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Human Body Modelling by Development of the Automatic Landmarking Algorithm

The State of the Art and concept of Ph.D. Thesis

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Abstract

In this work, I describe the methodology of automatic computer-based measurement for taking anthropometric data. The result of this process can be employed in many areas, e.g. security, medicine, sport or clothing industry. The designed methodology comes out from the demand to create, from the measured person's view, the least annoying system of the measurement. It must be simple (cheap and portable) as much as possible from the operating personnel's view. The proposed methodology comes out from the model of human body. Several potential sources of problems are discussed and some possible solutions are proposed. Complex system can be created when we solve these problems completely. This problem is currently being solved at a number of world workplaces. Efficiency of the proposed methodology is being verified on the use case of the clothing industry.

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1 Introduction

My work concerns how to fulfil the requirement of the anthropometry data acquisition. It comes out from the demand to measure hundreds of people in their everyday clothes for several reasons. This can be utilized in wide areas of the security, medicine, sport or clothing industry. The traditional method of taking human dimensions using a measuring tape can be not only very time-consuming but sometimes impossible or unsuitable. Thus, there is a need to create a portable contactless computer-controlled workplace to speed up this measurement process.

In the past few years, an active research on replacing traditional anthropometry measurements using a measuring tape with computer-based 2D ([6], [8], [10], [14]) or 3D techniques ([9], [14]) has been conducted. Based on literature and our basic experiments, we found that the creation of an image-based 2D anthropometric measurement system will be the best way. Performance of such measurement was already discussed in [8]. Requirements given by the project submitter were that the system must be portable, people cannot be required to get undressed, and the system must be very easy and fully automatic.

The objective of this work is to summarize everything needed for designing a complete, fully automatic 2D anthropometric system and propose a new technique for automatic detection of several spatial human body parts that would be useful in the areas named above.

2 State of the Art – Anthropometry

2.1 Definition, origins and uses

This part is completely overtaken from [17].

The beginning of quotation:

> The word “anthropometry’’ was coined by the French naturalist Georges Cuvier (1769–1832). It was first used by physical anthropologists in their studies of human variability among human races and for comparison of humans to other primates. Anthropometry literally means “measurement of man,’’ or “measurement of humans,’’ from the Greek words *anthropos*, a man, and *metron*, a measure. Although we can measure humans in many different ways, anthropometry focuses on the measurement of bodily features such as body shape and body composition (“static anthropometry’’), the body’s motion and strength capabilities and use of space (“dynamic anthropometry’’).
>
> The origins of anthropometry can be traced to the earliest humans, who needed information about body parts for many of the same reasons which apply today—to fit clothing, design tools and equipment, etc. No doubt they also used body measurements for other, “non-design’’ purposes, such as footprints to estimate the body size of potential adversaries. These and other early applications called for the measurement or estimation of height, as well as the shape and size of hands, feet, and other body parts. Such needs gave rise to the very early use of the terms, “span”, “cubit”, and “canon”, which connote extended arm width, height, and a standard, respectively.
>
> Body proportions were of great interest during classical times, which is clearly evident in the work of artists and sculptors of the period. Around the year 15 BC, the Roman architect Vitruvius wrote about the potential transfer of harmonious body proportions to the design of beautiful buildings. However, it was the work of Renaissance artist-anatomists, including Alberti, Pierro

della Francesca, Leonardo da Vinci, and especially Albrecht Durer, that ushered in the scientific beginnings of anthropometry. Durer's four-volume publication on human proportions was the first serious attempt to systematize the study of human size and shape.

Today, anthropometric measurements are used in a remarkably wide variety of scientific and technical fields, ranging from genetics and nutrition to forensics and industrial design. Within the field of ergonomics, there are myriad applications of anthropometry, primarily associated with different aspects of design for human use.

The goal of ergonomics is to design tools, workplaces, and environments in such a way that humans can function most effectively — in other words, to optimize human performance by achieving the best possible fit between the human operator, the equipment (hardware and software), and the working environment (physical and psychosocial). This fit is often referred to as "the human–machine interface.'' Anthropometry can and does play a major role in achieving this goal because variations in bodily features, such as shape, size, strength and reach, affect the way people perform tasks and, thus, have an important influence on whether the human–machine interface is a good one. The breadth of possible applications of anthropometry for improving the human interface is remarkably wide-ranging, from industrial equipment, clothing and furniture, to surgical tools, farm implements, aircraft controls, and virtually every item in the environment with which humans interact.

Over the years, engineers, designers, architects and others who design products or processes have increasingly recognized the need for anthropometric data on the users of their creations. Of course, the need for anthropometric information and the type of data required varies greatly from one application to the other. In some areas, the fit is "soft,'' as in a loose garment such as a bathrobe; in other areas, the fit is "hard,'' for example, in a respirator for protection against breathing toxic fumes. The fit of the bathrobe can be an approximation and still serve its intended purpose, whereas the respirator mask must conform closely to the geometry of the face in order to maintain adequate contact and prevent leakage. In the case of the bathrobe, data on height and a few body girth measurements for the prospective user population may be all the information needed to ensure adequate body coverage for a good interface. However, for the respirator mask, it may be necessary to obtain detailed three-dimensional measurements of individual facial geometry to ensure a satisfactory fit.

The end of quotation.

2.2 Traditional measurements

Traditional anthropometric measurements are performed by experienced anthropometrists using some instruments, mostly a measuring tape which is intended for measuring circumferences and curvatures. Most measurements taken on the subjects are taken in position of standing. However, a few measures need to be taken in different positions.

Although anthropometrists should be trained, they are the most common source of measurement error. It includes imprecision in landmark location, subject positioning, and instrument applications [9]. A landmark is an anatomical structure used as a point of orientation in locating other structures [18]. More informally, it can be specified as a particular point on human body which can be used to identify a particular body part. Landmarks identification is the key elements in the collection of anthropometric data, because it is important to know where to locate and how to align the measuring tape.

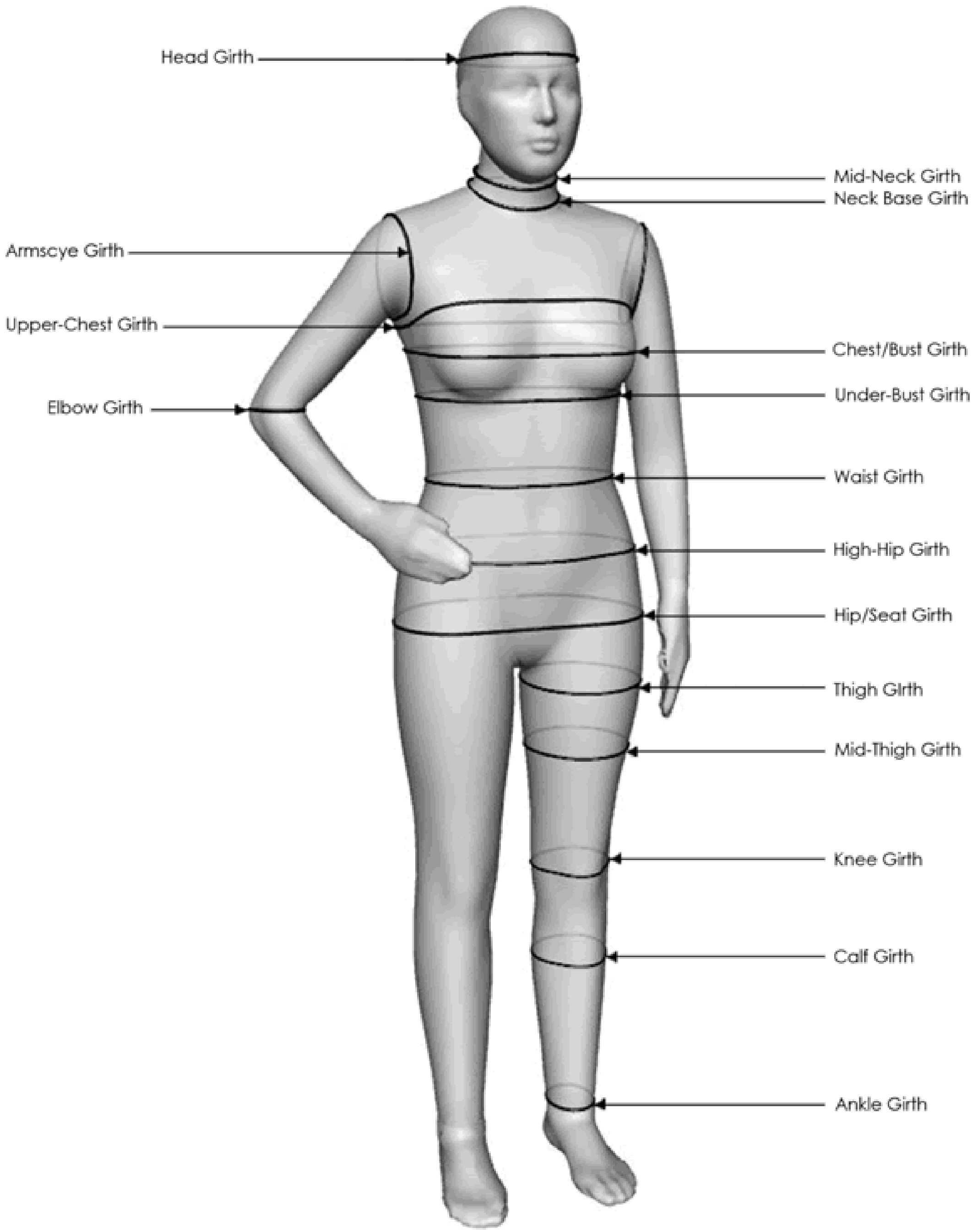

Figure 1. Body measurements defined in [1].

