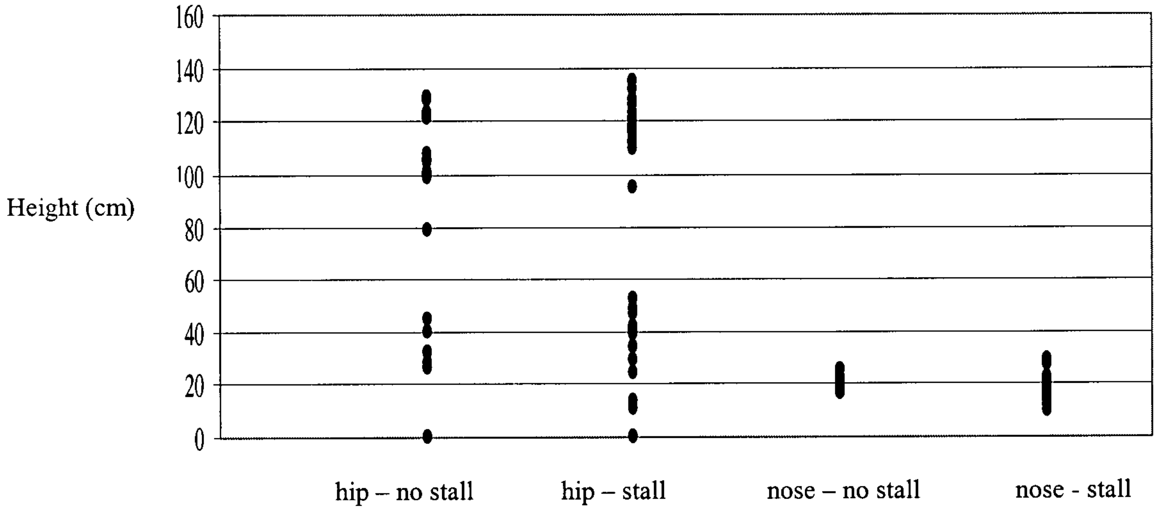

Figure 5: Height above the ground, or the stall bed, for both hip markers and the nose marker at the point of furthest displacement, for all cows and all events. Each dot represents one observation. Observations which appear as 0 cm indicate events during which a marker was not displaced away from it's starting position.

