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Anthropometric criteria for the design of tractor cabs and protection frames

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Improved human – tractor interface designs, such as well-accommodated operator enclosures (i.e. cabs and protection frames) can enhance operator productivity, comfort and safety. This study investigated farm-worker anthropometry and determined the critical anthropometric measures and 3-D feature envelopes of body landmarks for the design of tractor operator enclosures. One hundred agriculture workers participated in the study. Their body size and shape information was registered, using a 3-D full-body laser scanner. Knee height (sitting) and another eight parameters were found to affect the cab-enclosure accommodation rating and multiple anthropometric dimensions interactively affected the steering wheel and gear-handle impediment. A principal component analysis has identified 15 representative human body models for digitally assessing tractor-cab accommodation. A set of centroid coordinates of 34 body landmarks and the 95% confidence semi-axis-length for each landmark location were developed to guide tractor designers in their placement of tractor control components in order to best accommodate the user population. Finally, the vertical clearance (90 cm) for agriculture tractor enclosure in the current SAE International J2194 standard appeared to be too short as compared to the 99th percentile sitting height of male farm workers in this study (100.6 cm) and in the 1994 National Health and Nutrition Examination Survey III database (99.9 cm) and of the male civilian population in the 2002 Civilian American and European Surface Anthropometric Resource database (100.4 cm).

Keywords: Tractor; Anthropometry; 3-D scans; Accommodation; Agriculture

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1. Introduction

Tractors are companions for many agriculture workers. Well-designed human–tractor interfaces, such as well-accommodated tractor operator enclosures (i.e. cabs, hand-and-foot controls and protection frames) can enhance worker productivity, comfort and safety (Matthews 1977, Kaminaka 1985, Liljedahl *et al*. 1996).

Research on the human–tractor interface for tractor-operator enclosures can be traced back to the 1950s in Sweden (Moberg 1973). At that time, there were a number of fatal incidents involving tractor overturns; these incidents caused strong public reaction and especial concerns among the Swedish trade organizations. In response to these concerns, researchers developed test procedures to ensure the mechanical soundness of tractor cabs and protection frames. Subsequently, researchers developed a set of the dimensions for the operator protection zone, mainly in order to simplify the mechanical test work and to minimize variations in mechanical test results. More recent design parameters – impediment of steering wheel, hand controls and protection frames for tractor drivers – were not specifically examined at that time. Over the following five decades, two concepts – the need to establish operator space envelopes and tractor control locations that fit operators' body size – have been increasingly recognized as important design elements (Dupuis 1959, Adams *et*. *al*. 1975, Purcell 1980, Bottoms 1983, SAE International 1989, 1992, 1994, Yadav and Tewari 1998). At the current time, these design parameters are considered standards. Adjustable seats, steering wheels and other controls have become the norm and new heavy tractors are universally equipped with roll-over protective structures (ROPS), which include a seatbelt that keeps the operator within the bounds of the ROPS 'safety zone' (ASAE 2000a,b). However, the anthropometric design characteristics of these widely implemented technologies have been little evaluated, despite the importance of these characteristics for safeguarding workers. The tractor industry and the agricultural community have a pressing need for a scientifically rigorous assessment of the fit and function of these products.

Good human–tractor-interface design ensures that a tractor cab and ROPS will accommodate the body size of agricultural workers (Hansson *et al*. 1970). In the design process for operator cabs, adjustments for brake reach and linkages, seat position and seat height must be designed to position all potential operators so that they can adequately reach the brake controls and see over the tractor and beyond the protection frames. In addition, the cab space must be arranged in such a way that the steering wheel, hand controls and seat do not hinder the driver's operation. Moreover, the dimensions of the ROPS should adequately accommodate tractor drivers during normal operation and protect them from injury during a rollover. A review of the historical anthropometric sources for the agriculture tractor design standards (SAE International 1989, 1994) reveals that they are based on dimensions that were derived from US Army population databases collected in the 1960s and 1970s (SAE International 1989, 1994, Liljedahl *et al*. 1996). Large variations in body dimensions exist over the past decades and between military and civilian populations (Hsiao *et al*. 2003). An updated anthropometric data set of the nation's agricultural workers (or civilian population) is needed for improving tractor design.

Some recent anthropometric data on the USA's agricultural workers were collected in the National Health and Nutrition Examination Survey III (NHANES-III) in the early 1990s (Hsiao *et al*. 2002). This nutrition-based data set, however, is of limited use for safety or ergonomics analysis; few dimensions relevant to the present purpose were measured. A few other small anthropometric data sets of farm workers (e.g. Hansson *et al*. 1970, Casey and Kiso 1990, Victor *et al*. 2002) were also of limited use for the current US cab design applications. For one thing, the international farmer anthropometric information collected in the studies would not represent the dimensions of US farm workers. For another, dimensions measured and tabulated by traditional methods were not linked to one another. For example, knowing shoulder width would not enable a modeller to create an accurate representation of shoulder location related to the cab space for tractor-design applications. Updated 3-dimensional human form data would answer the subject cab design questions that could not be well addressed when using traditional 2-dimensional anthropometric approaches. Furthermore, in the previous farm machine designs, anthropometric data were generally used to estimate only the extremes of univariate distributions of a few gross dimensions, with little provision for individuals with unusual anthropometric proportions (e.g. Purcell 1980, Gite and Yadav 1989, Patel *et al*. 2000). Some individuals have a long torso and short extremities while others can have the opposite anthropometric characteristics for these dimensions. Similarly, a person can have a long buttock – knee length coupled with a small abdominal depth, while others may have a short buttock – knee length with large belly dimensions. These extreme ratios present difficult problems for accommodation in tractor cab design and there is limited published literature addressing this tractor accommodation issue. A multivariate anthropometric procedure, such as the principal component analysis (PCA) method, would be useful for adequately solving the above concerns (Zehner *et al*. 1992).

Finally, the key dimensions to address the tractor cab accommodation (i.e. effective anthropometric criteria for tractor design) have not yet been scientifically defined. Which measurements are significant and how they interact to affect the tractor cab accommodation are not well known. Controlled studies to identify the key dimensions for tractor cab and protection frame design are needed to ensure an effective cab design process.

The goals of this study were to: (1) determine the critical anthropometric measurements related to tractor cab accommodation as well as the validity of current anthropometric standards for tractor cabs; and (2) develop representative anthropometric tractor-operator models and the 3-dimensional feature envelopes of their body landmarks for tractor-cab space design, protection-frame dimension determination and compartment-control placement. The study results have a direct impact on farm tractor safety, especially in using digital human models for the above-mentioned designs for safe tractor operation.

2. Method

2.1. *Participants*

Good sampling is necessary to make sure that the anthropometric statistics resulting from a survey accurately represent the population of interest. For most anthropometric surveys, good sampling involves determining the sample size, as well as determining the sample structure in terms of age, gender and race. Since this particular study was to investigate the effect of anthropometry on tractor cab and protection frame accommodation, the full range of anthropometric variation is more important than just the number of subjects. The sample was stratified on body weight and stature, using agricultural worker data in the NHANES III database as the reference (Hsiao *et al.* 2002). It was estimated that 72 to 80 subjects would be needed to investigate the anthropometric differences (e.g. stature) among tractor cab accommodation scoring categories with a risk of 10% type I error and 5% type II error. The sample size was set at 100. This is small enough to be cost-effective, while large enough to contain the human variation needed to allow investigators to examine a full range of body sizes. There was not an option to do a random sampling from the applicants; it was somewhat challenging already in recruiting farm workers due to farming seasons. However, the final data strata seemed to match the original plan well with a slight skew towards heavy weight and tall stature.

A total of 100 volunteers (88 males and 12 females) participated in this study. Of this number, 94 of them were considered agriculture workers. The average height was 177.4 (SD 6.5) cm and mass was 87.8 (SD 17.5) kg for males with 165.9 (SD 6.6) cm and 72.6 (SD 19.6) kg respectively for females. All participants, except one male, were white. They were well distributed between the ages of 18 and 76 years. All participants drove tractors; 73% of them operated tractors on a regular basis. The protocol was approved by the Institute Review Board of the National Institute for Occupational Safety and Health (NIOSH). All participants gave informed consent prior to the study and were compensated for their time and inconvenience.

2.2. *Independent variables*

2.2.1. Accommodation scores. The level of accommodation experienced by the participants was assessed through a questionnaire. Participants answered questions about their own tractor when they were in the NIOSH laboratory. They had opportunities to interact with NIOSH researchers to clarify any questions they had. The questions concerned seat, steering wheel and gear handle accommodation. The seat accommodation score was based on a question: 'How well does your seat adequately fit you to the tractor?' The responses 'very good', 'good' or 'moderately good' were given one point. The responses 'bad' or 'very bad' were given no points. The steering wheel accommodation score was based on a question: 'Does the steering wheel impede your legs, thighs, hips or stomach while operating the tractor? If no more than one body part was impeded, the score was one. If two or more body parts were impeded, the score was zero. The gear handle accommodation score was based on a question: 'Do the gear handles ever impede your ability to move around on the tractor?' The responses 'never', 'almost never' or 'sometimes' were given one point. The responses 'almost all the time' or 'all the time' were given no points.

An overall accommodation score based on the sum of the individual scores was derived to summarize the overall level of accommodation experienced by the subjects. A sum of three points indicated a driver was reasonably well accommodated by his/her tractor. Less than three points indicated non-accommodation.

2.2.2. Postures. Three postures were selected for this study (figure 1). The first was a seated posture intended to mimic the way the subject normally sits to drive his or her tractor. The second position was a defensive pose intended to simulate posture during a rollover manoeuvre; the subject was asked to scrunch down in the seat, so it was referred to as the 'scrunch' pose. The third posture was a standing pose, which was used for collecting 'baseline' information to compare with traditional measurements in the literature.

2.3. *Dependent variables*

2.3.1. Body dimensions. Thirty-three dimensions that might be related to tractor cab accommodation and general characterization of the farm workers were selected (figure 2). Definitions for these dimensions are available in two major anthropometry source books (Webb Associates 1978, Gordon *et al.* 1989). Fifty anatomical landmarks were selected to provide references for the measurements. These landmarks are presented in figure 3.

2.3.2. Landmark coordinates. In order to establish 3-dimensional body-landmark feature envelopes for tractor operators, Cartesian coordinates for 34 of the 50 anatomical body landmarks were extracted from 3-D scans.