2.3 Computer-based measurements

In the past few years, there has been an active development of methods which would replace traditional measurements by a computer system. It is intended to provide more accurate human dimensions in a few seconds.

Computer-based measurements can be divided into two types – 2D measurements where only two-dimensional image of the person is taken (mostly by a digital camera), and 3D measurements where complete person's body is scanned and exact model is created. Description of existing measurement systems, their studies, advantages and disadvantages is discussed in following sections.

Automatic computer methods bring two main areas where all work must be focused. The first one is the technique how information about the person to be measured is transmitted to the computer. The purpose is to convert the object of the real world to the digital form in order to all measurements could be performed on it using the computer (and real object would not be needed any more). When this is managed, the complete semi-automatic system can be created. However, it still requires user cooperation to define where to the individual measures take from. To create fully automatic system, any need of user cooperation should be removed and all required measures must be taken automatically. This requires development of a proper landmarking algorithm. It is intended to find one or more concrete points which are helpful to localize certain body part to be measured.

2.3.1 2D measurements

One of the possible computer-based methodologies of human dimension measurements is based on image processing. One or more pictures of the person are taken by one or more cameras. The requested dimensions are computed from these pictures. This requires the camera to be perfectly calibrated so the image coordinates (in pixels) can be successfully transformed to the world coordinates (in millimetres or whatever unit required). When photo(s) is/are taken, the captured object needs to be extracted from it. In other words, it needs to be differentiated between background and person to be measured. The result of the extraction is the person's silhouette. For planar dimensions, distances (it does not necessarily have to be the minimum distance) between two points on the silhouette are just converted from pixels to millimetres. For spatial dimensions, human body model needs to be created to approximate circumferences. It is very often performed by taking person's image from different views (e.g. frontal and lateral) to have more measurements for modelling. Several studies on the 2D anthropometric measurements have already been performed.

The performance of a 2D image-based anthropometric measurement was tested in [8] to verify the accuracy and precision of the measurements. Their system consists of two (frontal and lateral) Kodak DC120 colour digital cameras with resolution 1280×960 pixels covering a blue backdrop that is approximately 2.5 × 1.8 metres and embedded with calibration markers. This corresponds to resolution slightly below 2.0 mm/pixel. Therefore, it is assumed that direct measurements will fluctuate within ±2 mm and circumferential measurements will fluctuate within ±6 mm of the true value (by assuming a cylindrical object).

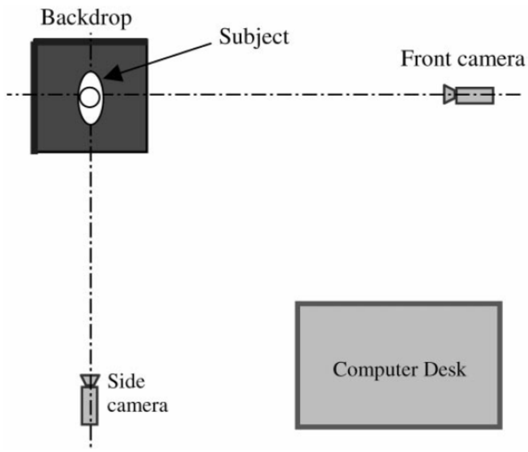

Figure 2. Plan-view of image capture set-up as introduced in [8].

The calibration of the cameras is performed using an algorithm developed by Tsai. They take simultaneous pictures of person's front and side views. They analysed 349 subjects (95 females and 254 males) and the results were compared with those of trained anthropometrists. Six dimensions (stature, neck circumference, chest circumference, waist circumference, hip circumference and sleeve length) were selected because of their relevance to clothing sizing, which was the main purpose of their system. The neck circumference was taken at the Adam's apple perpendicular to the long axis of the neck, chest horizontally at the fullest part of the breast, and hip horizontally at the maximum protrusion of the buttock. The definitions for waist circumference were different: the traditional measurement of waist circumference was taken horizontally at the level of the navel, whereas the image-based system measured where individuals wear the belt of their trousers. The means and standard deviations for the subjects measured manually and digitally are listed in Table 1. Waist circumference was excluded from this comparison due to mentioned difference in definitions.

Table 1. Accuracy results in mm of measurement performed in [8].

Measurement	Females			Males		
	Mean	Std. dev.	Correlation	Mean	Std. dev.	Correlation
Stature	n = 95			n = 254		
Manual	1633	60	0.98	1747	64	0.98
2D system	1633	59		1748	63	
Neck circumference:	n = 62[a]			n = 254		
Manual	329	18	0.88	395	23	0.94
2D system	329	16		395	22	
Chest circumference:	n = 88[a]			n = 254		
Manual	956	87	0.95	1024	83	0.94
2D system	957	84		1024	78	
Hip circumference:	n = 95			n = 238[b]		
Manual	1027	97	0.98	1005	72	0.94
2D system	1026	89		1004	68	
Sleeve length:	n = 95			n = 254		
Manual	799	34	0.79	876	35	0.76
2D system	800	27		875	26	

[a] Some subjects were rejected due to interference of hair with landmarking.

[b] Some subjects were rejected due to clothing interference (boxer shorts).

The precision of the system was determined by performing ten repeated measurements on a full plastic mannequin and on a human subject. The mannequin was used to exclude variations due to breathing movement and postural differences. As shown in Table 2, the error of the results performed on the mannequin was within 1 mm of the mean for stature and 3-6 mm for circumferences, 95% of the time.

Table 2. Repeatability results in mm [8].

Variable	**Mannequin**		**Human**	
	Mean (n = 10)	1.96 Std. dev.	Mean (n = 10)	1.96 Std. dev.
Stature	1822	1	1817	3
Neck circumference	360	3	369	4
Hip circumference	946	7	978	8
Waist circumference	856	4	873	10
Chest circumference	960	6	964	11
Sleeve length	829	15	887	20

It was concluded that image-based systems are quite comparable to traditional measurement methods, but the quality depends on the dependability of the automatic landmarking algorithms and the correct modelling of indirect measurements. Although this work does not specify the applied landmarking algorithm, it can be used as a very good base of 2D anthropometric systems.

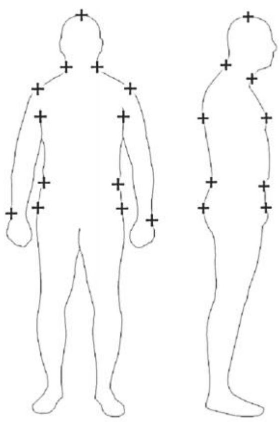

Figure 3. Paper [8] shows front and side silhouettes with landmarks, although the landmarking algorithm was not specified.

The paper [6] tried to show the effectiveness of a simpler and cheaper system than was introduced in [8]. It consists of a Canon IXUS colour digital camera with resolution 1600×1200 pixels. They take front view, back view and side view of 20 male subjects. Each image was captured with a calibration square of 15 × 15 cm. Its image size was on average of 192.85 × 193.98 pixels and hence each pixel corresponds to approximately 0.78 mm. It was used to compute ten actual dimensions using the following equation. Six linear and four circumferential measurements were obtained.

$$\frac{15\ cm}{\begin{matrix}Length\ of\ one\ side\ of\\ square\ in\ image\end{matrix}} = \frac{Actual\ dimension}{Length\ in\ image}$$

Figure 4 shows the diagram of all main procedures performed in this system.

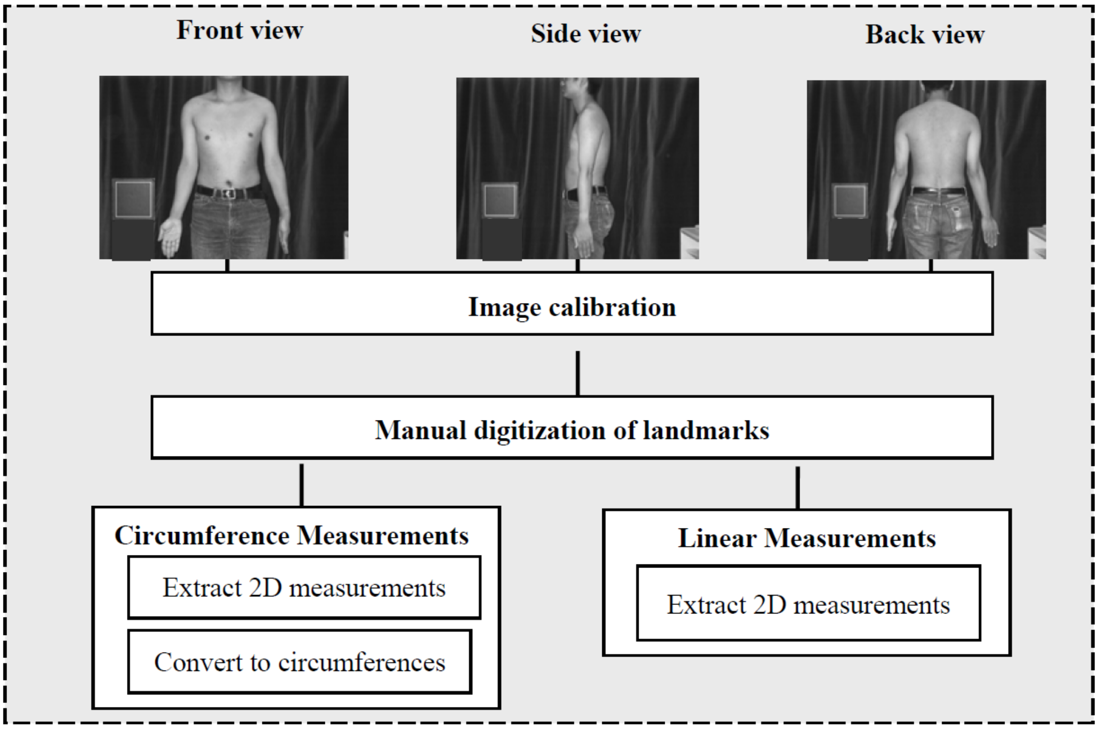

Figure 4. Work flow of the image-based system as presented in [6].

