ELSEVIER

Optics and Lasers in Engineering 28 (1997) 89–117

0143-8166/97/$17·00

PII: S0143-8166(97)00006-7

Three-dimensional Surface Anthropometry: Applications to the Human Body

Peter R. M. Jones[a] & Marc Rioux[b]

[a]HUMAG Research Group, Department of Human Sciences, University of Loughborough, Leicestershire, U.K., LE11 3TU
[b]Autonomous Systems Laboratory, National Research Council of Canada, Ottawa, Ontario, Canada K1K 0R6

ABSTRACT

Anthropometry is the study of the measurement of the human body. By tradition this has been carried out taking the measurements from body surface landmarks, such as circumferences and breadths, using simple instruments like tape measures and calipers. Three-dimensional (3D) surface anthropometry enables us to extend the study to 3D geometry and morphology of mainly external human body tissues. It includes the acquisition, indexing, transmission, archiving, retrieval, interrogation and analysis of body size, shape, and surface together with their variability throughout growth and development to adulthood. While 3D surface anthropometry surveying is relatively new, anthropometric surveying using traditional tools, such as calipers and tape measures, is not. Recorded studies of the human form date back to ancient times. Since at least the 17th century[1] investigators have made attempts to measure the human body for physical properties such as weight, size, and centre of mass. Martin documented 'standard' body measurement methods in a handbook in 1928.[2] This paper reviews the past and current literature devoted to the applications of 3D anthropometry because true 3D scanning of the complete human body is fast becoming a reality. We attempt to take readers through different forms of technology which deal with simple forms of projected light to the more complex advanced forms of laser and video technology giving low and/or high resolution 3D data. Information is also given about image capture of size and shape of the whole as well as most component parts of the human body. In particular, the review describes with explanations a multitude of applications, for example, medical, product design, human engineering, anthropometry and ergonomics etc. Crown © 1997 Published by Elsevier Science Ltd.

1 INTRODUCTION

Human morphology has been studied from the time of the ancient Greeks in an attempt to classify people predisposed to certain ailments. Hippocrates, c. 400 B.C., thought that there were two physical types, which he called the phthisic habitus and the apoplectic habitus. Since then many others have tried to classify the human form. Sheldon and his co-workers[3] further refined human classification into somatotypes. They maintained that the human form is intermediate between three extremes, the endomorph, the mesomorph and the ectomorph. The method of classification involved a series of detailed measurements taken from photographs but there was a significant element of anthroscopy (photoscopic appraisal) involved, in other words, a judgement of the appearance of photographs modified by the measurements. This work has been useful in many fields since it is far more accurate to use a typical somatotype than a simple average.

More recently, size surveys have been carried out, mainly for the clothing trade but with obvious spin-offs in the medical field. These have been direct measurements of the body using tape measures, spreading calipers and other manual measurement tools. For modern tight-fitting garments, more than 40 anthropometric measurements (displacements and circumferences) are desired; limitations include the cost of taking so many measurements and the time that the available subjects are prepared to give. Even if such measurements are taken the data are not sufficient to provide answers to questions involving body shape such as ‘What is the shape of the leg hole in a swim suit?’ Nor are they sufficient to provide accurate three-dimensional (3-D) computer simulation models.

The study of the human body as a 3-D object has only recently begun, starting in 1973 with a technique of light sectioning by Lovesey.[4] This was labour intensive in the interpretation of the data and extremely time consuming. The information gained from 3-D studies can be used in, for example, ergonomics, orthotics and prosthetics design, plastic/cosmetic surgery, obesity studies, the study of breathing and seating design for the disabled. The 3-D shape is dependent on underlying anatomical structures and therefore it is possible to study body shape distortion due to natural and pathological processes. This is of interest for assessment and diagnosis in clinical practice.

The clothing and manufacturing industry is able to use information about the human body shape for the design and processing of products. This has been assisted by the recent advances in computer-aided design (CAD) and computer-aided manufacture (CAM).[5]

Size and shape measurement of the human body is an important source of information. For example, determining the size and shape distribution of a population will provide norms for the study of abnormalities or the effects of ageing and disease or changes due to body growth and development, seasonal biological variations, or nutritional or pathological conditions.