2.4. *Apparatus*

2.4.1. Three-dimensional body scanner. This study used a Cyberware WB4 3-D full-body scanner (Cyberware Inc., Monterey, CA) to register the subject's body shape and landmark information during normal standing and seated poses on a tractor seat (figure 4). The accuracy of the scanning system was tested to an average error of 2.9 mm (range + 6 to −6 mm) (Hsiao *et al.* 2003). The use of this 3-D scanning technology made 3-D landmark registration an accurate and practical process. The technology also substantially shortened the experiment time for human subjects, which was critical in acquiring farm workers.

2.4.2. Tractor seat. A commercially available seat was modified (figure 4) for the seated scans in this study. The seat was attached to a pneumatic cylinder and secured to the scanning platform. The seat pan height was adjustable from 42 to 52 cm above the scanning platform. The seat back angle was 105°. These features are the same as those of the cab in a popular commercial riding mower.

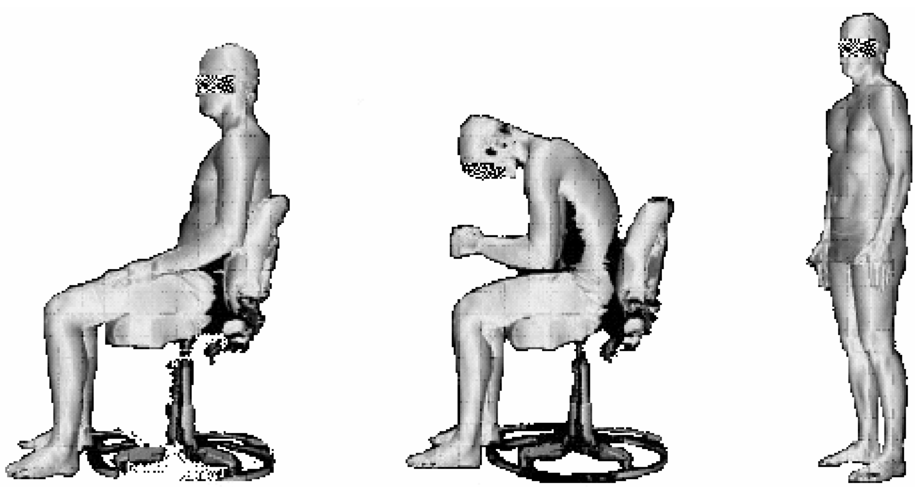

Figure 1. The three postures selected for this study: comfortably seated (a), defensive or scrunch pose (b) and standing (c).

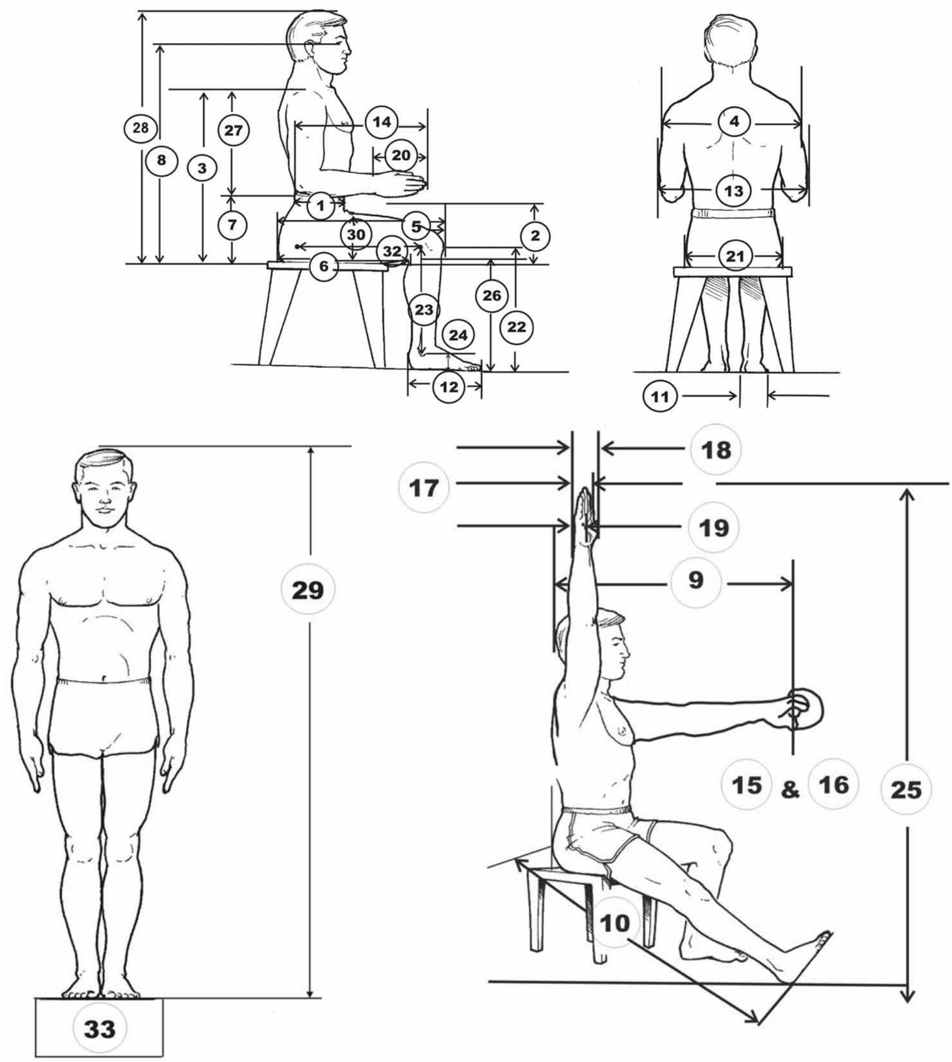

Figure 2. Dimensions measured in this study: (1) Abdominal extension depth, sitting; (2) Abdominal extension height, sitting; (3) Acromial height, sitting; (4) Bideltoid breadth; (5) Buttock – knee length; (6) Buttock – popliteal length; (7) Elbow rest height; (8) Eye height, sitting; (9) Functional grip reach; (10) Functional leg length; (11) Foot breadth; (12) Foot length; (13) Forearm – forearm breadth; (14) Forearm – hand length; (15) Grip strength, left hand; (16) Grip strength, right hand; (17) Hand breadth, four fingers; (18) Hand breadth, across thumb; (19) Hand depth (thickness); (20) Hand length; (21) Hip breadth, sitting; (22) Knee height, sitting; (23) Lateral femoral – lateral malleolus length; (24) Lateral malleolus height; (25) Overhead fingertip reach; (26) Popliteal height, sitting; (27) Shoulder – elbow length; (28) Sitting height; (29) Stature; (30)Thigh clearance; (31) Thumb tip reach (not shown); (32) Trochanter – lateral femoral epicondyle length; (33) Weight.

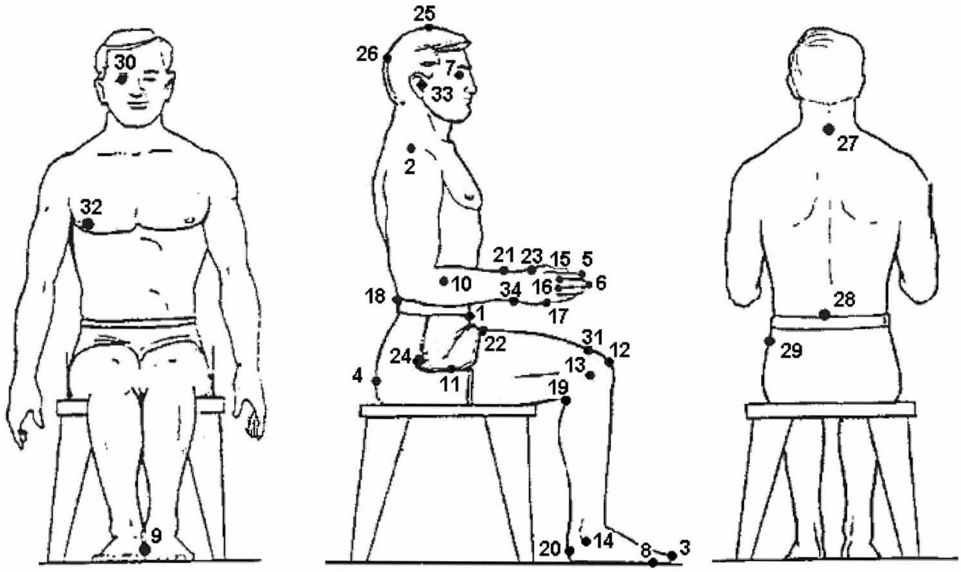

Figure 3. Fifty anatomical landmarks selected in the study to provide references for dimension measurement and tractor accommodation modelling: (1) Abdominal point, anterior*; (2) Acromion (right and left)*; (3) Acropodion – tip of the first or second toe, which is longer (right and left); (4) Buttock point, posterior, right; (5) Dactylion II – tip of the index finger (right and left); (6) Dactylion III – tip of the middle finger (right and left); (7) Ectocanthus; (8) Fifth metatarsophalangeal protrusion (right and left)*; (9) First metatarsophalangeal protrusion (right and left)*; (10) Forearm point lateral – the most lateral point, right; (11) Hip point – the most lateral point, right; (12) Knee point, anterior, right; (13) Lateral femoral epicondyle, right, sitting*; (14) Lateral malleolus, right*; (15) Metacarpale II (right and left)*; (16) Metacarpale III (right and left); (17) Metacarpale V (right and left)*; (18) Olecranon, right; (19) Popliteal fossa, right; (20) Posterior calcaneous (right and left); (21) Stylion; (22) Thigh point, top, right; (23) Thumb protrusion, right; (24) Trochanter, right*; (25) Vertex; (26) Back of head; (27) C7*; (28) L4*; (29) Posterior superior iliac spine (right and left)*; (30) Pupil (right and left); (31) Suprapatella (right and left)*; (32) Thelion (right and left); (33) Tragion (right and left)*; (34) Ulnar styloid (right and left)*. *Indicates a pre-marked landmark before scanning.

2.4.3. Traditional anthropometry measurement device. A set of anthropometry survey devices was used to take 33 traditional body measurements. These devices were an anthropometer (GPM, Switzerland), a beam caliper (rearranged pieces of the anthropometer), a Lufkin tape measure (Cooper Tools, Apex, NC) and a Toledo scale (Mettler-Toledo Inc., Worthington, OH).