The circumferential measures were generated by approximating the shape of the respective body part. For example, neck circumference was approximated with the elliptical shape. The major and minor axes lengths were obtained from the front and side views. The chest circumference was determined by approximating the shape as a combination of a rectangle and an ellipse.

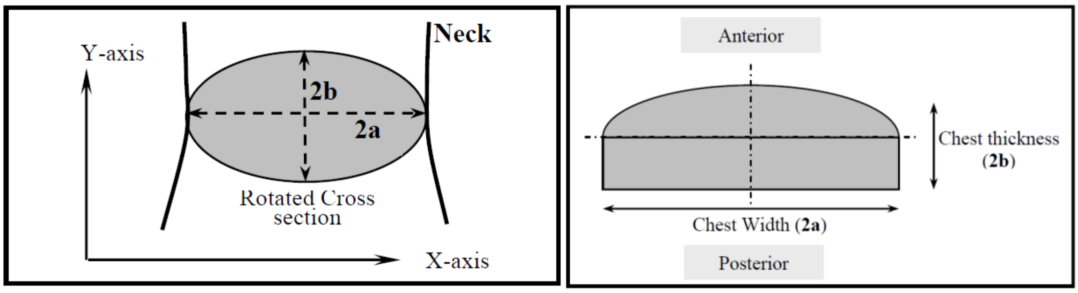

Figure 5. Approximate shapes for calculating circumferences [6].

The results (mean and standard deviation) are shown in Table 3. It was concluded that the measurement quality depends mainly on the proper identification of anatomical landmarks (manual method was used) and the characterization of body shape.

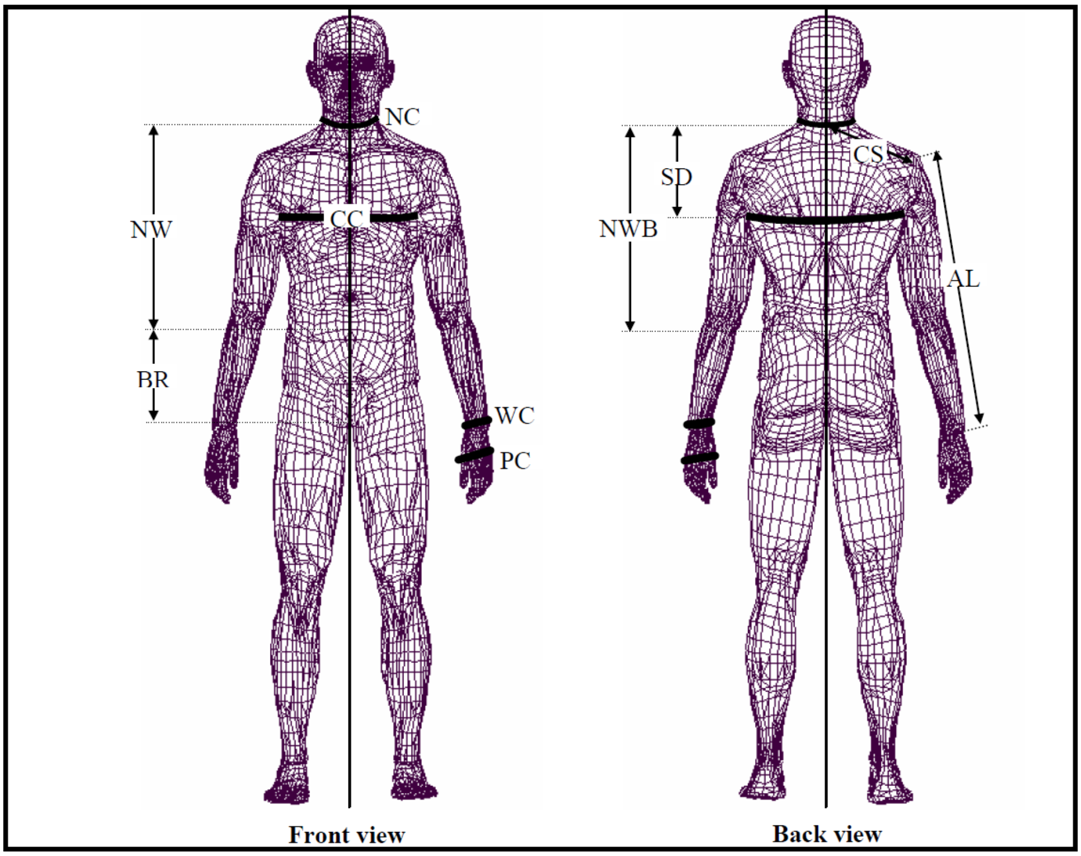

Figure 6. Anthropometric dimensions and associated abbreviations measured in [6].

Table 3. Statistics of the measurements for the 20 subjects [6].

Measurement	Method	Mean	Std. Dev.
Neck front to Waist (NW)	Manual	45.97	4.19
	2D Image based	47.12	4.17
Nape to Waist Center Back (NWB)	Manual	48.19	3.53
	2D Image based	48.19	3.98
Scye Depth (SD)	Manual	21.07	1.89
	2D Image based	21.92	2.70
Cross Shoulder over Neck (CS)	Manual	21.93	1.49
	2D Image based	22.61	1.66
Arm Length (AL)	Manual	55.92	2.98
	2D Image based	54.72	3.31
Body Rise (BR)	Manual	24.22	1.44
	2D Image based	27.19	2.57
Chest Circumference (CC)	Manual	86.48	4.99
	2D Image based	89.86	5.76
Neck Circumference (NC)	Manual	35.78	1.71
	2D Image based	34.58	2.01
Wrist Circumference (WC)	Manual	15.61	1.00
	2D Image based	15.79	1.29
Palm Circumference (PC)	Manual	23.38	1.48
	2D Image based	23.79	2.05

Similar technique was presented in [10]. It takes photos of the persons standing 50 centimetres in front of the green background. The Canon Power Shoot A560 digital camera with resolution 640×480 pixels was posted three metres from the background. An algorithm was developed that creates 3D model of the human body using only data obtained from 2D subject's image, and ellipses as basic building objects. Anthropometric data obtained for three subjects were compared (see Table 4) with manual measurements and generalized anthropometry tables.

Table 4. Measurement comparison performed in [10].

	Body segments	Measured by meter	Anthrop. tables	Comp. vision
Sub. 1	Hand	20.0 cm	19.5 cm	19.5 cm
	Forearm	28.0 cm	27.5 cm	26.5 cm
	Upper arm	30.0 cm	34.0 cm	30.5 cm
	Whole arm	78.0 cm	81.0 cm	76.5 cm
Sub. 2	Hand	18.5 cm	19.0 cm	17.5 cm
	Forearm	25.0 cm	25.5 cm	25.5 cm
	Upper arm	29.0 cm	32.5 cm	27.0 cm
	Whole arm	72.5 cm	77.0 cm	70.0 cm
Sub. 3	Hand	18.0 cm	19.5 cm	18.5 cm
	Forearm	28.0 cm	26.5 cm	24,5 cm
	Upper arm	29.0 cm	33.5 cm	33.5 cm
	Whole arm	75.0 cm	79.5 cm	76.5 cm

The reference [13] presents a data-driven shape model for reconstructing human body models from one or more 2D photos. It captures images in front of a blue background by the Nikon Coolpix 5000 camera in resolution 1920×2560 pixels which has been reduced to 480×640 pixels to speed up the process. When matching the template model to the target subject in the image, they use 12~15 feature points on the silhouettes. The text says "only a limited set of feature points can be found automatically, such as those on the top of the head, the bottom of the feet and the tip of hands". The rest is manually placed by the user.

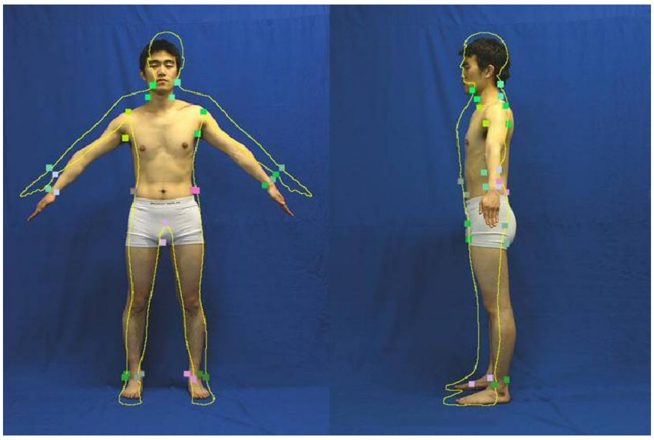

Figure 7. Distance between corresponding feature points on the front and side photos of a male subject presented in [13].

An intelligent system for customized clothing making has been developed in [14]. It allows collection of anthropometric data either from 2D photographs or 3D scanners.