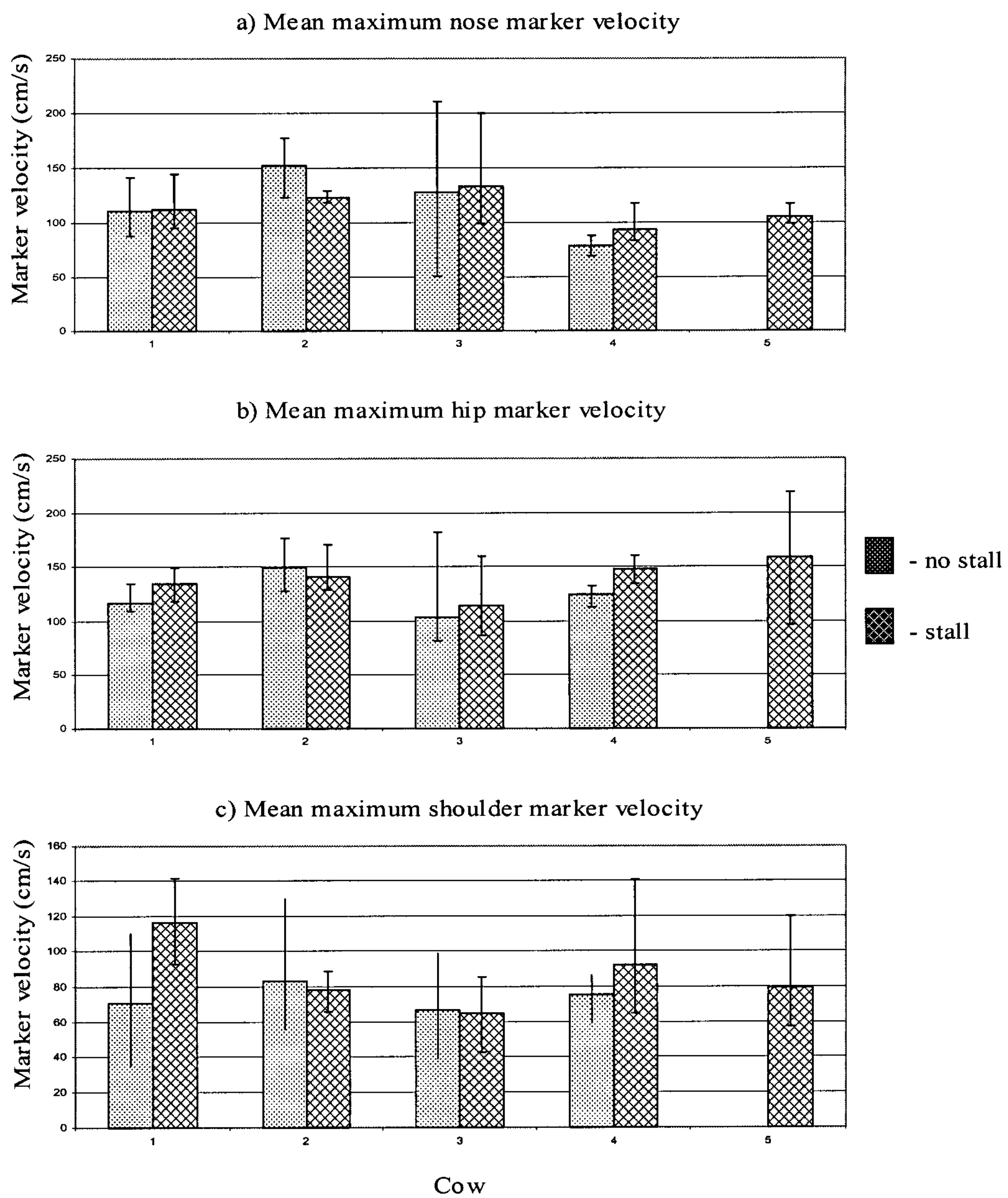

Figure 6: Mean maximum instantaneous velocities attained by each of the nose, hip and shoulder markers during the lying down movement. Data were not distinguished between left and right shoulders or hips. Error bars show maximum and minimum values.