2.5. *Procedures*

Upon arrival, the subjects viewed a PowerPoint^{TM} presentation, which described the study and the tasks that they were to perform. Each participant had the opportunity to ask questions before signing an informed consent form and filling out a short

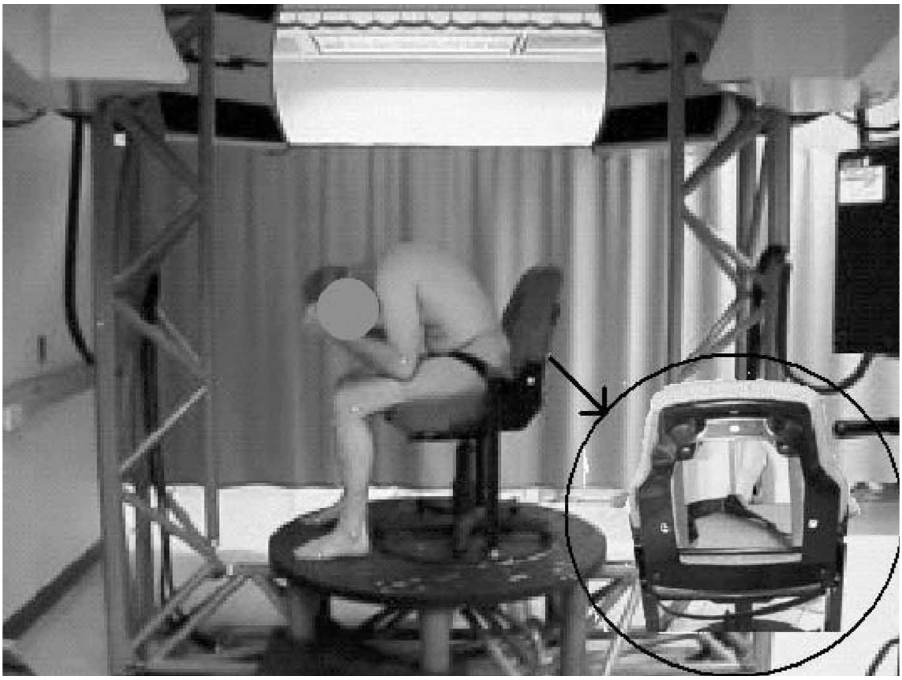

Figure 4. A subject scrunched for a full-body 3-D scan within the whole body scanner. The modified tractor seat used for the study is shown at the bottom right corner. The open seat back allows a back support while not losing information/image from the back of the subject's torso and pelvis during the body scanning process.

questionnaire. The subject was then taken to a dressing room, where he/she changed clothing – bike shorts for men and bike shorts with halter top for women. A form-fitting cap was also placed on the head to cover the hair. The subject sat on a stool and looked straight ahead with shoulders relaxed. They lined up their feet with the pre-marked footprints on a platform. The platform was adjustable through a hydraulic control such that the subject's knee angle was kept at 90°. An investigator located 24 skeletal landmarks on the subject's skin, by gently feeling for some bones and joints (figure 3). These landmarks were then marked with a grease pencil. Pencil marks were placed on the clothing overlying the actual landmarks if landmarks were covered by the clothing. The other 26 landmarks did not require a pencil mark because their skeletal landmark characteristics could easily be identified visually. After landmarking, 31 seated and two standing measurements were taken and entered into a laptop computer, using the traditional anthropometry survey devices described in section 2.4.3.

Following collection of the traditional anthropometry, a fiducial (1-cm white dot) was placed over the top of the grease pencil marks. This was to prepare the subjects for three scans on the Cyberware WB4 whole-body scanner. In the event that a fiducial fell off at some point during the process, the grease mark enabled investigators to quickly replace it. Prior to scanning any subjects, five locations were identified on the tractor seat and three on the scanner platform to use as a frame of reference in data analyses.

Three scans were performed in seated, scrunch and standing postures. For the seated scan, the seat was attached to the scanner platform and the subject was instructed to sit in the seat in a comfortable seated posture, hands on his/her thighs, looking straight ahead and feet flat on the platform. A few subjects could not reach 'feet-flat' posture; the seat height was kept to the lowest point (42 cm) for them. A small makeshift seat belt was used to secure the subject. Although the effect of human sway on image fidelity in Cyberware whole-body scans is minimal (Corner and Hu 1998), a sway stick was placed on top of the subject's head to further reduce any possible body movement (Brunsman *et al.* 1996). Subjects were instructed to hold their breath during the scan to reduce the variation in torso measurement resulting from respiration (Daanen *et al.* 1997). The scan took about 17 s. After the first scan, the subject crouched over and held up his/her arms as if he/she was gripping a steering wheel (figure 1) to mimic a possible defence posture during a tractor rollover. The subject was scanned a second time. The subject's respiration was not interrupted for this scan. Instead, the focus was on trying to remain as motionless as possible. The seat was then removed. The subject was scanned the third time while he/she was standing. The same body-movement control strategies as used in the seated scans were applied. Finally, the subject changed back into street clothes, was compensated for his/her time and was dismissed.

3. Data extraction and analysis

3.1. *3-D image editing*

As each of the three scans was made for each subject using the Cyberware full-body scanner, the initial image was viewed to ensure that the quality of the image was acceptable when the subject was still in the laboratory. The Integrate™ software was then used to digitize the landmarks to locate their coordinates (Burnsides *et. al.* 1996). The landmark coordinates were further imported into Morpheus software (Slice 1999) and were linked together in a connect-the-dot fashion, creating a 'stick figure' representation of each subject to visually inspect each landmark file for errors.

3.2. *Quality control and data analysis of traditional anthropometric measurements*

Traditional measurements were edited during data collection as they were entered into a laptop computer. This procedure identified potential measurement or recording errors using anthropometric relationships from earlier anthropometric databases (e.g. Gordon *et al.* 1989). Differences between the entered value and the expected value larger than a preset amount were signalled to the investigator and the measurement was retaken. If the value was confirmed by a second measurement, then the software allowed the recording of data. Data were edited once again after data collection using a combination of regression and outlier identification techniques. Finally, univariate normal summary statistics were calculated.

3.3. *Analysis of accommodation data*

Accommodation is determined by the questionnaire that recorded users' perceptions of the interface of body parts with tractor components. Descriptive statistics and multivariate analyses of variance were performed to analyse the association of anthropometric dimensions with accommodation categories, based on the accommodation levels described in section 2.2.

3.4. *Human body models*

Human body models are a set of design specifications intended to portray the population for which the design is targeted. Obviously, the better these models actually represent the population, the better the design will accommodate the population. PCA approaches have been used by some scientists for developing human body models for cockpit accommodation (Zehner *et al*. 1992, Meindl *et al*. 1993) and for human body shape analysis and quantification in medical diagnosis applications (Wilson and Loesch 1989, Cootes and Taylor 1995, Csernansky *et al*. 1998). It is a multivariate technique used to reduce the number of variables needed to explain the variance in a population to a smaller, more manageable number of variables. The main advantage of PCA for anthropometric modelling is 'data or information' compression and dimension reduction, since the vectors with low variance can be discarded and thus the full data set does not need to be retained in order to examine the fit of a product (e.g. machines or personal protective gears) to workers. This study used the PCA approach to identify a set of 15 human body models for the tractor cab design process. In the study, 13 anthropometric dimensions important to tractor design were selected and reduced to three new variables; the selection process for the 13 anthropometric dimensions is described in section 5.2. The three new variables were linear functions of the original dimensions and were designated as principal components. The first component described the direction and orientation of the axis presenting the most variation in the data. The second component described the largest variation on an axis perpendicular to the first component and the third component was perpendicular to the first two as generated within a non-Euclidean space. The original data were entered into three linear equations, one for each component, to obtain a set of three 'scores' for each individual. A scatter plot of these three scores (p_1, p_2, p_3) would show that their distribution approximates an ellipsoid. A $(1-\alpha)100\%$ confidence ellipsoid, containing $(1-\alpha)100\%$ of the data points, was then computed for this distribution. This concept is similar to that of a univariate confidence interval, but takes into account the variance in multiple variables at once. The α level was set at 0.05 in this study. The axes of this ellipsoid divided the data into eight sections (octants). Since there were three axes, there were six intercept points. These 14 points (eight surface-centred octant points and six intercept points) described the surface of the confidence ellipsoid and were the basis for the anthropometric models to be selected. In a design context, if the design accommodates each of these models, the design should accommodate $(1-\alpha)100\%$ of the user population.

Once the six axes and eight octant points had been located, a backward process from the principal component functions was performed to determine the actual anthropometric dimensions associated with each of these points, thus resulting in a set of 14 anthropometric models. The actual dimensions for these models plus the centre-point model can then be applied in the design process, especially in using digital human modelling techniques, to ensure that the finished product will accommodate the desired proportion of the user population.

3.5. *Feature envelopes of landmarks*

PCA approaches have also been used to describe feature envelopes of human body landmarks (Whitestone and Naishadham 1996). Feature envelopes define the location and orientation of areas of interest for equipment design – in this case, the location of the landmark features that are important for optimal tractor accommodation. For example, designers need to know where the knees, elbows and belly are with regard to the seat, for positioning the steering wheel. Visually, a feature envelope can be thought of as an ellipsoid enclosing a cloud of three-dimensional data points representing the variability in a landmark location. Multiple landmarks were considered at the same time and were aligned with a three-mark triangle on the scanner platform. For each of the 34 feature landmarks in this study, a 3-D ellipsoid, enclosing 95% of the 100-subject landmark points, was constructed. Each ellipse is specified by a centroid, the length of its three axes and the orientation of the centroid and axes relative to the seat reference point (SRP). The determination of SRP can be found in ISO 3462 – 1980(E) standard (ISO 1980). The mathematic description of the feature-envelope-accommodation concept is summarized in Appendix I.

4. Results

4.1. *Determining critical anthropometric measurements for tractor design*

4.1.1. Anthropometric characteristics of the sampled agriculture workers. This study represents a comprehensive anthropometric effort to characterize agricultural workers' physical profile in both standing and sitting poses for determining design criteria for farm tractor cabs and protection frames. The 33 traditional measurements are summarized in table 1. Three of the measurements (sitting height, stature and weight) that were available for agricultural workers in the NHANES III literature (Hsiao *et al*. 2002) were compared. It appeared that the average sitting height, stature and weight of the farm worker subjects in West Virginia were somewhat greater than those of the national averages that were reported in NHANES III. These measurements, however, are very close to those of general civilian populations that were described in NHANES III and the Civilian American and European Surface Anthropometric Resource (CAESAR; SAE International 1998).

4.1.2. *Accommodation analysis*

4.1.2.1. *Overall accommodation*. Twenty-seven participants were considered totally accommodated by their tractors and 37 subjects were not well accommodated. The large number of missed responses (36) was due to non-response on seat adjustment and fit; 34 subjects used only non-adjustable tractor seats and two who used adjustable seats did not answer about the fit of their steering wheels.