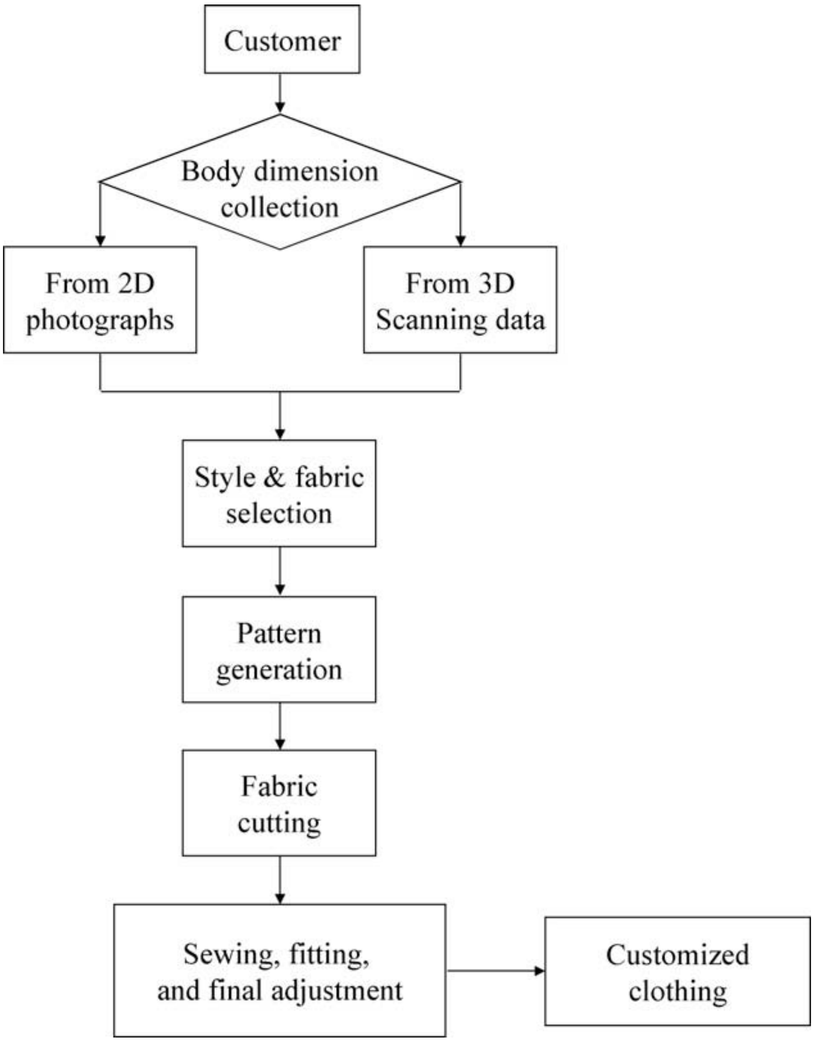

Figure 8. Flow chart of the intelligent systém developer in [14].

The two-dimensional measurement procedure takes place in the same manner like the previous studies. For obtaining the correct distances, horizontal and vertical lines with specified lengths were taped on a rectangular frame of size 2.0 m × 1.0 m. After two (frontal and lateral) photographs of the person standing in front of a mono-colour background were taken, 36 landmarks were identified manually to define the starting and ending points for collecting body dimensions. Then a total of 23 linear dimensions could be collected automatically. This collected dimensions were used to generate a 3D model of the subject which was compared with the corresponding standard model (six standard models of different sizes for males and females were available). Finally, clothing patterns were generated.

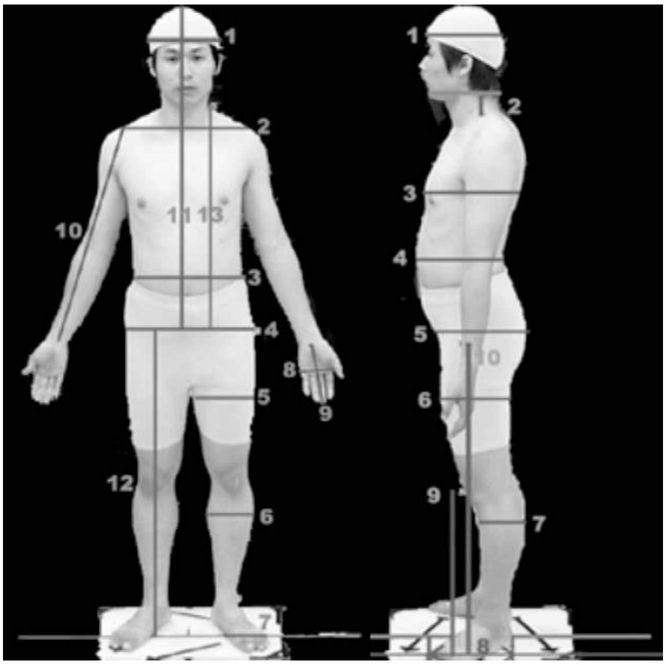

Figure 9. The 23 linear dimensions collected from 2D photographs in [14].

Like the previous paper generated the clothing pattern, [16] develops automatic system for generating pattern of men's pants. The user provides front, side and back photos of him. Human silhouette and sizes (width, thickness and height) of each position are automatically extracted from them, and the girth of each position is fitted through fitting formulas. Then the system can automatically generate the patterns according to the body type and the pant style of the user.

The paper [2] tries to recover anthropometric measurements from a single uncalibrated image. It means that the camera parameters are unknown. The technique is based on vanishing lines/points. Its goal is not to achieve very accurate estimation, but rather to obtain as accurate estimation as possible with limited input information. Their method is primarily targeted for forensic-style identification, but can also be useful for tracking people across multiple camera views in surveillance applications. But it says that the landmark localization needs to be automated, which is one of their ongoing and future works. Similar technique for recovering object height using vanishing lines/points is discussed in [3].

The paper [5] introduces a new technique for automatic building recognisable moving 3D models of individual people from multi-view images. The objective of its feature extraction is to establish the correspondence between the captured data and synthetic model images for body parts such as the arms, legs, head and torso. It has developed an algorithm for reliable extraction and localisation of a set of features based on the knowledge of the silhouette contour structure. The base of the algorithm lies in detection of local extremum points. Initially it traverses the contour to locate five extremum points *e1* – *e5* as shown in Figure 10. These are then used to identify feature points *f1* – *f5*. It has been found that other potential features points such as the neck cannot be reliably localised as small changes in shape can result in a large variation in position.

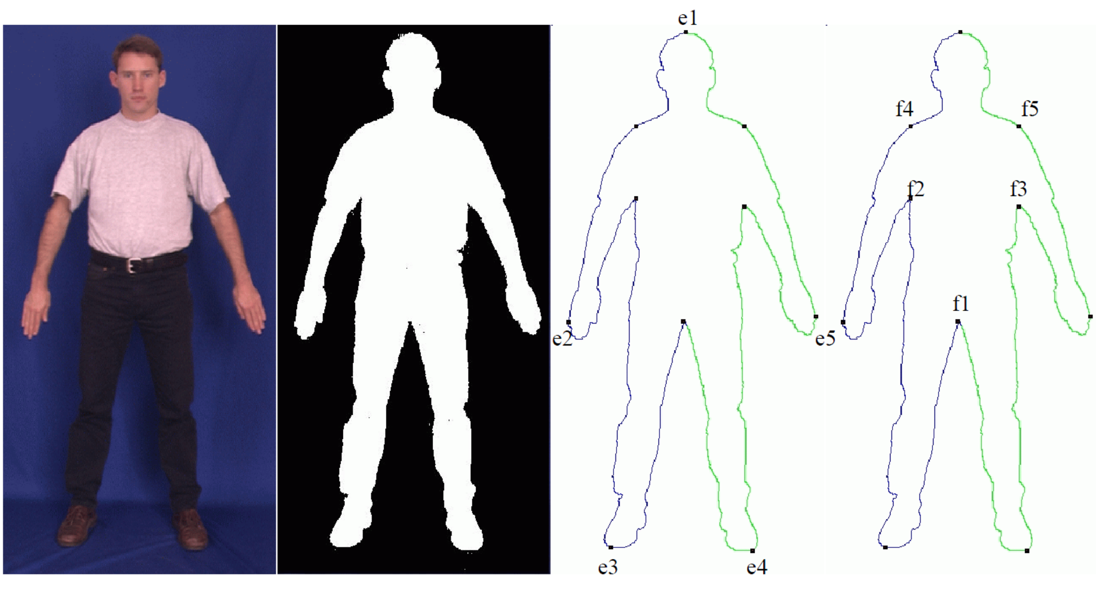

Figure 10. Image, silhouette, extrema and features by algorithm introduced in [5].

Similar technique for creating virtual humans was described in [19]. The sense of feature extraction was same as in [5] – to establish the correspondence between the silhouette of the photograph and the silhouette of the synthetic model. Several key feature points are defined in the silhouette which can be used to obtain other auxiliary feature points.