2 MEDICAL APPLICATIONS

2.1 Body deformity

The term body deformity applies to the deviation of various anatomical regions of the body from the feet to the head in either the saggital, coronal or both planes. These deformities maybe as a result of trauma, pathology or occupation or a combination of either.

Body deformity or abnormal morphology can be related to genetic disorders or they might be acquired, syndromal or from unknown causes. A compilation of body measurements using anthropometry is reported in Meaney and Farrer.[6] Craniofacial abnormalities related to fetal alcohol syndrome are reported in Hiritz *et al.*,[7] using close range photogrammetry.

2.2 Glaucoma

Three-dimensional measurement of the optic disk in the early diagnosis of glaucoma is described in Takamato and Schwartz.[8] The technique is now routinely used and found to be highly reproducible and sensitive in detecting changes in cupping of the optic nerve head. Resolution needed is in the order of tens of micrometres.

2.3 Orthodontics

Laurendeau *et al.*[9] and Coté *et al.*[10] have used 3-D imaging techniques to measure wax dental imprints. A segmentation software to process 3-D images is used to automatically measure teeth interstices.

2.4 Orthopaedics

Assessment of foot disorders using stereophotogrammetry is reported in Craxford *et al.*[11] Monitoring recovery after surgery has also been evaluated by Houghton *et al.*[12] Twenty-nine patients were assessed by X-rays and surface scanning both before and after surgery for scoliosis.

2.5 Surgery

Most of the applications reported in this field are related to maxillo-facial surgery. Three-dimensional imaging techniques are used to digitize the subject's facial morphology. Computer graphics tools allow visualisation and editing in order to evaluate surgical strategies. Vannier *et al.*[13] use a multi-camera multi-projection system to digitize patient shapes in less than a second. Images are taken a few hours before the operation, 24 h after, and 2 weeks later.

Linney and co-workers[14,15] use both laser scanner for 3-D imaging and CT data. Various editing tools have been developed to computer simulate surgical procedures. Applications reported are facial reconstruction, cranioplasty and ear prosthetics.

Two laser scanned images taken before and after surgery can be registered and subtracted to demonstrate soft tissues changes. Accuracies of better than 0·5 mm are reported.[16]

Coombes *et al.*,[17] describes a surface patch model used to analyze the facial geometry. They discuss surface primitives based on mean and Gaussian curvatures which are used for segmentation. These authors suggest using this method for the development of normative standards for facial aesthetics.

2.6 Thorax

Many devices are designed to measure the back of the torso to assist with the diagnosis of scoliosis.[18,19] A commercial system developed by AXIS Software Systems Ltd[20] can digitize either the back or the front of the body. A detailed review of this field of research can be found in the proceedings of bi-annual symposia dedicated mainly to spinal deformity diagnosis using surface topography.[21–25] Occupational postural deformities have also been studied, e.g. an assessment of injuries among violinists[26] and a study of postural asymmetry related to chronic back pain.[27]

2.7 Lung function studies

Similar measurement technologies (close range photogrammetry) have been used to study breathing and respiratory mechanics. Projected patterns to extract volume changes and velocity of surface point displacements are reported in Kováts *et al.*[28] Lewis and Sopwith[29] described a method using an array of dots to measure the anterior and posterior surfaces of the thorax for lung function studies. Clinical diagnosis in the breathing-pump mechanism is proposed along with potential applications in pediatrics, sports medicine and ballet-choreography. Respiratory mechanics are analyzed in the context of the measurement of vital capacity. Other studies related to growth and ageing effects are discussed in Kováts[30] and Adams *et al.*[31] Gourlay *et al.*[32] propose solutions to hair interference, shadow effects and patient motion.

2.8 Custom prostheses for dentistry, orthopedics and rehabilitation

Application of 3D anthropometry to achieve function and fit is well established in orthotics and prosthetics. Specialised sensing components produce measurement sets that are subsequently processed to manufacture the customised orthotics or prostheses.

Three-dimensional imaging has been used mainly for fitting artificial limbs and dental restoration. In each case a detailed 3-D map of the receiving part is used for the production of a negative shape that will interface the prosthesis to the subject's body.

Duret and Blouin[33] devoted considerable time and energy to the development of a complete process for tooth-crown fabrication, from *in situ* optical recording to Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) interface, modelling and manufacturing. Challenges are related to multiple view registration, data shape modification for cement and the generation of a CAM file for machining. A similar application is described in Yeung *et al.*[34] where the *in situ* recording is replaced by the scanning of a dental impression to transfer the shape. CAD/CAM technology is used to generate a tooth-crown with an accuracy of 25 μm.