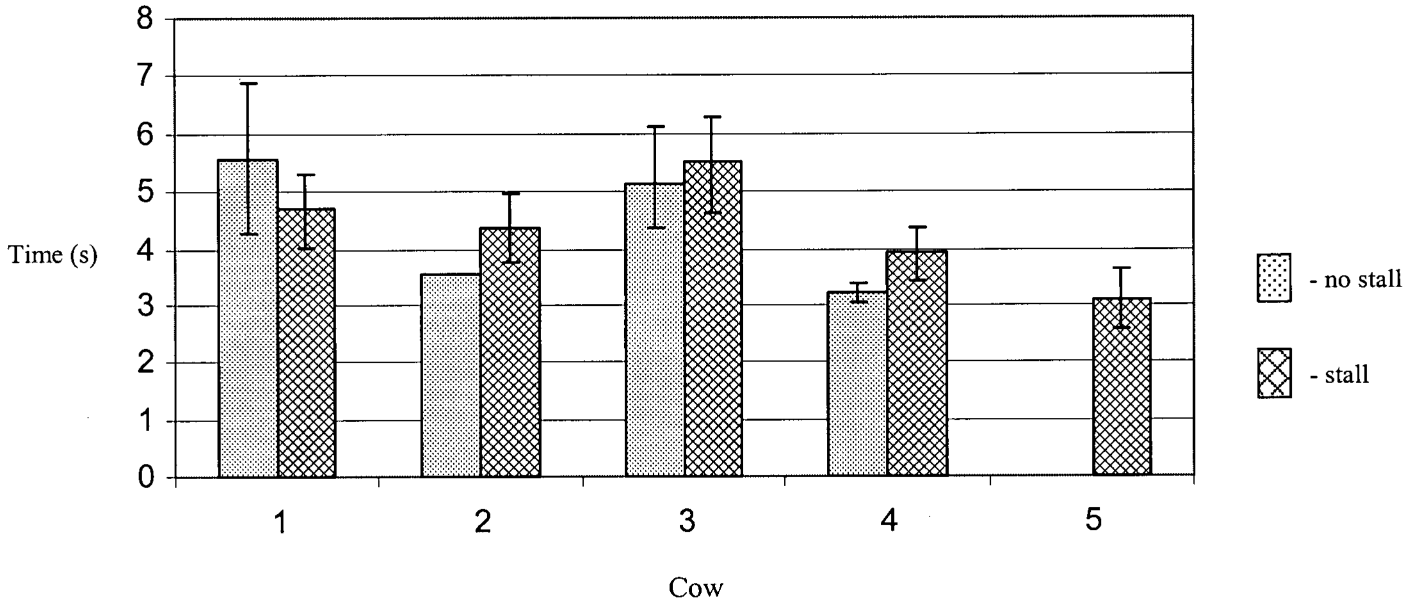

Figure 7: Mean time taken to complete the lying down movement for each cow in each condition. Error bars show maximum and minimum values.