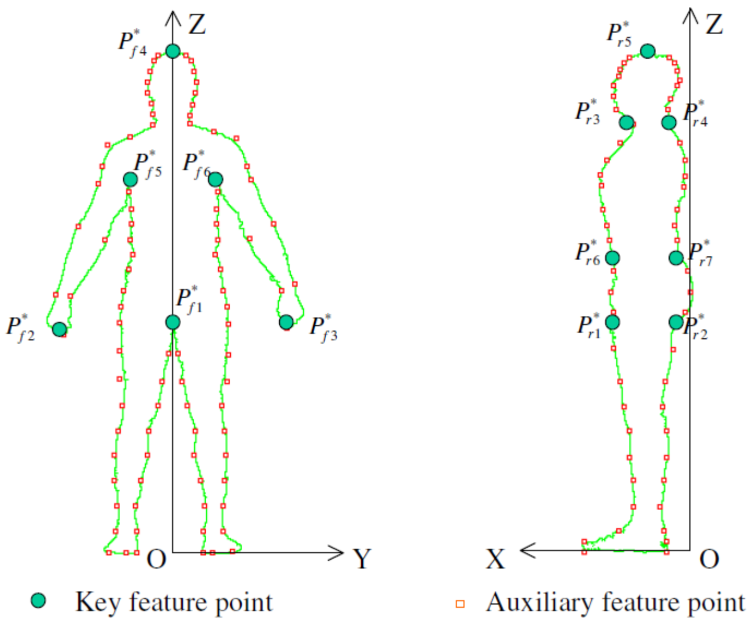

Figure 11. Silhouettes with feature points from [19].

Another method of automatically extraction body features from 2D images has been proposed in [7]. They take frontal and side images by digital camera with resolution of 1280 × 960. Person is standing in front of the black background, 5 metres away from the camera. The silhouettes are extracted from the images. The landmarking algorithm is based on representing the silhouette contour using Freeman's chain code. The number 0-7 is used to represent 45° increment in a counter clockwise direction.

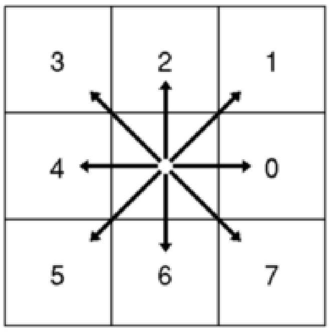

Figure 12. Freeman's eight-direction chain code used in [7].

The proposed algorithm detects all the turnings points by comparing the chain codes on the silhouette. The turning point with the number different from the starting point can be considered as a feature on the silhouette curve, and it will be stored in a new chain. For the new chain, the points with a 90° directional change (i.e. absolute directional difference between two points is equal to 2) are considered as feature points representing a human body contour. A series of feature points from head to foot can be identified following this procedure. 30 subjects including 15 males and 15 females were tested to verify the effectiveness of the proposed method. It states that the recognition rate was 100%.

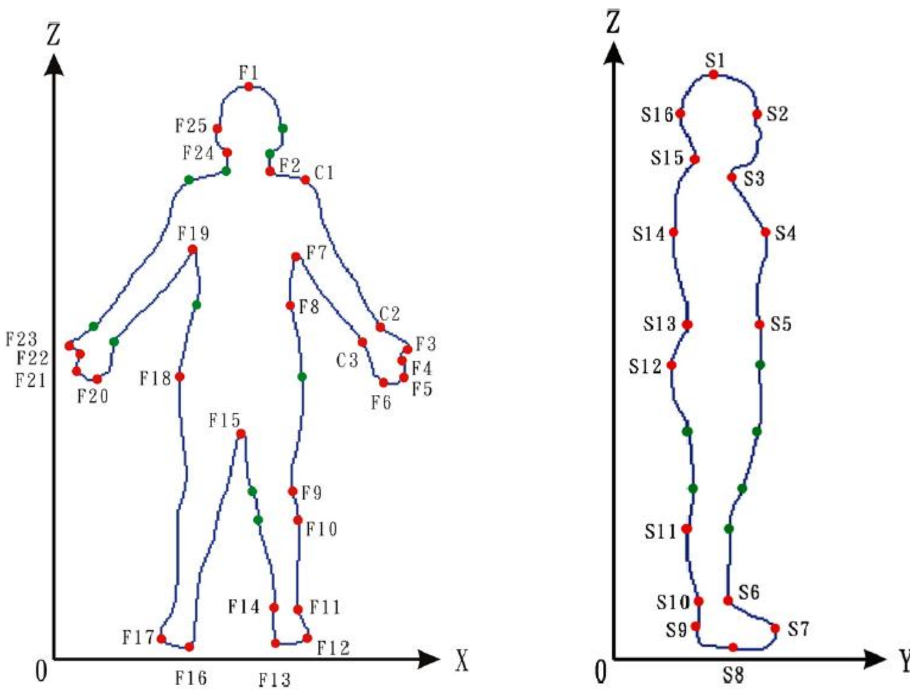

Figure 13. Feature points extracted by the algorithm [7].

The paper also presented table with the comparison of the detected feature points in front and side images by using the proposed method and method developed earlier. As it can be seen, the proposed method extracts more feature points than that of the other methods both the front and side images.

Table 5. The comparison of the detected front feature points from the method proposed in [7] and the other methods.

Body region	The front feature points	[7]	Seo et al. (2006)	Wang et al. (2003)	Meunier and Yin (2000)	Hilton et al. (2000)	Lee et al. (2000)	Seldon et al. (1940)
Head	Vertex	✓		✓	✓	✓		
	Head points	✓					✓	✓
	Intersection of the head and neck	✓					✓	✓
	Intersection of the neck and shoulder	✓	✓	✓	✓		✓	✓
Shoulder	Left acromion and right acromion	✓			✓	✓	✓	
Wrist	Left radial stylion	✓	✓		✓		✓	
	Left unlar stylion	✓	✓				✓	
	Right radial stylion	✓	✓		✓		✓	
	Right unlar stylion	✓	✓				✓	
Hand	The tips of the left fingers	✓		✓		✓		
	The tips of the right fingers	✓		✓		✓		
Chest	Armpit	✓	✓		✓	✓	✓	
Abdomen	Waist level	✓	✓		✓		✓	
Hip	Buttock point	✓			✓		✓	
Thigh–knee	Crotch	✓	✓	✓		✓	✓	
Knee–Shank	Knee	✓						
	Shank	✓						
Ankle	Left lateral mallcolus & left medial mallcolus	✓	✓				✓	
Foot	Metatarsoph. V & Metatarsoph. I	✓				✓		
	Ground, foot point	✓				✓		
Total		**38**	**15**	**6**	**13**	**10**	**23**	**6**

Table 6. The comparison of the detected side feature points from the method proposed in [7] and the other methods.

Body region	The side feature points	[7]	Seo et al. (2006)	Wang et al. (2003)	Meunier and Yin (2000)	Hilton et al. (2000)	Lee et al. (2000)	Seldon et al. (1940)
Head	Vertex	✓		✓	✓			
	Glabella	✓						
	Head posterior	✓						
Neck	Neck anterior	✓	✓	✓	✓		✓	✓
	Neck posterior	✓	✓	✓	✓		✓	✓
Chest	Bust point	✓			✓		✓	
	Backside	✓			✓		✓	
Abdomen	Waist level	✓	✓	✓	✓		✓	✓
	Waist level of back	✓	✓	✓	✓		✓	✓
	Buttock point	✓			✓		✓	✓
Knee – Shank	Shank	✓						✓
Ankle	Ankle	✓	✓				✓	
Foot	Acropodion & Pternion	✓						
	Ground	✓						
Total		**22**	**8**	**7**	**9**	**0**	**10**	**10**

2.3.2 3D measurements

Three-dimensional anthropometric measurements consist of a larger device which purpose is to scan the person and create its 1:1 model. More types of the scanners exist. The person can be scanned either by light or laser beams.

Figure 14. Cyberware 3D whole body scanner: Model WB4.

The work [9] concerns with the comparison of several body measurement techniques using 3D non-contact body scanners. It compares three laser-based scanners – ImageTwin, Cyberware and SYMCAD. It states that the scanners are capable of extracting an infinite number of data types, instantly and accurately. However, there exists the inconsistency how the scanners capture specific body measurements. It concludes that this technology cannot be utilized within the apparel industry until the body measurements are standardized.

Table 7: Comparison of WB4 and WBX Scanners

	WB4	WBX
Field of view		
Diameter	120 cm	
Height	200 cm	
Scan heads	4	4
Cameras	4	4
Mirrors	4	0
Scan cycle time	40 secs	25 secs
Cost	$350K	$150K
Booth size		
Width	360 cm	244 cm
Height	292 cm	244 cm
Diameter	300 cm	244 cm
Weight	450 kg	

The development of a system for automated landmarking and anthropometric data collection from the 3D whole body scanning was the objective of the study [15]. It uses the Vitus 3-D 1600 whole body scanning system and the surface of human body is captured by four sets of laser beams and CCD cameras in 20 seconds. Their automatic landmarking consists of four algorithms. Each one can help to extract several landmarks. The study results in automatic detection of 12 landmarks and three characteristic lines. Further, by using the approximation methods, 104 body dimensions can be obtained. To evaluate the validity and reliability of the newly developed system, 189 human subjects were scanned and tested. And the evaluation results suggest that the system was very effective and robust.