Univariate tests to compare the anthropometric difference between the subjects in the accommodated and non-accommodated groups found nine dimensions to be significant at $\alpha = .05$ (table 2). While group means for foot and hand length were significantly different, they probably are not essential to tractor overall layout, except for the detail design of pedals and control knobs; they also can be explained as a part of forearm – hand length and functional leg length described below. However, the other seven dimensions with significance (forearm – hand length, functional leg length, knee height sitting, lateral femoral – lateral malleolus length, popliteal height, shoulder – elbow length and stature) probably are of practical importance to tractor design in that they are mostly related to limb length. A careful examination of the summary statistics for the seven dimensions revealed that those who were not accommodated were consistently smaller than those who were; the mean differences were 16 mm for forearm – hand length, 27 mm for

Table 1. Summary statistics for anthropometry of agricultural workers (weight in kg, and grip strength in N; all other values in cm).

	Dimension	n (M)	Mean (M)	SE of the mean (M)	SD (M)	n (F)	Mean (F)	SE of the mean (F)	SD (F)
01	Abdominal extension depth, sitting	88	27.8	0.5	4.6	12	26.6	1.9	6.7
02	Abdominal extension height, sitting	88	23.5	0.2	2.2	12	20.9	0.6	1.9
03	Acromial height, sitting	88	60.7	0.3	3.0	12	57.3	0.8	2.7
04	Bideltoid breadth	88	50.5	0.4	4.2	12	45.0	1.4	4.9
05	Buttock – knee length	87	62.2	0.3	2.8	12	60.0	0.9	3.2
06	Buttock – popliteal length	87	52.1	0.3	2.4	12	51.0	0.8	2.8
07	Elbow rest height	88	24.1	0.3	3.0	12	23.0	0.7	2.5
08	Eye height, sitting	88	80.3	0.4	3.4	12	75.2	1.0	3.4
09	Functional grip reach	88	75.8	0.4	3.7	12	69.2	1.1	3.7
10	Functional leg length	88	110.5	0.6	5.3	12	105.4	1.4	4.8
11	Foot breadth	88	10.1	0.6	5.5	12	9.2	0.2	0.6
12	Foot length	88	27.1	0.1	1.2	12	24.7	0.4	1.4
13	Forearm – forearm breadth	88	56.5	0.7	6.3	12	49.0	2.6	8.8
14	Forearm – hand length	88	48.2	0.2	2.1	12	44.4	0.6	1.9
15	Grip strength, left hand (N)	88	472	11	100	12	300	19	63
16	Grip strength, right hand (N)	88	502	10	93	12	319	15	51
17	Hand breadth, four fingers	88	9.1	0.05	0.5	12	8.0	0.1	0.5
18	Hand breadth, across thumb	88	10.8	0.1	0.6	12	9.5	0.2	0.5
19	Hand depth (thickness)	88	3.0	0.02	0.2	12	2.5	0.1	0.2
20	Hand length	88	19.7	0.1	1.0	12	18.2	0.3	0.9
21	Hip breadth, sitting	88	40.6	0.4	3.3	12	42.8	1.4	4.9
22	Knee height, sitting	88	56.0	0.3	2.7	12	52.1	0.7	2.4
23	Lateral femoral – lateral malleolus length	88	42.7	0.2	2.3	12	40.0	0.5	1.9
24	Lateral malleolus height	88	7.1	0.1	5.7	12	6.6	0.1	0.4
25	Overhead fingertip reach, sitting	88	138.2	0.6	5.6	12	129.1	1.4	4.8
26	Popliteal height	88	44.7	0.3	2.4	12	41.3	0.7	2.3
27	Shoulder – elbow length	88	36.7	0.2	1.7	12	35.2	0.8	2.9
28	Sitting height	88	92.5	0.4	3.5	12	86.7	1.0	3.4
29	Stature	88	177.4	0.7	6.5	12	165.9	1.9	6.6

(continued)

Table 1 (*continued*)

	Dimension	n (M)	Mean (M)	SE of the mean (M)	SD (M)	n (F)	Mean (F)	SE of the mean (F)	SD (F)
30	Thigh clearance	88	17.4	0.2	1.8	12	16.7	0.6	2.1
31	Thumbtip reach	88	81.2	0.4	3.9	12	73.8.	1.3	4.7
32	Trochanter – lateral femoral epicondyle length	88	42.3	0.2	2.2	12	41.3	0.9	3.1
33	Weight (kg)	88	87.8	1.9	17.5	12	72.6	5.7	19.6

M = male; F = female.

functional leg length, 17 mm for knee height sitting, 16 mm for lateral femoral – lateral malleolus length, 14 mm for popliteal height, 10 mm for shoulder – elbow length and 41 mm for stature.

4.1.2.2. *Steering wheel impediment*. Approximately 19% of the subjects reported that the steering wheel impeded their legs. Tests were performed to examine the possibility that this response was correlated to leg length-related dimensions. There did not seem to be any relationship between those dimensions (functional leg length and stature) and obstruction of the legs (Wilks' Lambda, $p = 0.64$ for two parameters combined; or t-test, $p = 0.38$ for functional leg length and $p = 0.55$ for stature). There was no relationship between buttock – knee length and knee height (sitting) and leg obstruction either (Wilks' Lambda, $p = 0.60$ for two parameters combined; or t-test, $p = 0.60$ for buttock – knee length and $p = 0.39$ for knee height). Apparently, leg anthropometry alone did not explain the leg obstruction by steering wheels.

4.1.2.3 *Gear handle impediment on body movement*. There were 21, 23, 46, 5 and 5% respectively of the subjects who reported gear handle impedance to body movement as 'never happens', 'almost never', 'sometimes', 'almost all the time' and 'all the time'. A multivariate analysis of variance was run with all anthropometric measurements as dependent variables and gear handle impediment rating as the independent variable in order to determine which ones, if any, might be linked to this response. Results show that taking all the dimensions into account at once, there is a significant difference among the five rating categories at $\alpha = 0.05$ (Pillai's Trace $p = 0.029$ and Wilks' Lambda $p = 0.016$). Univariate between-subjects tests were also performed to determine which variables might be contributing to this finding. It appeared that only abdominal extension height (sitting) is significant at $\alpha = 0.05$ ($p = 0.022$). Tukey's multiple pairwise comparisons of group means for abdominal extension height (sitting) showed that none of the group mean differences was significant at $\alpha = 0.05$. Therefore, the group differences are not truly significant. For the differences to be of practical importance for tractor design, some trend would be expected in the mean values from one end of the scale to the other. For example, the means would increase from those who responded 'never' to those who responded 'all the time'. Examination of the group statistics for this dimension indicates no such trend. In short, the analysis of the results revealed that multiple anthropometric dimensions interactively affected the gear handle impedance; abdominal extension height (sitting) alone did not explain the issue.

Table 2. Univariate between-subject tests for overall accommodation rating.

Dependent Variable	Type III Sum of Squares	df	F	Sig.
Abdominal extension depth, sitting	239.61	1	0.11	0.75
Abdominal extension height, sitting	210.32	1	0.39	0.53
Acromial height, sitting	433.05	1	0.41	0.52
Bideltoid breadth	2139.95	1	0.91	0.34
Buttock – knee length	2665.68	1	3.17	0.08
Buttock – popliteal length	681.31	1	1.12	0.29
Elbow rest height	190.94	1	0.22	0.64
Eye height, sitting	3094.98	1	2.11	0.15
Foot breadth	14.00	1	0.34	0.56
Foot length	1376.43	1	6.40	0.01*
Forearm – forearm breadth	3116.14	1	0.65	0.42
Forearm – hand length	4128.58	1	6.37	0.01*
Functional grip reach	5587.05	1	2.65	0.11
Functional leg length	11350.48	1	4.15	0.05*
Hand breadth, four fingers	52.84	1	1.69	0.20
Hand breadth across thumb	92.05	1	2.06	0.16
Hand depth	2.20	1	0.32	0.57
Hand length	638.44	1	4.47	0.04*
Hip breadth, sitting	258.07	1	0.21	0.65
Knee height, sitting	4467.18	1	5.07	0.03*
Lateral femoral – lateral malleolus length	4009.01	1	6.94	0.01*
Lateral malleolus height	33.98	1	1.10	0.30
Overhead fingertip reach, sitting	15342.57	1	3.80	0.06
Popliteal height	3093.66	1	4.40	0.04*
Shoulder – elbow length	1638.12	1	4.74	0.03*
Sitting height	3410.20	1	2.20	0.14
Stature	26555.49	1	4.85	0.03*
Thigh clearance	294.19	1	0.86	0.36
Thumbtip reach	6204.19	1	2.53	0.12
Trochanter – lateral femoral epicondyle length	1045.53	1	1.94	0.17
Weight	23361.92	1	0.65	0.42

*Anthropometrically different between the subjects in the accommodated and not-accommodated groups at $\alpha = 0.05$.

4.1.2.4 *Protection frames*. Nearly 20% (n = 12) of the subjects who had operated a tractor with a ROPS (n = 62) had at some time folded it away during operation. While some subjects may just prefer to fold it away, others may have a reason for doing so, based on their sitting height. Figure 5 is a scatter plot showing that sitting height had an effect on folding the ROPS away. The dashed line indicates the general range of sitting height, about 91 cm, at which subjects began folding away the ROPS. In fact, over 24% of those subjects with a sitting height of 91 cm and over folded away the ROPS while only 9% of subjects with less than 91 cm sitting height did the same. This result warrants looking into the specifications for ROPS clearance. (The bideltoid breadth did not show the same effect as sitting height on folding away the ROPS.) The minimum vertical clearance for agricultural tractor enclosures (cabs, ROPS) in the current SAE J2194 standard is 90 cm from seat reference point to the ceiling (ASAE 2000b). Table 1 showed that the mean sitting height and standard deviation in this study were 92.5 (SD 3.5) cm for male subjects and 86.7 (SD 3.4) cm for female subjects. Considering that sitting height is the essential dimension for determining ROPS or cab vertical clearance and that it is