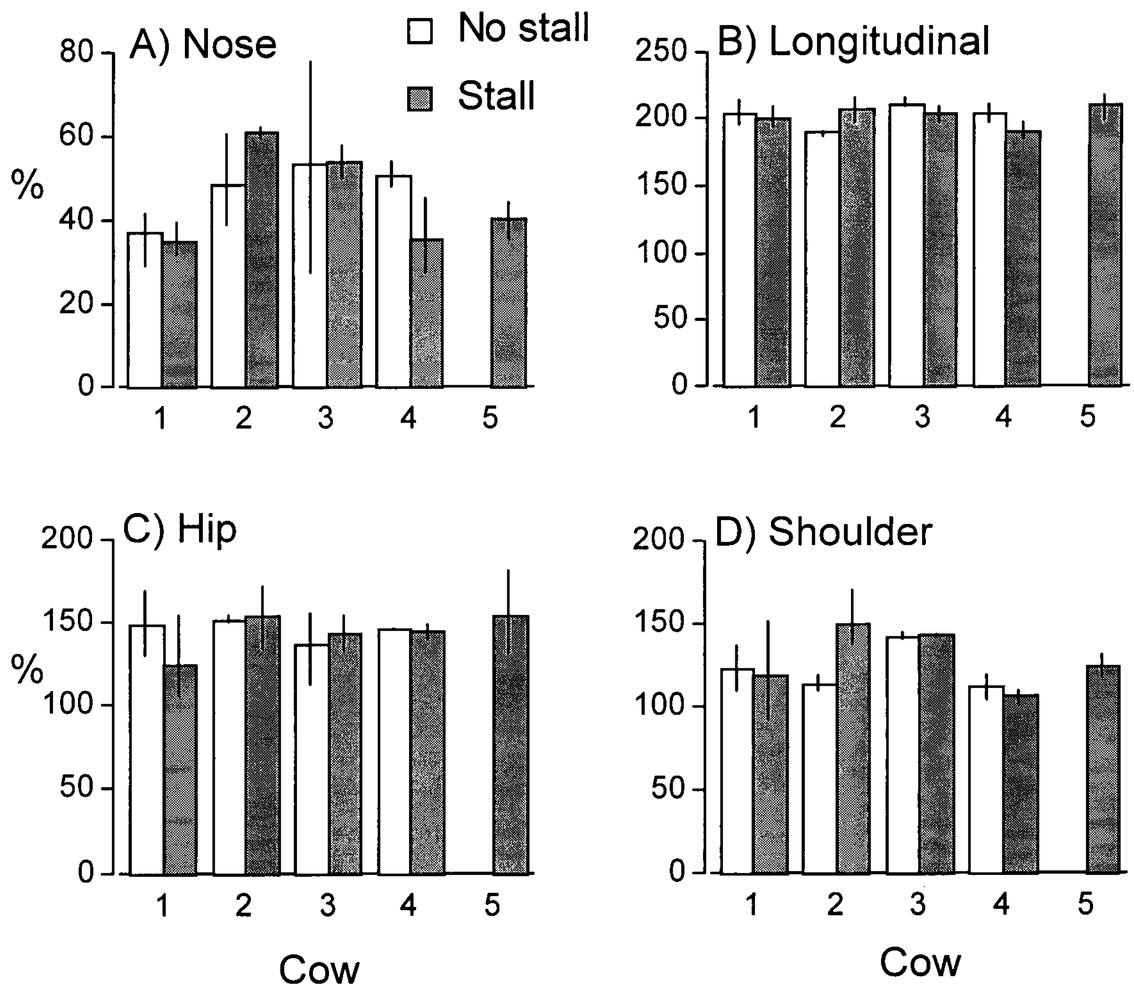

Figure 8: Normalized displacements of a) the nose marker, b) the nose marker plus the back virtual marker, c) total hip marker displacement, and d) total shoulder marker displacement. Note that a) and b) are normalized to the calculated back length, while c) and d) are normalized to the calculated hip and shoulder widths, respectively. See Table 3 for calculated body measurements. Error bars show maximum and minimum values.

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Appendix 1: Biomechanics

Kinematic Analysis

Biomechanics is the field of study that applies mechanical laws to the analysis and quantification of biological movement and forces (Barrey, 1999). Within the field of biomechanics, kinematics specifically deals with the study of changes in the position of body segments in space during a particular time. The motions are described quantitatively by linear and angular displacements, velocities and accelerations. No attempt is made to describe the causes of the motion. Kinetics, or dynamics, is the field of study that relates causes to biological movements, and as such is concerned with forces, energy and work in relation to the kinematic variables listed above.

Kinematic measures are obtained by determining the trajectories of joints and segments of the body during a particular time period. Modern methods use markers, referred to as "subject markers", which are attached to specific anatomical landmarks on the subject. These markers are then video recorded and the video recordings digitized using a video interface. Modern motion analysis systems can automatically detect the motion of the markers on the video image, greatly reducing the amount of time needed to digitize video clips, thus allowing much more data to be gathered in a shorter period of time. Algorithms, such as DLT (direct linear transformation), can then reconstruct the three-dimensional co-ordinates of each subject marker from the two-dimensional image co-ordinates. With modern analysis systems and careful calibration, three-dimensional reconstruction of subject marker locations can result in positional accuracies of within a few millimeters, as has been demonstrated by a number of researchers (Wood and Marshall, 1986, Hatze, 1988, Challis and Kerwin, 1992, Hinrichs and Maclean, 1995).

Planar techniques

Lidfors (1989) describes a number of studies that measured cow movements using techniques referred to as planar, or multiplier, techniques. In order to measure movement using these techniques, an object of known length (the multiplier), must be placed in view of the camera, and must be parallel to the film plane. As well, the loci of all measured points on the subject must be in a single plane that is parallel to the film plane Further, the images must be close to the longitudinal axis of the lens in order to minimize parallax error. Lastly, the distances between the camera, the multiplier and the subject must be known precisely. If these requirements are met, the image of the multiplier can then be used as a scaling co-efficient to determine the real-world displacements of the subject markers from the image displacements obtained from the camera. If these conditions are not met, errors are introduced. These errors can be compensated for by using trigonometric corrections Modern motion analysis systems make use of algorithms, such as DLT, that allow movement reconstruction as well as error determination.