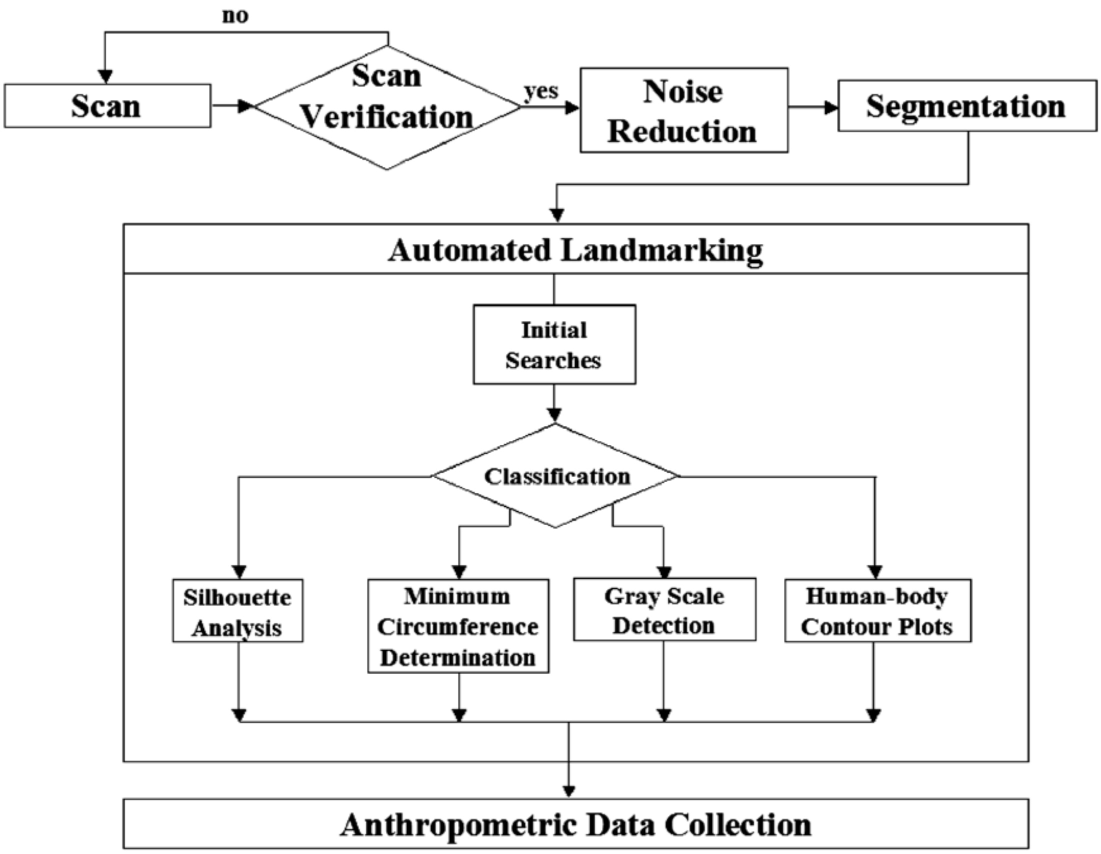

Figure 15. Schematic flow of the system implemented in [15].

3 Proposed Measuring System

The proposed system comes out from many realized experiments which were already published in previous work (e.g. [5], [6] or [8]). Some partial results will be also mentioned in the following text.

3.1 Camera system

The person to be measured stands in front of a background board with the arms away from the body. A camera is positioned in front of the person, three meters from the board. The frontal image is captured and the person is instructed to turn left to capture the lateral image. This allows modelling spatial dimensions such as waist or chest circumference. The technique from other work use two different cameras placed in front of and on the side of the measured object. We use one camera only because it is cheaper and satisfies the requirement of portability better – fewer devices, only one background and only one illumination.

The selection of the proper cameras is a subject for discussion. It must be relatively cheap and provide a good quality image. The resolution of camera should not be low but it is not required to be very high. 1280×960 pixels should provide good accuracy (this was verified by experiments) and comfortable performance of image processing. The main requirements are the ability to focus at the distance of three meters, good colour contrast, the ability to deal with different conditions of illumination (i.e. setting of exposure value, shutter, etc.) and low noise in the captured image. We tested several web cameras and their main drawback is their inability to focus at the requested distance, regardless of the price of the web camera. The basic experiments can be done using a digital camera which satisfies all above conditions and is easily available to common users. This allows the end software to be designed for home usage, for example, in web shop applications.

However, the classic digital cameras cannot be used in final solution as they do not mostly provide capability to record video to the computer in real time. This disadvantage would slow down the measurement process.

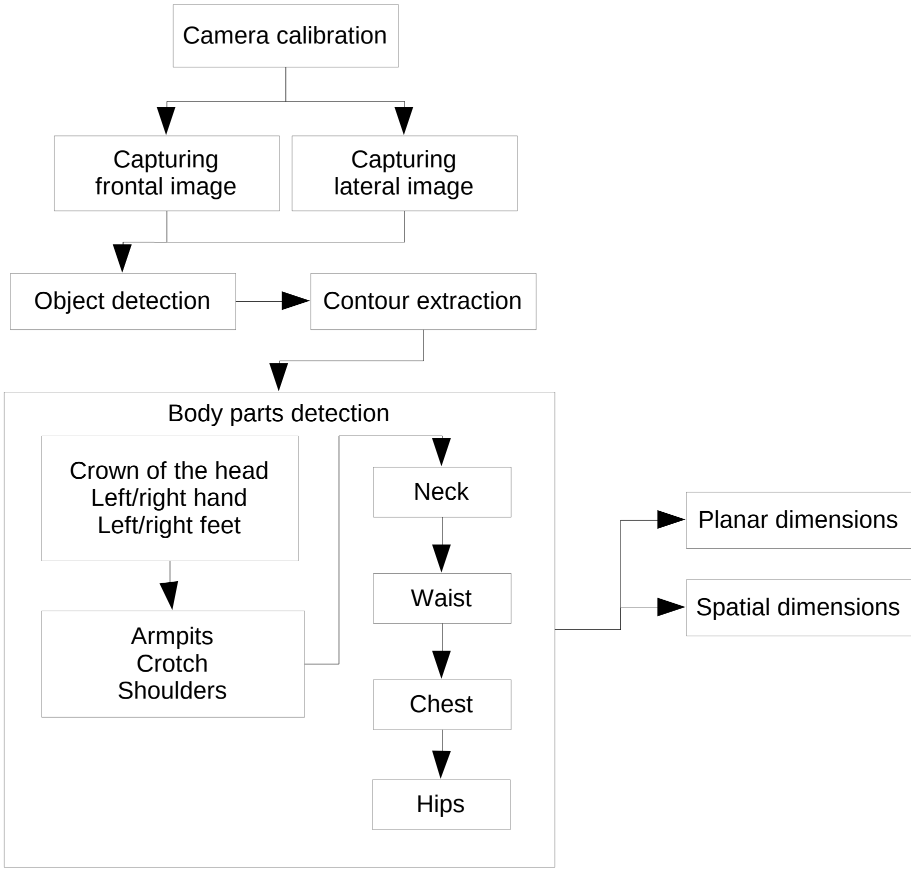

Figure 16. Diagram of the measurement.

3.2 Measuring area

The green backboard covers the whole area behind the object and its dimension is 150 cm × 220 cm. Nine red calibration dots are placed on the backboard and five dots are placed on the floor. This allows automatic camera calibration and fixing camera misplacement (see next chapters). At the beginning, the calibration dots were black-coloured but we decided to choose red colour later. It allows much better automatic detection, because red colour cannot be found elsewhere in the scene while black colour can originate by inferior light, shadow etc. Footprints are printed on the floor to establish the position where the person to be measured should stand.

Figure 17. Measuring area

Another subject for discussion is the colour of the background board. At first, we used white colour but this disallows measuring of people in white clothes. References [5], [8] or [13] use blue background. The reference [7] proposes using green background, because it is commonly used in chrome key technique for object extraction from video sequence. But it says that "this technique presumes that object is coloured differently, if possible complementary to the background colour." According to the project submitter the green clothes are not worn as often as white ones are, so we selected the green background colour too. One possible solution to this problem would be to have different background colours and prepare final application to deal with it. Then select the proper colour for measurement.

Since the whole system should be portable, we did not install the experimental workplace in a special room but in a corridor where the camera looks through a doorway. This nicely simulates difficult circumstances for measuring in real situations and allows testing with several illumination conditions, as light can be directed from several directions.

3.3 Possible difficulties

Several difficulties can arise during measurement. It is very important to deal with them, because they can influence results' accuracy a lot. The most important potential sources of these problems are:

- camera calibration
- object extraction and landmarks detection
- body part modelling
- person's posture
- person's clothing

The first three problems can be solved by correct system design but there is currently no correct way how to deal with inaccurate data obtained from bad person's posture or unsuitable clothing he/she wears during the measurement.

3.4 Getting world coordinates

Since distance between calibration dots is a known constant, it could be used for transforming pixel dimensions to object's real dimensions in centimetres. However, measured person is not flat and it stands some distance in front of the back board thus perspective effects applies, i.e. object seems to be higher than it really is, see Fig. 2.

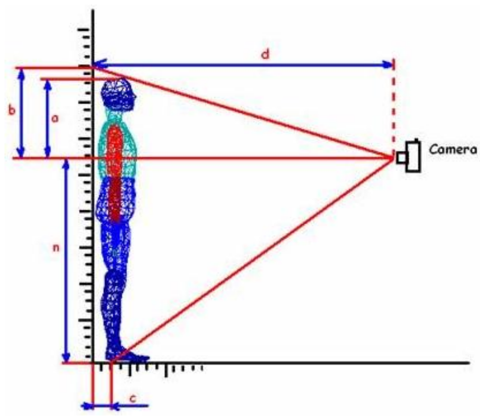

Figure 19. Perspective effects.