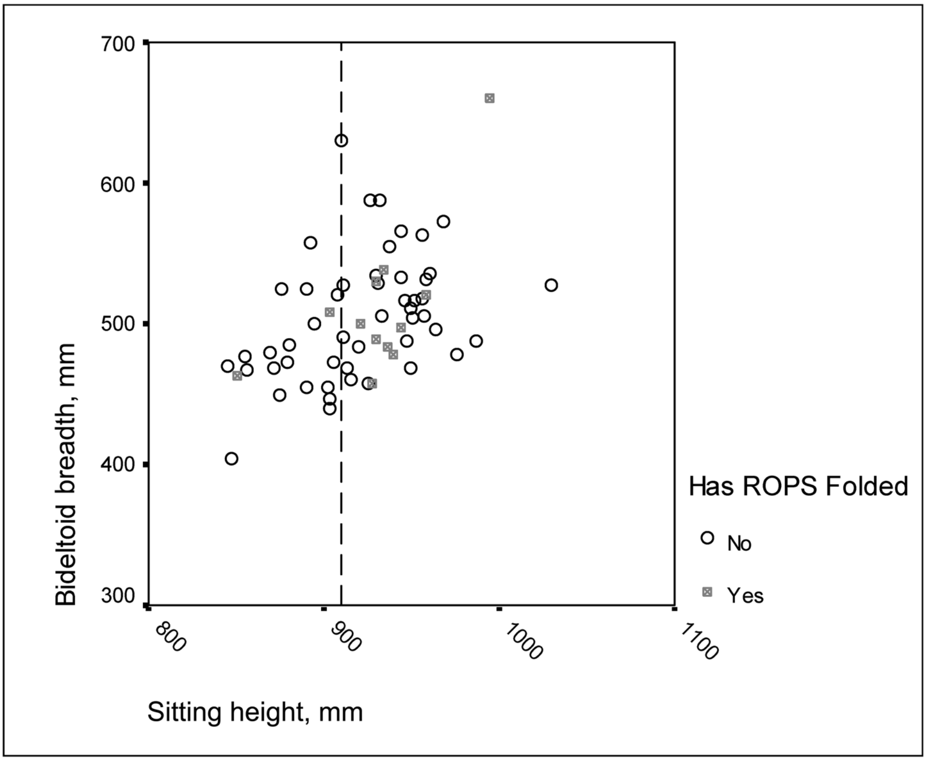

Figure 5. Scatter plot illustrating sitting height and bideltoid breadth of subjects who folded (n = 12) and did not fold roll-over protective structures (ROPS) (n = 50). Thirty-eight subjects who did not use ROPS are not included in this plot.

desirable to accommodate at least 99% of the farm worker population, the 99th percentile of the male population would be chosen as the design target. Therefore, using the equation: Sitting Height $_{.99}$ = Mean + Z $_{.99}$ * standard deviation (Hsiao and Halperin 1998), where Z $_{.99}$ = 2.326 is a coefficient, the vertical clearance should be at least 92.5 + 2.326 * 3.5 = 100.6 cm. If the accommodation is lowered to 95% of the farm worker population, the minimum clearance would be 92.5 + 1.645 * 3.5 = 98.3 cm from the seat reference point. The minimum vertical clearance for agriculture tractors in the current SAE J2194 (90 cm) standard appears to be too small. While ROPS is not directly above the seat and thus the 'clearance' shortage may not be directly pointed to an immediate injury potential, the association between the 'short head-ROPS vertical distance' and 'folding ROPS away' has a safety meaning. Workers are not likely to be protected if they fold the ROPS away; extending the ROPS clearance is worth a consideration in order to reduce the rate of folding ROPS away. It is understandable that a tall ROPS may interfere with farm works, such as in entering a low-clearance barn or orchard; a foldable (2 or 3 folds) and auto-deployable ROPS (with a taller extended total height than the current ones) may ease the problem. Finally, the minimum vertical clearance for a tractor cab in the current SAE J2194 (90 cm) standard can be updated with the newly available anthropometric information described above.

Table 3. Anthropometric variables used in the principal component analysis and the factor correlation matrix.

Dimension Type	Dimension	Factor 1	Factor 2	Factor 3
Volume indicator	Abdominal extension depth, sitting	0.589	0.637	−0.297
	Hip breadth, sitting	0.629	0.555	−0.198
	Thigh clearance	0.745	0.468	−0.010
	Weight, 10th kg	0.885	0.403	−0.102
	Forearm–forearm breadth	0.814	0.395	−0.103
Location indicator	Elbow rest height	0.454	0.332	0.721
	Abdominal extension height, sitting	0.554	0.230	0.279
Body length	Shoulder–elbow length	0.445	− 0.683	−0.186
	Stature	0.782	− 0.576	0.148
	Knee height, sitting	0.759	− 0.551	−0.163
	Forearm–hand length	0.733	− 0.532	−0.144
	Sitting height	0.731	− 0.345	0.525
	Buttock–knee length	0.852	− 0.252	−0.220

4.2. *Tractor-operator anthropometric models and the 3-dimensional feature envelopes*

4.2.1. Models for characterizing tractor drivers. Table 3 presents the PCA factors correlation matrix involving 13 anthropometric dimensions (see section 5.2 for the selection process of these dimensions). The listed three PCA factors explain 81.5% of the total variation. Other PCA factors contributed less than 5% each to the total variation and thus are not addressed in detail in this report. Since the variations contributed by all other PCA factors are relatively small and negligible, the data can be adequately approximated by the three-component model. Furthermore, a SCREE plot (a graphic substitute for a significance test) shows that the three-component model effectively summarizes the total sample variance. The coefficients of the first factor are all positive, indicating that all the dimensions are contributing to the component score in the same direction; the factor is considered an overall-size component. The second component is a contrast (i.e. a shape component) because it contains some positive and some negative coefficients. Table 3 shows that all the negative correlations of factor 2 are associated with body lengths; it appears that the second component is a contrast of body lengths and all other dimensions. The third component is a contrast of elbow rest height, sitting height, abdominal extension height and stature with all the other dimensions. Given the magnitude of the factor correlations, elbow rest height and sitting height appear to be the main sources of variation for this component.

Table 4 describes 15 representative human body models derived from the PCA analysis for tractor cab accommodation. The centre of the ellipsoid or ‘average’ model centre is at the point defined by the 50th percentile for each dimension. The remaining 14 models are labelled A to H and U to Z. Models A to H are models that locate at surface-centre octant points and models U to Z locate at axis intercept points. Table 4 also gives the univariate percentiles associated with each dimension; it is understandable that no model is 5th percentile or 95th percentile for all dimensions, even the overall smallest or largest model. In order to find tractor subjects that might represent each of these models, the Euclidean distance of each subject from each model was computed. Subjects closest to the

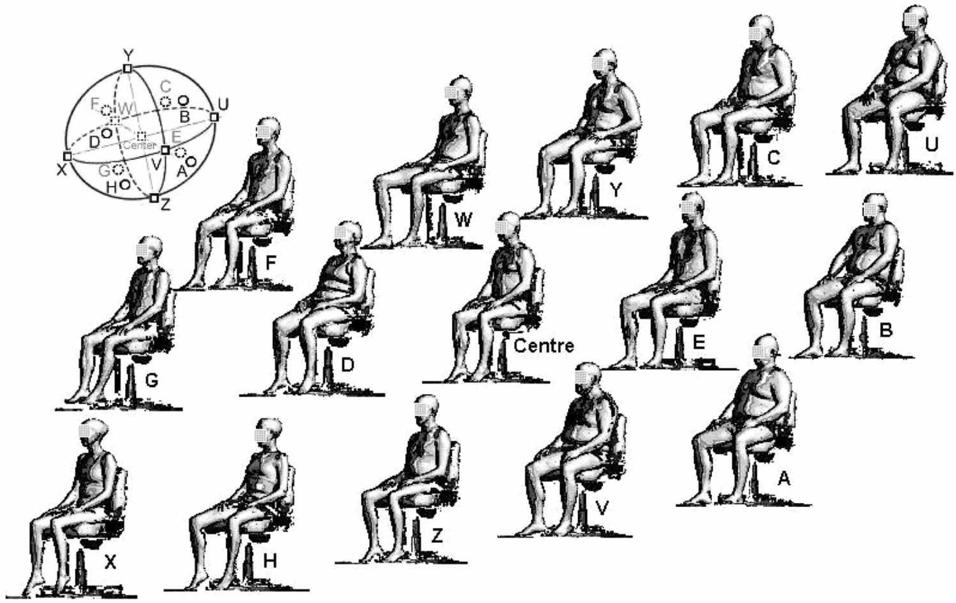

Figure 6. The 15 representative body models derived from the principal component analysis for tractor accommodation test.

models are presented in figure 6 and table 4 with one subject for each model. For instance, model D represents a short person with very short hand and leg reaches; model X represents a very short person in general. Model V represents a person with a large abdomen with short arms or legs; model U represents a very heavy person in general. Rather than designing to specific dimensions, tractor designers can use the models as representatives of a population that must be accommodated. If a virtual 'try-on' is to be used, so that the 3-D scans of actual subjects are needed, then the best approach would be to use the specific subjects identified here. However, from a design point of view, the better design targets are those indicated in the rows entitled 'Model'.

4.2.2. Feature envelopes of body landmarks. Unlike traditional 2-D feature envelope (such as reach envelope) approaches for defining the layout of tractor cab components, this study used the location of the landmark features in 3-D format that are important for optimal tractor accommodation. Out of the 50 available landmarks, 34 were used to provide an overall indication of the orientation of the subject in the tractor seat in driving pose (table 5) and in scrunched pose. The landmarks were chosen because they provided the best information for design applications. Somewhat redundant landmarks were eliminated. For instance, olecranon, lateral humeral epicondyle and medial humeral epicondyle all describe a similar region and thus only olecranon was used in this visualization practice. Figure 7 represents the feature envelopes of 13 out of the 34 selected landmarks during the relaxed seated pose; it also shows the directions of the coordinate system used in table 5. The 13 landmarks are pupils (2), acromia (2), olecranons (2), dactylia (2), suprapatellas (2), toes (2) and vertex (1). These 13 landmarks were selected for demonstration purposes; they are the most known body joints and the number of data points would not overwhelm the demonstration.

Table 4. Variable values for '3-D human' models and their representative subjects (mm).