Calibration

Calibration was done by fixing the positions of all the cameras being used in the study, and then filming a stationary object known as the control object (see Appendices 5 and 6 for a photograph and schematic representation of the control object). The control object was made up of a number of control markers, whose exact positions had to be determined and entered into the motion analysis system.

In order to obtain accurate subject marker position reconstruction, the following conditions had to be met when constructing the control object:

1) The subject markers should not be located outside of the volume encompassed by the control object used to calibrate the cameras (Wood and Marshall, 1986).

2) A large number of control markers, well distributed throughout the volume to be used by the subjects, should be used for the control object. If compromises must be made, the control points should be located around this volume, rather than within it (Wood and Marshall, 1986, Challis and Kerwin, 1992).

3) The angle between camera axes should be close to the theoretically optimum angle of 90° (Wood and Marshall, 1986).

Within the pen, I constructed the control object by suspending a metal tube frame from the roof of the barn. Nine lengths of fishing line with retro-reflective control markers (3 cm diameter foam balls covered with 3M reflective tape) were hung from this frame to form a control object with overall dimensions of 370 cm (X direction) x 338 cm (Y direction) x 202 (Z direction) cm. Note that I had to move markers 31-35 inward, in order for them to be in view of camera 2. This did not affect the accuracy of the subject marker position reconstruction, so long as the cows stayed within the volume defined by the control object. Each line had five markers attached, and lead weights on the end of the lines were placed in water-filled bowls in order to dampen any movement during filming for calibration.

A total of 45 markers formed the control object, and an orthogonal reference system was defined, with the origin located at the bottom north-west corner of the control object (control marker #1). The X - Y plane was the horizontal plane, with the Z – axis being the vertical axis. I manually leveled and surveyed the control object. Control marker #1, as the origin, was assigned a position of (0,0,0) (cm), therefore all of the other markers were measured relative to this origin. After calibration filming, the control object was removed. Four 60-Hz cameras (Panasonic WV-BP310) were located and fixed in position around the pen, with recording being done in an adjacent room on four VCRs. A light (60 W residential) was mounted above each camera, to allow maximum reflection from the subject markers.

The camera images were synchronized by suspending a light above the middle of the pen, in full view of each of the cameras. The light was controlled by a laboratory timer, which turned the light on and off every 10 seconds.

Appendix 2: Anatomical locations of real subject markers and definitions of virtual markers.

The positions of the real subject markers were chosen in order to allow me to determine the furthest displacement of the extremities of the animals. As well, these locations prevented easy removal of the markers by the cow. Generally, the use of round balls as subject markers is preferred because they allow the center of the marker to be seen from all angles. However, the markers placed on the legs (marker numbers 1,3,5 and 7) were made of 3M reflective tape (1 cm wide) glued to non-reflective black fabric approximately 10 cm wide and,, wrapped around the joint. Preliminary work had demonstrated that round balls attached to the legs were very quickly crushed or rubbed off by the cow when she lay down. The remaining markers were wooden balls (approximately 2.5 cm in diameter) covered with reflective tape, attached to black fabric. The black fabric allowed for easy attachment of markers to the cow, as well as providing good contrast. All markers were attached to the cows using bull cement, and were removed upon completion of filming.