Firstly, we tried using very simple method to convert pixel dimensions to centimetres – the first measured (call it reference) person had to be of known height and the rest were computed from it as:

$$d = \frac{reference\_height(cm)}{(bottom - top)(px)} \cdot (p_2 - p_1)(px)$$

where p_1 and p_2 are edge points of any wanted dimension and any subtraction is distance of two points defined as:

$$b - a = \sqrt{(a_x - b_x)^2 + (a_y - b_y)^2}$$

This is very similar to [4] or [7] which use a special calibration board but we decreased the need of another item which accordingly simplifies requested portability. However, this could falsify the measurement results when reference person's posture was different than posture of another measured person. Therefore, according to [5], the non-coplanar Tsai calibration method [20] was incorporated into our system. Fourteen calibration dots are automatically detected by the Hough transformation [12]. The calibration process results in internal and external camera parameters which allow converting image coordinates to world coordinates. Secondly, it should provide possibility to fix lens distortion although the used implementation does not provide results as we expected. Some calibration error can arise from calibration process.

For proper measurements, the floor (or a base point) must be identified in the scene. Earlier this was performed by placing one special dot on the floor. But since the base position is exactly specified (between the footprints), the point's image coordinates can be automatically recovered from the known world coordinates. Currently, the black floor point is still present there but it is used just for an assertion that the floor has been detected correctly.

Calibration becomes invalid when the camera setup is changed. This is not optimal for automatic measurements with a portable solution; thus, there is still room for improvements. It would be useful to perform a correction when the camera is moved during measurement. This could theoretically be easily possible because calibration dots are still visible during measurement; thus camera misplacement can be easily detected. On the other hand, red dots detection can be more difficult at this moment, because they can interfere with the measured object.

3.5 Object Detection

Proper object detection is the next important part of measurement if we want to have the automatic system. It means separating captured object from the background and marking its border. This procedure can be made difficult by improper choice of the camera and unsuitable lightning conditions. When the object is separated body landmarks can be detected.

3.5.1 Background removal

The captured image is converted into HSV (Hue-Saturation-Value) colour space which provides much better view on individual colour than RGB (Red-Green-Blue) space. Because the R, G, and B components of an object's colour in a digital image are all correlated with the amount of light hitting the object, and therefore with each other, image descriptions in terms of those components make object discrimination difficult. Especially the hue component allows us to detect the particular colour regardless the amount of incident light.

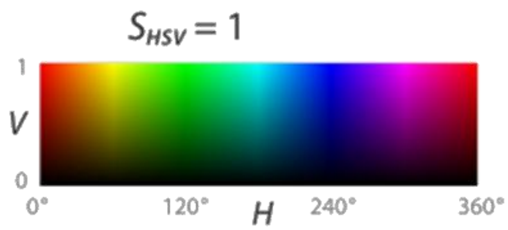

Figure 20. HSV space shows how individual colors are distributed

Figure 19 shows colour distribution in HSV space. Since our background is green-coloured, we are interested in distribution of green colour. We can see that this colour is located around 120° and therefore everything around this hue is distinguished as the background. The only difficulty is to specify the hue range, i.e. where the green colour begins and ends in HSV system. This can be decided from experiments only.

The part overlapping the floor is ignored completely, because the algorithm sometimes recognizes legs as one part due to shadow thrown by the person. This is not important as we are not interested in measures in this area. Later, we can solve this by placing a green plate (or a carpet) on the ground. It is also very difficult to extract the areas that blend with the background colour.

3.5.2 Object contouring

Contours are retrieved from the image using the algorithm [11] and the largest contour is selected to be the person's contour. The rest is rejected. To make the contour as smooth as possible, the polygon approximation is performed.

Figure 21. Object extraction and contours detection.

4 Automatic landmarks localization

As was mentioned above, the automatic landmarks and body parts localization is the main topic towards which this work should be directed in future research. The current literature talks mainly about manual landmarks localization (e.g. in [2]) and complete automatic detection seems to be done in 3D body scanners [9], [15]. The concept of the automatic landmarks detection in 2D images has been proposed in [5] but this method is very limited and it does not reflect the real position of particular body parts. It is able to detect only basic landmarks such as the crown of the head, armpits or crotch. However, it could serve as the base for creating a new technique.

Another method of automatically extracting human body features has been proposed in [7]. It is based on representing the body contour using Freeman's chain code and feature points are identified by evaluating the difference between the coding sequences. Although it states that the recognition rate was 100%, it does not seem to work correctly when the measured object is dressed, as the clothes can cause unexpected changes in the contour direction. It does not reflect the clothing standard either. Therefore, a better method needs to be developed.

This chapter will try to outline how landmark localization without any other manual steps could be done and introduce algorithms to solve (with minimal error) this problem in 2D non-contact anthropometry system.

4.1 New proposal

Our proposal tries to localize body parts so they correspond with the definitions stated in the standards for body and garment dimensions [1] and given by an experienced anthropometrist as much as possible. We are required to follow them to satisfy the project submitter. Whole idea lies in dividing the human body into several segments, specifying a body part level (or an area) and localizing the exact body part emplacement within this area.

The algorithm works in several phases. The first two phases detect the basic points as defined in [5]. This is based on finding the global extremum points followed by finding the local extremum points. The first phase localizes the crown of the head as the contour point with a minimum vertical coordinate, both hands as the contour points with minimum and maximum horizontal coordinates, and both feet as the contour points with maximum vertical coordinates on each side of the body horizontally divided by a centre line. The second phase localizes both armpits and the crotch as the contour points with minimum vertical coordinates between the corresponding hands and feet. Both shoulders are located as the contour points with the same horizontal coordinate as the armpits and minimum vertical coordinate. Since it is possible that more points with the same minimum/maximum coordinate can exist, the original algorithm had to be slightly modified to maintain body symmetry.

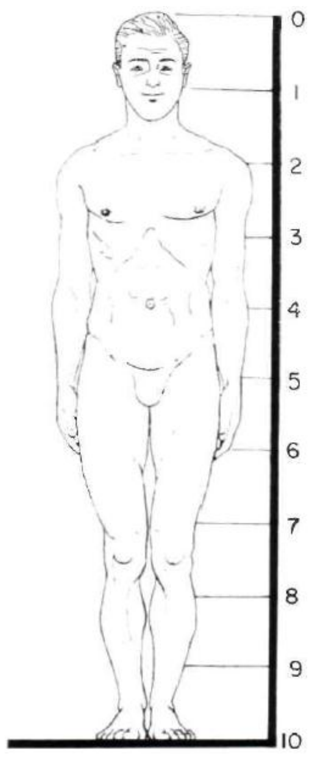

Figure 18. Kollmann's decimal canon

The following phase iterates over the body height and tries to localize spatial body parts. To achieve this, the human body height is divided into one hundred equal parts, as was introduced by Kollmann at the beginning of the twentieth century [4]. His decimal standard divides the body height into ten segments and each of these is subdivided into ten subunits. Certain body levels can be estimated then. Currently, it is important to correctly arrange the area (level) of the neck, chest, waist and hips. The other body parts are the subject for future research. From the experiments, we deduced the following: Although Kollmann's standard specifies the head height as 13 subunits, this is not always the truth and it is better to begin the neck area at the

10th subunit. The lower boundary can be defined by shoulder points detected in the second phase. The chest will be searched from five subunits above the armpits and one subunit below the armpits. The waist area is distributed from the 40th to 50th subunit and the hip area is localized between the detected waist and the crotch. The back length can be identified using some of these landmarks. One idea for the future research could be creating large statistics of body parts distribution.

4.2 Circumferences computation

The spatial body parts are modelled as an ellipse where its major axis is taken from the frontal image and its minor axis is taken from the lateral image. The system [6] models some body parts, e.g. neck, as an ellipse and some parts, e.g. chest, as a combination of a rectangle and an ellipse. However, in our experiments, the chest approximation with the ellipse gives better results. Hence, the circumferences are currently represented as

$$C = \pi \cdot \left[\frac{3}{2} \cdot (a + b) - \sqrt{a \cdot b}\right].$$

4.3 Landmarks definition

When the human body is divided into one hundred segments, we can look at the concrete body parts definitions. These definitions are very important and they must be stated precisely else automatic detection will not be possible. Sometimes, the landmark (or body part) can be defined in different ways which can be seen at the 3D body scanners where two different scanners can localize one landmark differently (e.g. SYMCAD vs Cyberware). The comparison of several three-dimensional body scanners was discussed in [9]. The correct statement must be discussed with the anthropometrist.

Following sections will try to introduce the body part definition as emerged from discussion with the anthropometrist. When some uncertainty appears, it will be consulted with existing standards. Current standards for body and garment dimensions include those established by the Association of Standards and Testing Materials (ASTM) [1] and the International Standards Organization (ISO). Also difficulties in 2D anthropometry system will be outlined.

4.3.1 Body height

The body height is according to [1] defined as the vertical distance from the crown (= top) of the head to the floor, taken with subject standing without shoes.

The crown of the head could be specified as the highest point in the body contour. The problem is that hair can interfere with this landmark making this localization more difficult. This results in stating that the person is taller than it really is.

4.3.2 Neck circumference

The neck girth is defined as the circumference of the neck, taken over the cervicale at the back and the top of the collarbone at the front. However, there can be a problem with the detection of these landmarks, especially when the person is wearing a shirt with a collar. Therefore, after a consultation with the anthropometrist, we decided that we can specify the neck girth as the place with the minimum circumference around the neck at the neck level, measured horizontally in the front and diagonally on the side. The experiments show that this works as expected when the lateral neck height is set to three subunits with the ellipse major axis in the middle. We can specify the neck circumference as

$$N = \min C \ in \ (S_{10}, shoulders)$$

where S_i denotes i-th subunit according to Kollmann's standard.