		Abdo ext. dp, sit	Abdo ext. ht, sit	Butto - knee lgth	Ebw rest ht	F arm-f. arm brth.	F arm-hand length	Hip brd, sit	Knee ht, sit	Shld. elbow length	Sit.ht	Stature	Thigh clearance	Wt. (kg)
Ellipsoid Centre Point														
Model	**Ctr**	**277**	**232**	**613**	**240**	**556**	**478**	**409**	**555**	**365**	**918**	**1760**	**173**	**85.9**
Percentile	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Subject	50	277	267	601	244	567	467	390	541	355	946	1767	165	84.4
Octant Centre Points														
Model	**A**	**355**	**274**	**639**	**314**	**691**	**480**	**470**	**558**	**351**	**979**	**1806**	**211**	**123.7**
Percentile		94	96	74	99	97	53	95	53	23	94	73	98	97
Subject	69	333	263	653	300	643	492	452	580	353	965	1834	210	117.7
Model	**B**	**404**	**252**	**661**	**242**	**717**	**492**	**495**	**574**	**363**	**908**	**1768**	**212**	**130.2**
Percentile		99	80	92	54	98	72	99	74	46	40	54	98	99
Subject	80	395	242	687	252	688	492	466	584	378	926	1807	221	129.1
Model	**C**	**249**	**256**	**664**	**281**	**595**	**525**	**401**	**614**	**396**	**1026**	**1956**	**182**	**98.1**
Percentile		27	85	93	92	70	97	41	97	94	99	99	67	74
Subject	03	243	239	635	301	540	513	404	600	398	1030	1926	187	92.3
Model	**D**	**257**	**230**	**553**	**269**	**493**	**419**	**392**	**481**	**322**	**881**	**1604**	**164**	**67.6**
Percentile		33	46	1	85	18	0.1	31	0.1	1	17	1	30	15
Subject	27	226	229	586	248	524	451	343	516	355	876	1658	157	62.9
Model	**E**	**298**	**234**	**686**	**210**	**620**	**537**	**426**	**630**	**408**	**955**	**1917**	**182**	**104.6**
Percentile		66	53	98	14	81	99	68	99	98	82	98	69	84
Subject	54	309	283	661	251	653	495	420	598	387	949	1860	179	107.3
Model	**F**	**306**	**208**	**575**	**198**	**518**	**431**	**417**	**497**	**335**	**810**	**1566**	**165**	**74.1**
Percentile		72	14	6	7	29	2	58	2	5	0.1	0.1	32	25
Subject	35	300	200	596	179	517	444	434	519	340	810	1601	172	72.5
Model	**G**	**151**	**212**	**578**	**236**	**396**	**463**	**323**	**537**	**367**	**927**	**1753**	**135**	**42.0**
Percentile		0.1	19	7	45	1	27	0.1	25	53	59	45	1	0.1
Subject	99	211	177	568	221	418	430	377	507	346	854	1643	144	53.2
Model	**H**	**200**	**190**	**600**	**165**	**422**	**476**	**348**	**553**	**379**	**856**	**1715**	**135**	**48.5**

(*continued*)

Table 4 (*continued*)

		Abdo ext. dp, sit	Abdo ext. ht, sit	Butto - knee lgth	Ebw rest ht	F arm-f. arm brth.	F arm-hand length	Hip brd, sit	Knee ht, sit	Shld. elbow length	Sit.ht	Stature	Thigh clearance	Wt. (kg)
Percentile		5	3	25	0.1	2	46	4	46	76	5	26	1	2
Subject	51	266	246	588	159	473	434	349	517	355	851	1665	138	53.8
							Axis End Points							
Model	**U**	**362**	**270**	**694**	**278**	**728**	**531**	**476**	**622**	**390**	**1003**	**1936**	**214**	**134.7**
Percentile		96	95	99	91	99	98	97	98	90	98	99	98	99
Subject	70	370	255	638	274	636	466	519	562	360	956	1783	216	127.3
Model	**V**	**369**	**248**	**598**	**268**	**640**	**439**	**469**	**507**	**327**	**877**	**1631**	**199**	**108.2**
Percentile		97	75	22	84	88	5	95	4	2	15	4	91	88
Subject	42	375	241	625	229	627	478	427	547	368	892	1720	191	105.3
Model	**W**	**235**	**251**	**600**	**301**	**535**	**467**	**387**	**541**	**355**	**979**	**1794**	**173**	**80.5**
Percentile		18	79	25	98	37	33	27	31	28	94	67	48	37
Subject	32	224	243	608	268	559	484	386	555	364	970	1805	177	77.2
Model	**X**	**192**	**194**	**545**	**200**	**384**	**424**	**341**	**489**	**340**	**832**	**1585**	**133**	**375**
Percentile		3	4	0.1	8	0.1	1	2	1	9	1	0.1	1	0.1
Subject	17	204	184	549	233	324	435	371	496	425	847	1603	142	50
Model	**Y**	**185**	**216**	**642**	**211**	**473**	**517**	**349**	**604**	**403**	**958**	**1890**	**148**	**640**
Percentile		2	24	77	15	11	94	4	95	97	84	95	8	11
Subject	71	223	233	625	245	532	483	383	590	366	953	1852	168	72.2
Model	**Z**	**320**	**213**	**639**	**177**	**578**	**488**	**430**	**570**	**376**	**856**	**1727**	**174**	**917**
Percentile		81	20	74	1	62	66	72	68	71	5	32	51	62
Subject	76	265	229	632	176	583	499	413	565	366	876	1734	185	89

Table 5. Feature envelope ellipsoid centres and semi-axis lengths (mm) – comfortable seated pose.

				Centroid with regard to Seat Axis System*			Semi-Axis Lengths (95% accommodation)		
Item No.	Landmark No.	Feature	n	X	Y	Z	Major	1st Minor	2nd Minor
1	02L	Acromion, left	90	201.6	398.2	219.7	91.0	77.2	34.9
2	02R	Acromion, right	94	–204.1	392.4	208.7	91.1	76.5	40.1
3	26	Back of head	96	–4.6	592.4	183.1	117.3	100.0	27.6
4	27	C7	99	–1.2	447.8	155.6	82.8	76.3	26.1
5	28	L4	99	3.2	9.0	79.4	97.2	70.6	36.4
6	15L	MCP II, left	96	138.3	–82.0	483.6	127.0	96.4	51.4
7	15R	MCP II, right	95	–127.9	–84.9	487.4	122.9	88.4	48.8
8	16L	MCP III, left	97	173.6	–85.5	491.0	134.6	104.1	51.7
9	16R	MCP III, right	99	–170.4	–87.6	491.6	131.7	92.4	48.6
10	17L	MCP V left	98	210.4	–116.5	459.1	129.7	98.0	43.3
11	17R	MCP V, right	98	–209.3	–122.3	458.9	132.5	84.0	40.8
12	09L	MTP I, left	98	164.9	–780.8	631.2	164.3	140.7	49.9
13	09R	MTP I, right	99	–151.1	–781.9	628.0	180.2	117.1	51.4
14	08L	MTP V, left	84	246.9	–779.3	577.9	177.8	145.3	52.9
15	08R	MTP V, right	97	–241.9	–783.5	582.9	166.1	118.1	48.6
16	18L	Olecranon, left	99	277.7	56.3	173.1	131.2	108.3	70.2
17	18R	Olecranon, right	98	–277.2	48.7	171.9	137.9	119.2	70.2
18	20L	Posterior calcaneous, left	89	183.0	–713.0	458.1	152.0	119.3	66.4
19	20R	Posterior calcaneous, right	78	–168.0	–712.8	455.2	152.2	112.5	64.3
20	29L	PSIS, left	94	59.7	–12.0	70.3	77.2	44.2	41.5
21	29R	PSIS, right	93	–55.0	–12.2	70.1	78.3	42.9	40.4
22	30L	Pupil, left	99	29.1	554.8	369.9	106.1	89.3	28.3
23	30R	Pupil, right	99	–32.9	554.6	368.0	108.6	91.7	29.7
24	31L	Suprapatella, left	98	210.8	–230.0	648.5	118.3	84.2	44.1
25	31R	Suprapatella, right	98	–197.1	–232.8	647.6	120.2	79.6	44.3
26	32L	Thelion, left	97	115.1	203.8	333.5	100.7	83.9	42.0
27	32R	Thelion, right	97	–110.7	199.9	328.3	102.0	83.1	43.5
28	04L	Tip of toe, left	99	193.7	–804.7	686.2	190.9	151.5	47.4
29	04R	Tip of toe, right	98	–191.8	–806.0	682.5	193.0	127.0	50.8

(*continued*)

Table 5 (*continued*)

Item No.	Landmark No.	Feature	n	Centroid with regard to Seat Axis System* X	Y	Z	Semi-Axis Lengths (95% accommodation) Major	1st Minor	2nd Minor
30	33L	Tragion, left	99	72.8	548.3	288.9	101.9	86.3	27.1
31	33R	Tragion, right	99	–78.5	547.2	285.8	103.7	93.5	29.1
32	34L	Ulnar styloid, left	98	212.3	–73.0	401.9	132.2	87.4	41.7
33	34R	Ulnar styloid, right	99	–208.4	–77.2	404.1	133.3	86.8	39.9
34	25	Vertex	99	12.8	679.4	281.4	132.5	99.8	54.3

Centroid coordinates (X, Y, Z) with regard to seat axis system (origin at the seat reference point). X: lateral (+ : left to subject in subject's view; –: right to subject in subject's view). Y: upward (+) and downward (–). Z: anterior (+) and posterior (–) in subject's view. (For the directions, see also figure 7.)

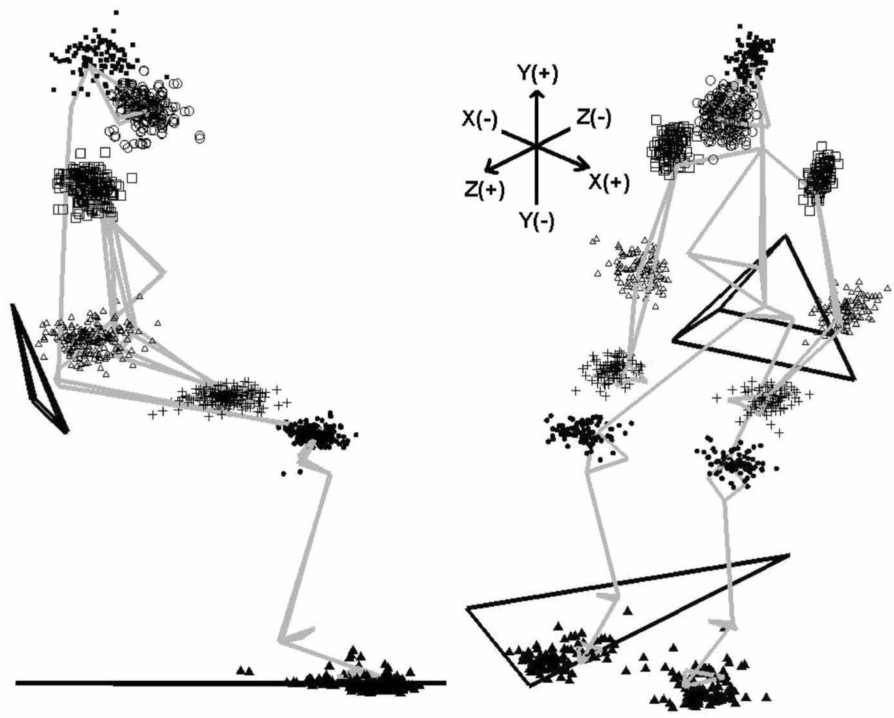

Figure 7. The feature envelopes of 13 selected landmarks of 100 subjects during the relaxed seated pose.