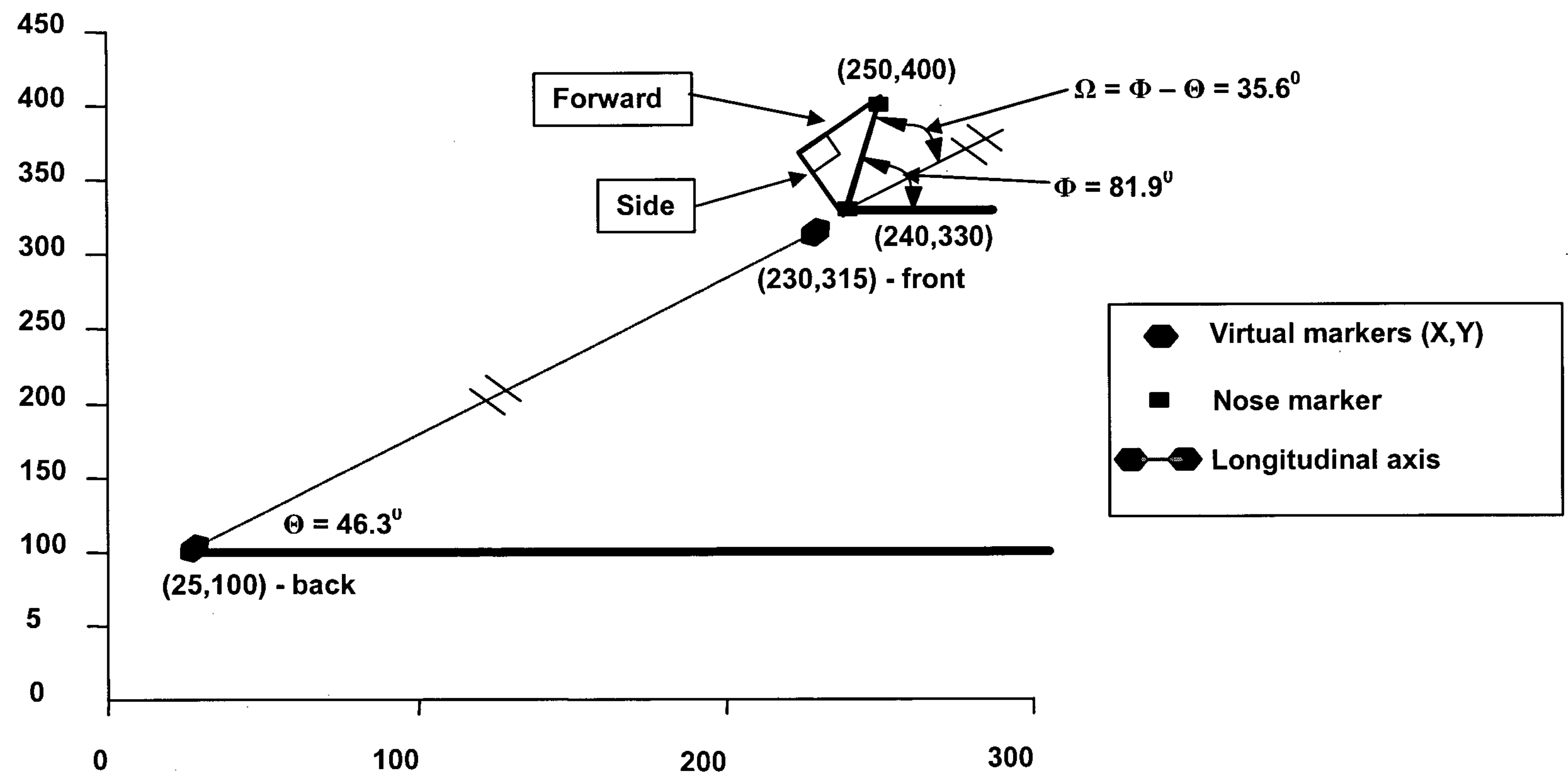
Marker #	Marker location
1	10cm distal to the left carpus (front left knee marker)
2	Major tubercle of the left humerus (left shoulder marker)
3	10cm distal to the left calcaneal tuber (back left hock marker)
4	Left sacral tuber (left hip marker)
5	10cm distal to the right carpus (front right knee marker)
6	Major tubercle of the right humerus (right shoulder marker)
7	10cm distal to the right calcaneal tuber (back right hock marker)
8	Right sacral tuber (right hip marker)
9	Dorsal surface of the head, 10 cm caudal to the nose (nose marker)

Virtual Marker	Definition of Virtual Marker
Front	Midway between segment formed by real markers # 2, 6
Back	Midway between segment formed by real markers # 4, 8

Appendix 3: Sample calculations and schematic overhead view of virtual back markers and nose marker.