4.3.3 Waist circumference

The waist girth is defined as the minimum horizontal circumference around the body at waist level. This definition corresponds with the definition given by the anthropometrist. However, one can see that the waist is not parallel to the floor in the lateral image. Thus we can specify the waist circumference as

$$W = \min C\ in\ (S_{40}, S_{50}).$$

4.3.4 Chest circumference

When the waist is identified, we can move to identification of the chest. The chest circumference is defined as the maximum horizontal girth at chest level measured under the armpits, over the shoulder blades, and across the nipples with the subject breathing normally; parallel to the floor [9]. First, we approximate the body trunk with two bisectors (left and right side of the trunk as shown in Figure 21) starting at the waist contour points and passing through the armpit points. This ensures that the chest is bounded above the armpits where the ellipse major axis is taken as the horizontal distance between these two lines. Then we specify its circumference as

$$Ch = \max C\ in\ (armpits - 5 \cdot S, armpits + \mathrm{S}).$$

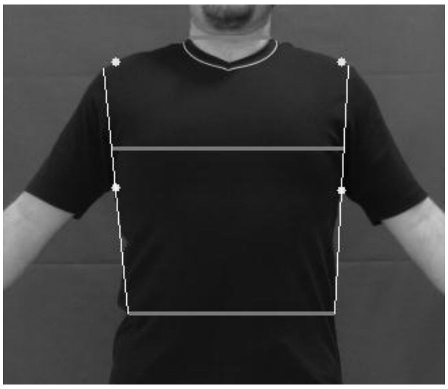

Figure 22. Approximation of body trunk for the chest detection.

4.3.5 Hips/seat circumference

The hip girth is defined as the maximum horizontal circumference around the body at hip height. This definition corresponds with the definition given by the anthropometrist and it is always parallel to the floor. Thus we can specify the hip circumference as

$$H = \min C\ in\ (W, crotch)\ .$$

5 Experiments

5.1 Software solution of the proposed system

The laboratory system has been implemented in C++ with the help of the OpenCV image processing library. Microsoft Visual Studio was used as the IDE with the debugger.

OpenCV is a library which provides a rich set of functions for programming of real time computer vision applications. Among others, it implements functions such as a conversion between several colour spaces, contours detection, polygon approximation or Hough transformation for circles detection. It also provides a very simple GUI functions (i.e. a window with captured images where it is possible to output any text, graphics objects, catch keys, mouse control etc.) which is sufficient for any testing purposes.

Although the OpenCV library provides functions for the camera calibration, they are not sufficient for our purpose. It uses Zhang's calibration technique and it is fully (i.e. detection both internal and external parameters) implemented for planar calibration patterns only (where z-coordinates of the object points must be all 0's). Tsai's calibration technique is not available with this library. Thus, we used Tsai3D implementation [22] for the proper non-coplanar calibration of the camera using Tsai's method.

The software was verified on the computer with Intel Core 2 Duo E8400 CPU @ 3 GHz, 4 GB RAM and NVIDIA GeForce 9300 GE graphic adapter. Microsoft Windows 7 Professional was used as the operating system.

5.2 Calibration error

Calibration error has been computed as absolute difference between calibration dot's real coordinates [mm] and its coordinates transformed from image [converted from pixels to mm]:

$$e_i(x, y) = abs(W_i(x, y) - I2W_i(x, y))$$

Maximum calibration error in X = 1.624 cm

Maximum calibration error in Y = 0.411 cm

Maximum elliptical error = 3.487 cm

Average error in X = 0.496 cm

Average error in Y = 0.200 cm

Average elliptical error = 1.143 cm

5.3 Results of experiments

The effectiveness of the proposed method was tested on nine males and two females. Four of the males were tested repeatedly at different times, with different illumination and in different clothes. The purpose of the experiments was not only to compare traditional tape measurements with camera-based measurements, because this was already verified by previous work [8]. They were mainly focused on detection of body parts on dressed persons. The accuracy of the experiments was verified by the experienced anthropometrist (who was a tailor in our use case). Hips circumferences were measured for females only and waist circumferences were measured for males only.

Hair was the problem causing inaccuracy in measuring body height. Bald persons' height was detected very accurately (with precision about 0.5 cm). Neck circumference measurement inaccuracy can be seen in case of person #8 where hair interfered with the body. The big differences can be seen for some cases of chest measurements, this can be caused by modelling error and could be solved by developing better chest model in the future research. Imprecision in waist measurement is mostly caused by the looser clothing, because persons with a tucked shirt were measured very precisely.

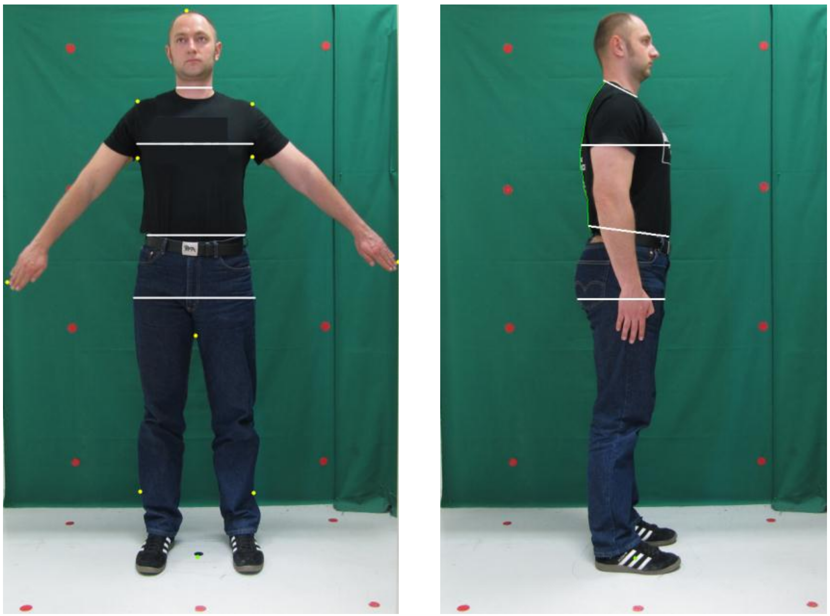

Figure 23. Successful automatic detection of neck, chest, waist and hips.

The results of the experiments indicate that we were successful in detection of neck, chest, waist and hips. The only two conditions are the colour difference between background and clothes colours and wearing clothes which do not cover or optically change a person's shape (e.g. thick coat, etc.). Upcoming research will focus on more experiments on females, better bust modelling and detection of the under-bust circumference, which is special dimension required for women.

Table 8. Comparison between the tape measurement and our 2D system [cm].

		Height	Neck circumference	Chest circumference	Waist circumference	Hips circumference
1	Manual	171.5	37.5	92.5	84.5	
	Computer	171.73	38.29	95.09	84.59	99.15
2	Manual	172.5	42	114	96	
	Computer	175.49	42.35	111.01	93.67	110.78
3	Manual	182.5	38.5	110	87	
	Computer	185.45	38.88	102.53*	89.08	100.27
4	Manual	181	40	107	103.5	
	Computer	184.20	42.06	102.39*	103.77	115.07
5	Manual	194	39.5	104	91	
	Computer	194.51	38.05	104.37	91.08	111.32
6	Manual	189.5	39.5	113	105	
	Computer	188.63	44.33*	109.20*	105.98	116.04
7	Manual	191	38	97	83	
	Computer	191.58	38.70	98.91	95.34*	109.17
8f	Manual	161	30.5	87.5		100
	Computer	159.30	46.22*	83.65*	76.99	96.20
9f	Manual	159.5	29.5	80		94
	Computer	159.55	31.53	74.39*	70.51	96.55
10	Manual	184	36	94	87	
	Computer	186.90	39.15	99.80*	86.34	102.04
11	Manual	195.5	39	105.5	103*	
	Computer	203.89	41.41	103.23	109.66	124.84
	Avg.error	**2.21**	**3.08**	**3.75**	**2.83**	**3.175**

* Measurement error was larger than calibration error.

Hips circumference is valid for females only and waist circumference is valid for males only.

6 Future work

This work describes the methodology of anthropometric measurement by computer. We focused on summarization of everything needed for designing an automatic 2D anthropometric system. We went through camera calibration, separation of the object from the background and simple body parts modelling. A new method for automatic detection of neck, chest, waist and hips circumferences has been proposed, applied and verified. Eleven persons were tested to verify the effectiveness of the proposed method. All requested body parts were successfully detected when the person was dressed in fitted clothes, i.e. clothes which are not too loose, and hair was not hanging down along the body. The same technique can be used for other body parts, e.g. thigh circumference, etc.

Several problems appeared during system design and we must cope with them in future research. It will be focused mainly on more anatomical landmarks localization, better modelling of body parts and finding a possible solution when a person wears unsuitable clothes. We would like to improve the accuracy of the measurement as much as possible.

The system prototype will be verified in the practice by measuring hundreds of subjects. All measured data will be provided to us and properly analysed. The results will significantly influence following parts of our anthropometric system:

- the measurement of the remaining body parts, especially sleeve length, back height and seat height
- the bust circumference measurement for females including under-bust circumference
- improvement of the chest modelling
- statistical analysis of individual body parts layout for more accurate automatic landmark localization

The mentioned system parts represent very considerable contribution from a practical point of view, but they are not so valuable from a scientific point of view. The automatic landmarks localization and measurement in looser clothing seems to be much more significant (which resulted from conference discussion [21]) and not so much explored problem towards which I would like to direct my future research.

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Appendix

Measured person #2

Measured person #3

Measured person #5