Table 5 provides centroid coordinates and semi-axis lengths for ellipsoids of 95% accommodation. The centroid coordinates tell the designer where to place each landmark ellipsoid (e.g. body joint centre) with regard to the tractor seat reference point (ISO 1980) in a CAD program. The semi-axis lengths tell the designer how big to make the ellipsoids. Ultimately, the ellipsoids can be used to determine where to place tractor components (i.e. controls and displays) in order to accommodate the user population (i.e. avoid impeding body movements, allow effective operation of controls and permit un-obscured displays). This approach visualizes the critical landmark locations in a multivariate way, which is different from using 5th and 95th percentiles from univariate statistics. Alternatively, the point-cloud plot of landmarks of the 15 representative human models would serve a similar function.

Figure 8(a) presents the surface envelope of the 15 human models in side and top views during their scrunched poses. Figure 8(b) presents a stick human model with the centroid coordinates and the point clouds of coordinates of the remaining 14 body models for the same driving poses. Similar feature envelopes for the relaxed driving posture are also available (although not shown in the paper). Tractor designers can import data of the 15 body models from table 4 to their digital human modelling software to evaluate their current and future designs, using relaxed driving posture as well as additional postures that the software can simulate. Figure 9 demonstrates a digital mock-up test, using the 15 representative models identified in this study. Eight selected landmarks in relation to a tractor workspace are presented. Designers also can

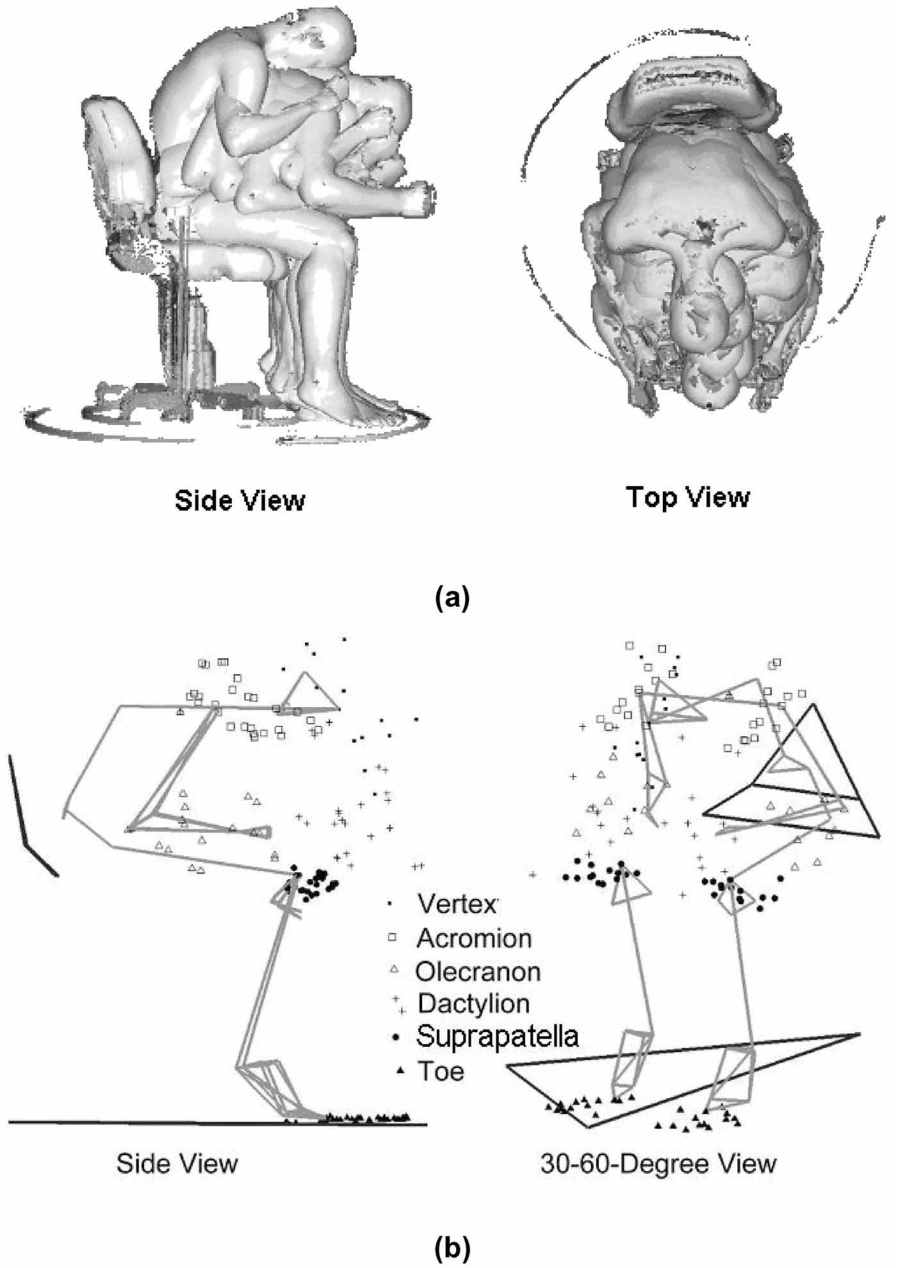

Figure 8. Digital feature envelopes defined by: (a) the body surface; and (b) six selected landmark locations of the identified 15 body models during their scrunched poses. The stick human model in (b) indicates an 'average' or 'centre-point' person and the dark triangles represent seat and floor plan.

import the data from table 5 (or raw data of scrunched pose, which are available from the research team) into their computer-aided tractor 3-D drawings to evaluate their cab designs.

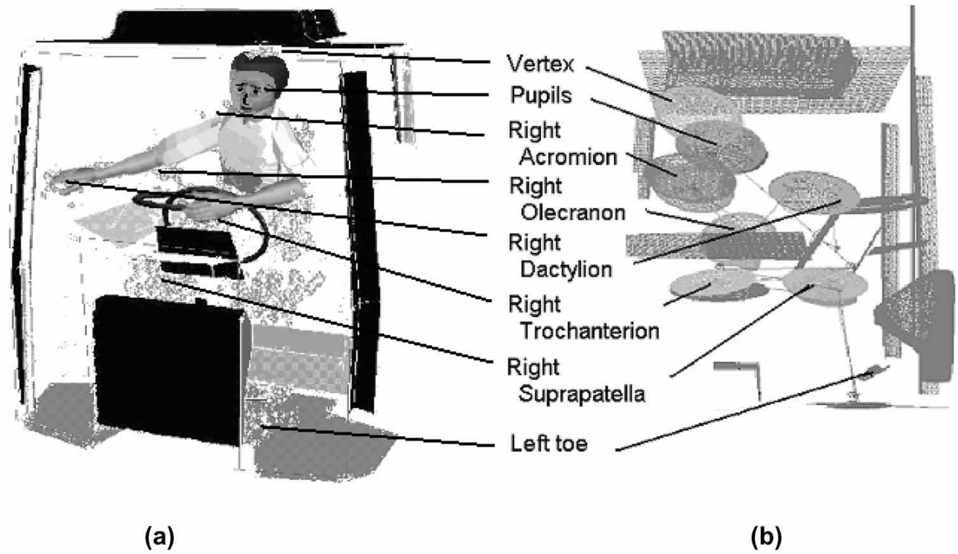

Figure 9. (a) Landmark locations (eight selected body elements) of the 15 representative body models related to an 'average' model. (b) The 95% ellipsoid representations of the feature envelopes for the eight selected landmarks related to the tractor workspace from the side view of the workspace.

5. Discussion

5.1. *Anthropometric parameters for modelling process*

In the PCA process it is necessary to reduce the amount of correlation between variables to an aggregate variable. However, it is also important to include every major body segment, such as arms and legs, so that there is as complete a representation of the whole body as possible. In selecting measurements for the PCA process in this study, four major criteria were considered: (a) the portion of the body involved; (b) the value of the measurement to tractor design; (c) the magnitude of the correlations between measurements; and (d) the reliability of the measurement.

Accommodation score analysis (section 4.1.2 and table 2) indicates that foot length, forearm – hand length, functional leg length, hand length, knee height (sitting), lateral femoral – malleolus length, popliteal height, shoulder – elbow length and stature affected the overall accommodation rating for tractor design. These are candidate body portions to be used in the PCA. As indicated in section 4.1.2, while group means for foot and hand length are significantly different between accommodated and non-accommodated groups, they are not particularly important for tractor design. In addition, popliteal height and lateral femoral – malleolus length both have a high correlation with knee height (sitting). Therefore, one dimension is rather redundant in the presence of the other in that each portrays the same body segment, the lower leg. Only knee height (sitting) instead of three of the dimensions was included in the final list of variables for PCA. On the other hand, although not statistically significant in terms of affecting the accommodation rating, abdominal extension depth (sitting), abdominal extension height (sitting), buttock – knee length, elbow rest height, forearm-forearm breadth, hip breadth, sitting height, thigh clearance and weight would have value for tractor design. They could interactively affect the operation of the steering wheel, control handles and tractor seat.

Table 6. Bivariate correlation matrix for selected measurements.

		1	2	3	4	5	6	7	8	9	10	11	12	13
Abdominal extension depth, sitting	1	1.00												
Abdominal extension height, sitting	2	0.38	1.00											
Buttock – knee length	3	0.37	0.33	1.00										
Elbow rest height	4	0.27	0.32	0.15	1.00									
Forearm – forearm breadth	5	0.75	0.53	0.58	0.38	1.00								
Forearm – hand length	6	0.15	0.24	0.71	0.05	0.45	1.00							
Functional leg length	7	0.24	0.26	**0.93**	0.04	0.48	0.79	1.00						
Hip breadth, sitting	8	0.71	0.31	0.47	0.34	0.63	0.14	0.34	1.00					
Knee height, sitting	9	0.14	0.21	0.82	0.02	0.43	0.87	**0.91**	0.20	1.00				
Shoulder – elbow length	10	(0.04)	0.06	0.54	(0.10)	0.05	0.67	0.59	(0.01)	0.65	1.00			
Sitting height	11	0.05	0.42	0.59	0.57	0.38	0.59	0.59	0.19	0.60	0.44	1.00		
Stature	12	0.05	0.32	0.80	0.23	0.40	0.83	0.87	0.16	**0.90**	0.65	0.86	1.00	
Thigh clearance	13	0.63	0.45	0.52	0.43	0.76	0.31	0.43	0.73	0.33	0.00	0.36	0.31	1.00
Weight, kg	14	0.85	0.51	0.65	0.45	0.89	0.46	0.54	0.78	0.46	0.18	0.45	0.44	0.82

( ) indicates negative correlation.