The X and Y axes are those of the global co-ordinate system that was defined by the control object. The longitudinal axis is defined by the front and back virtual markers at the start of the lying behaviour. The angle of the longitudinal axis (**Θ**), relative to the global co-ordinate system, is calculated as shown.

The nose marker is shown at the start of the movement, and at the point of furthest forward displacement. **Φ** is the angle of the vector defined by the start and end points of the nose marker, and is calculated in an identical fashion. **Ω** is the difference between **Θ** and **Φ**. **Side** and **Forward** represent the perpendicular and parallel components of nose marker displacement relative to the angle X. A vertical component was also calculated, using displacement in the Z-direction. Hip and shoulder calculations are identical, except that the final position is at the furthest sideways (perpendicular) displacement. In this example, the nose marker was displaced 23.4 cm forward (parallel to the longitudinal axis).



$$\sin \Theta = \Delta Y / \sqrt{(\Delta Y^2 + \Delta X^2)}$$
$$= (315-100) / \sqrt{((315-100)^2 + (230-25)^2)}$$
$$= 0.724 \qquad \therefore \Theta = \sin^{-1}(0.724) = 46.4^0$$

$$\text{Forward} = \sqrt{(400-330)^2 + (250-240)^2} \cos \Omega$$
$$= 70.7 \cos 35.6^0$$
$$= 23.4 \text{ cm}$$

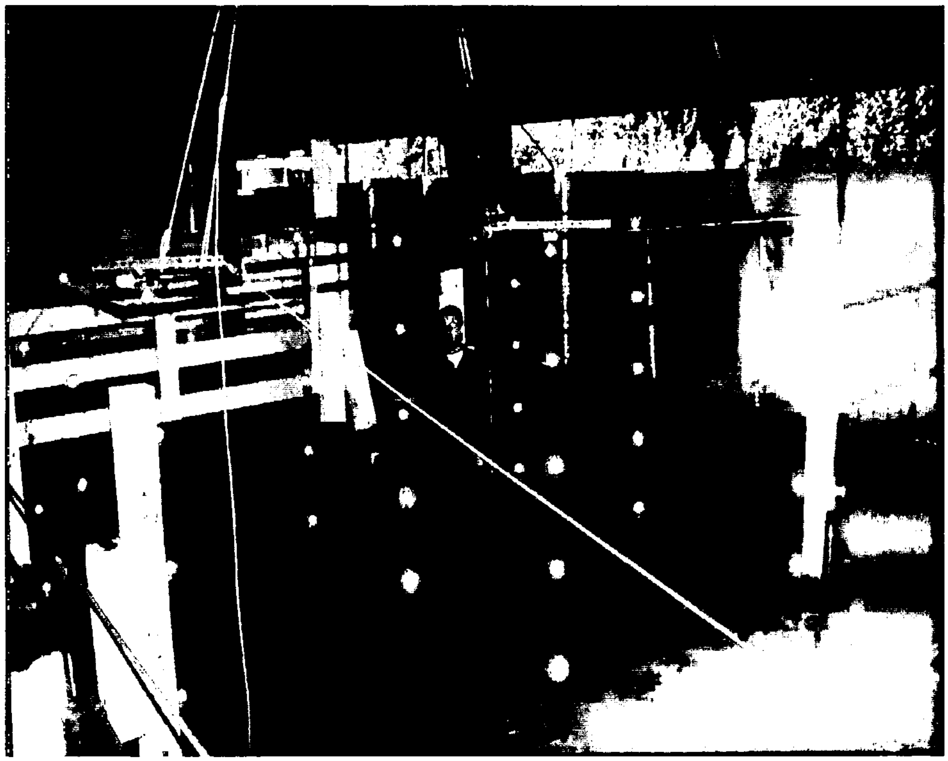
Appendix 4: Control marker errors.