Table 6 contains the bivariate correlation matrix for the above 13 selected measurements. Functional leg length has a correlation of 0.93 with buttock – knee length and 0.91 with knee height (sitting). Although the sum of these two measurements does not result in functional leg length, the upper leg and the lower leg are components of functional leg length. Therefore, it makes sense to either drop functional leg length or use functional leg length and drop buttock – knee length and knee height (sitting). To decide which option to select, the allowable observer errors established for the 1988 ANSUR survey were utilized as criteria (Gordon *et al.* 1989). They established an allowable observer error of 17 mm for functional leg length, 6 mm for buttock – knee length and 2 mm for knee height (sitting). This information indicated that functional leg length is not as reliable as its two components. In addition, it was felt that, overall, buttock – knee length and knee height (sitting) are more useful to tractor design practice than functional leg length. Therefore, functional leg length was dropped from the final variable list. Although stature has a correlation of 0.9 with knee height (sitting), it was decided to keep it in the analysis since it is a standard anthropometric measurement and can be a useful index for tractor operators (i.e. stature is known to most operators) in adjusting their cab control compartments.

5.2. *Vertical clearance of protection frames*

Figure 5 and section 4.1.2.4. showed that those subjects who folded the ROPS away during tractor operation tended to have taller sitting heights than those who did not, and that subjects began folding away the ROPS at the general range of sitting height of about 91 cm. Based on the standard anthropometric procedure (Hertzberg 1972) and on a consideration of accommodating 99% of the farm worker population, the minimum vertical clearance for agricultural tractors would be 100.6 cm above the seat (i.e. seat reference point; see section 4.1.2.4) plus allowance for safety hat and seat suspension travel if applicable. The allowances for safety hat (5 cm) and seat suspension travel plus maximum vertical adjustment (8 cm) can be found in SAE J154 (SAE International 1992). The vertical clearance for agriculture tractors in the current SAE J2194 (ASAE 2000b) (90 cm) standard appeared to be somewhat short. The 99th percentile sitting height of the male farm worker group in the NHANES III database (99.9 cm) and the 99th percentile sitting heights of the male civilian population in the CAESAR database (100.4 cm) further confirm the need to extend the vertical clearance zone in the current tractor enclosure standard (SAE International 1998, Hsiao *et al.* 2002). It is desirable to use the 99th percentile sitting height of males in determining the minimum ROPS vertical clearance for a maximum protection zone. In the event that the 95% accommodation level is chosen for cost or practical reasons in determining the ROPS vertical clearance, the current SAE J2194 (ASAE 2000b) (90 cm) standard still needs to be updated; the ISO 4252 standard (96 cm from the seat index point; equivalent to 105 cm from the seat reference point) seems to be more reasonable (ISO 1992). The 95th percentile sitting height of male farm workers was 98.3 cm in this study and 97.3 cm in the 1994 NHANES III database ($n = 843$) and the 95th percentile sitting height of the male civilian population in the CAESAR database ($n = 1119$) was 98.5 cm.

5.3. *Limitations of the study and direction for future tractor cab design*

The study used subjects mainly from the West Virginia areas, who appeared to have greater average body height and weight than those of national agricultural workers

(Hsiao *et al*. 2002). This farm worker database should be used in designing tractor cabs with this understanding. However, Figure 6 shows that the subjects do represent a variety of body types, which demonstrates the usefulness of this modelling procedure for tractor cab accommodation tests; these models can serve as a useful population to test tractor accommodation until a larger survey of the nation's agricultural workers can be made. It is worthy of mention that accommodation analysis (section 4.1.2.) showed that those who were not accommodated were consistently smaller than those who were. In addition, based on the NHANES III data, national agricultural workers are shorter in height than other worker groups (Hsiao *et al*. 2002) and the West Virginia farm worker subjects. The national agricultural workers would have a higher challenge for tractor cab accommodation, except for the height of ROPS. On the other hand, the average sitting height, stature and weight of the West Virginia farm worker subjects were very close to those of the general civilian populations that were described in the NHANES III and CAESAR databases. The results from the present study would be immediately useful for the design of general purpose tractors, such as ride-on lawn mowers, for which the general civilian population, instead of just farmers, are the end users.

The PCA results provided useful representative body models for testing cab designs. This is a valuable tool for designers to evaluate their designs at the post-design stage. Yet, a 'feature envelope' for defining the layout of tractor cab components is still needed during the design process. Scientists have described head envelopes in two-dimensional forms (Ratnaparkhi *et al*. 1992). This study used the location of the landmark feature and PCA approach (session 4.2.1.) to determine where to place tractor components in order to accommodate the user population. It has laid a foundation, in the context of the 3-D feature envelopes for tractor cab accommodation during different operating postures. The research team is exploring the use of the 3-D feature envelope for a larger national 3-D database of 2,340 subjects from the CAESAR project (SAE International 1998, Robinette 2000) to establish an effective approach for the tractor cab design process for the national civilian population. It is worth noting that several other tractor cab-related topics can be further studied to advance knowledge in tractor design, including the following questions: How to expand the feature-ellipsoids approach in tractor design if a tractor seat has a fore-and-aft adjustment? Would a derived variable, such as BMI and sitting-height:stature ratio, offer additional insight to the determination of cab accommodation and human body model selection? How does head clearance affect operator postures? How much difference in posture among individuals is there in their defence poses? Finally, the cab accommodation ratings in this study were based on a 'natural' experiment, in which participants judged their accommodation based on the tractors that they have used. The result reflects a general view of the tractors currently in use and may not be applicable to a specific model. A further analysis of the differences in cab dimensions among different tractor models that the participants have used may provide additional insight into the effect of anthropometric information on tractor accommodation rating by tractor models.

6. Conclusion

This study provided the first available detailed 3-D and traditional anthropometric information about agricultural workers, which is valuable for the design of farm machines and agriculture-related personal protective equipment. The tractor accommodation evaluation results indicated that foot length, forearm – hand length, functional leg length, hand length, knee height (sitting), lateral femoral – malleolus length, popliteal height, shoulder–elbow length and stature affected the overall accommodation ratings. Those who were not accommodated were consistently smaller than those who were. On the other hand, the vertical clearance of ROPS for agriculture tractors in the current SAE J2194 (ASAE 2000b)(90 cm) standard appears to be too short. In this study, more subjects with a sitting height of 91 cm and over folded the ROPS away than subjects with less than 91 cm sitting height. The minimum vertical clearance for agriculture tractors, based on the farm worker anthropometric information, would be 101 cm above the seat. A 13 cm allowance for safety hat and seat suspension travel can be added as needed.

Multiple anthropometric dimensions interactively affected the impediments of steering wheel and gear handle; leg anthropometry or abdomen dimension alone did not explain the leg or abdomen obstruction of the steering wheel or gear handles. A PCA has identified 15 representative body models for testing tractor cab and protection frame accommodation. The identified body models can serve as a useful design target to test tractor design until a larger survey of the nation's agricultural workers can be made. The analysis also identified 13 variables that are practically important for tractor cab design and space layout: abdominal extension depth (sitting); hip breadth (sitting); thigh clearance; weight; forearm–forearm breadth; elbow rest height; abdominal extension height (sitting); shoulder–elbow length; stature; knee height (sitting); forearm–hand length; sitting height; and buttock–knee length. These 13 anthropometric variables can be further applied to a data pool of a national population, such as the recently completed CAESAR database (SAE International 1998) through the same PCA procedure to establish body models for improving tractor cab design process for the national civilian population.

Finally, the study demonstrated the utility of combining traditional anthropometry, whole body surface scans and a digitized workspace layout for placing a digitized human model in the electronic tractor cab. The 34 centroid coordinates and the semi-axis lengths for ellipsoids of 95% accommodation for each of the 34 landmarks provide designers with an effective tool to place tractor components in the cab space that would accommodate the user population. It may become more widespread as a technique as designers of workspaces increase their use of digital human models and are seeking accurate anthropometric information to build, position and refresh their models.

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Appendix I

Mathematic description of the feature-envelope-accommodation concept

Principal component analysis of landmark coordinates reveals the geometric description of a multivariate normal distribution of a multivariate normal ellipsoid of constant density. This ellipsoid approximates the distribution of the landmark point cloud. The mean values for each coordinate define the centre of the ellipsoid and the origin for a new axis system. Geometrically, the three new axes, represented by the three components, are formed by rotating from the original landmark coordinates about their means. The major axis of the ellipsoid, represented by the first component, provides the best possible fit to the data points (as measured to have the minimum sum of the squared perpendicular distances from the data point to the new axis). The first minor axis of the ellipsoid, represented by the second component, has the minimum projected distances of the points in a direction orthogonal to the first component. The second minor axis of the ellipsoid, represented by the third component, has the minimum projected distances of the points in a direction orthogonal to both the first and the second component. The elements of the eigenvectors of the landmark coordinate covariance matrix are the direction cosines of the new axes related to the old. The semi-axis length of the new axis is proportional to the square root of each corresponding eigenvalue of the landmark coordinate covariance matrix and can be calculated by the following equations:

Semi-axis lengths of ellipsoid = $c\sqrt{\lambda_i}$

Axes of the ellipsoid = $\pm\, c\sqrt{\lambda_i}\, e_i$

Where

$\Sigma\, e_i = \lambda_{i,}\, e_i\; i = 1, 2, 3$

Σ is the covariance matrix of the landmark data.

λ_i is the eigenvalue of the covariance matrix Σ.

e_i is the eigenvector of the covariance matrix Σ associated with eigenvalue λ_i and has unit length.

$c^2 = \chi_3^2(\alpha)$ where $\chi_3^2(\alpha)$ is the upper (100 α)th percentile of a chi-square distribution with three degrees of freedom.

Ellipsoids of equal concentrations with (1-α)100% probability can be described by choosing $c^2 = \chi_3^2(\alpha)$. Theoretically, the probability that any landmark in the distribution falls within a 95% probability ellipsoid is 95% (Johnson and Wichern 1988).