Point[1]	Computed[2]			Residual[3]			Position[4]
	X	Y	Z	X	Y	Z	
1	-0.408	0.198	0.579	-0.408	0.198	0.579	0.735
2	0.012	-0.897	49.928	0.012	-0.897	-0.072	0.9
3	-0.009	-0.981	99.557	-0.009	-0.981	0.057	0.982
4	0.244	0.156	148.29	0.244	0.156	0.288	0.409
5	0.873	0.447	197.6	0.873	0.447	0.097	0.986
6	0.694	169.69	-3.601	0.694	0.686	-0.601	1.146
7	0	0	0	0	0	0	0
8	-0.647	169.12	96.114	-0.647	0.12	-0.886	1.104
9	-0.139	169.53	145.73	-0.139	0.533	-1.069	1.202
10	0	0	0	0	0	0	0
11	0.573	338.64	0.204	0.573	1.138	-0.296	1.308
12	0.517	338.27	49.496	0.517	0.772	-0.504	1.056
13	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0
15	1.181	337.21	198.23	1.181	-0.292	0.23	1.238
16	144.24	0.047	1.278	0.044	0.047	-0.222	0.231
17	144.15	-0.098	50.921	-0.046	-0.098	0.221	0.246
18	144.47	0.646	100.24	0.269	0.646	0.243	0.74
19	144.49	-0.732	148.87	0.291	-0.732	-0.128	0.798
20	144.72	0.339	198.71	0.516	0.339	0.712	0.943
21	144.01	175.27	-9.683	-0.192	0.273	0.117	0.353
22	143.6	174.17	40.115	-0.601	-0.83	0.615	1.195
23	144.46	174.77	89.331	0.262	-0.227	0.331	0.479
24	143.86	175.61	138.46	-0.342	0.611	-0.04	0.702
25	144.2	174.37	187.91	0	-0.631	0.305	0.701
26	0	0	0	0	0	0	0
27	143.95	337.61	50.811	-0.253	0.314	0.311	0.509
28	0	0	0	0	0	0	0
29	144.42	337.97	149.17	0.223	0.673	-0.132	0.721
30	143.78	337.72	198.85	-0.423	0.419	0.349	0.69
31	312.44	84.338	-1.745	0.838	-0.562	-0.245	1.038
32	311.8	84.372	48.01	0.195	-0.528	-0.49	0.746

[1] Marker number.
[2] X, Y and Z co-ordinates as calculated by PEAK Motus motion analysis system.
[3] Difference between computed X, Y and Z co-ordinates and surveyed co-ordinates.
[4] RMS positional error for each marker.

33	312.2	84.826	96.935	0.597	-0.074	-1.065	1.223
34	311.78	85.13	146.44	0.175	0.23	-1.064	1.102
35	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0
37	378.11	182.07	41.783	0.809	-1.026	0.283	1.336
38	0	0	0	0	0	0	0
39	377.69	183.01	139.89	0.386	-0.086	0.386	0.553
40	378.46	182.83	188.59	1.161	-0.272	0.485	1.288
41	369.87	338.09	0.254	-0.433	0.192	0.254	0.538
42	0	0	0	0	0	0	0
43	370.4	338.65	99.01	0.104	0.75	0.01	0.757
44	0	0	0	0	0	0	0
45	370.08	337.38	197.61	-0.222	-0.516	0.212	0.601
		Average ms error		**0.507**	**0.564**	**0.478**	**0.896**

Appendix 5: Photograph of control object in pen.



Appendix 6: Schematic representation of the cow pen, control object with control markers and the camera layout, looking downward. The markers are labeled from #1-45 and the cameras are labeled C1-C4. Each dot in this view represents a length of fishing line with five control markers attached. When in place, the free-stall was located in the upper right-hand portion of the pen as seen in this view. The origin of the orthogonal co-ordinate system was located at marker #1, with the Z-direction being defined as positive upwards.