A commercial product for the automation of the production of inlays (CEREC) has been available from Siemens[35] since 1989. It uses an *in situ* optical probe to digitize the site and a compact milling machine to carve the final shape. Titanium oxide powder with a wetting agent is also used to enhance optical measurements. Accuracy is in the order of 100 μm. A 20-μm resolution 3-D imaging system for *in situ* measurement has been reported by Altschuler.[36] It uses a space-coded structured light approach to image the shape of the teeth. An intensity image is also digitised to help the user interact with the data in providing visual cues. The main problem with teeth imaging is the resolution, which must be very high ($\sim$20 μm) for good matching.

In contrast, for limb prostheses, the resolution needed is not that high, but one is dealing with soft tissues, which complicate data analysis. The proper fitting is not only related to the exterior skin surface, but depends heavily on underlying bone structure, which cannot be measured optically. Saunders[37] and Duncan[38] describe a complete system that optically measures the shape of the stump, transfers the data to a CAD system for editing and formatting and produces a CAM file for NC machining of the prosthesis. An improved optical measuring technique has also been described by Halioua *et al.*[39] It uses a technique called phase-measuring profilometry to digitize the stump.

Several prototypes of computer-controlled prostheses have been designed and manufactured by (CAD/CAM) technology.[40] The basis for using CAD/CAM techniques in prostheses design is a laser surface scanning device used to capture the geometry of the affected body part. The processed 3D data file is then interfaced with a CAD modeler where reconstruction, mirroring, scaling, etc., can be performed. The resultant CAD model is then passed on to CAM, which concentrates purely on producing a 'positive core' for moulding the prosthetic device.[41] Computer-aided design and computer-aided manufacturing techniques, though often technologically associated with engineering and applied sciences, are central to the practical implementation of 3D anthropometry.

2.9 Breast topography

Malignant lesions are detected by a measurement method to quantify breast volume and volume distribution.[42,43] Asymmetries in volume distributions have been correlated to lesion detection.

Jones *et al.*[44] describe how their 3-D scanner (LASS) is used to monitor breast surgery (mastectomy due to breast cancer). The subject is scanned before and after surgery. The pre-operative data are used to manufacture a bespoke prosthesis that restores the original outer appearance of the removed breast tissue. This ensures better fit and comfort which is essential for psychological rehabilitation of the patient.

2.10 Pediatrics—scoliosis and craniofacial deformities

The main objective of the research in automatic diagnosis of scoliosis is to mass screen children in an attempt to produce an early diagnosis before too much damage is done to the body structure. School screening using moiré photography has been reported by Neugebauer and Windischbauer[45] and cost analysis discussed. The challenge is in the automation of the diagnosis process. Batouche[46] presents a knowledge-based system and 3-D reconstruction to achieve automatic diagnosis.

Mehta[47] suggests that associated facial asymmetries could be used to make a very early diagnosis of scoliosis. Related research on the growth process in childhood[48–51] provides data to model normal growth. More recently, Richtsmeier[52] described a model for prediction of a child's skull growth. Computer tools have been developed to compare a simulated (or grown) skull to samples of head images of normal and abnormal children of an age/sex/ethnic population that matches the patient. Moss *et al.*[53] have taken a very unusual set of 3-D measurements. They were able to compare face plaster casts of a subject taken over a period of more than 50 years. It is also noted that plaster induces substantial deformation of tissues (~1 cm) due to the weight of the plaster.

2.11 Medical management

In this field of application, accurate data on the volume and/or surface area of the human body are desired to allow the physician to manage homeostasis or drug administration with precision. The measurement of body surface area (BSA) in children aged between 3·5 and 15 years, with liver disease, by a novel 3-D body scanning device is reported by Jones *et al.*[54] Their study showed that this type of whole body imaging was acceptable to young children (precision 1%). It is interesting to note that traditionally used anthropometric equations for estimating BSA in children[55] overestimates by 10% when compared to the accurately calculated BSA from 3-D scanning. The clinical implications of this are discussed in relation to drug dosage and medical management.

A structured light approach to body surface area and volume measurement is reported by Dunn *et al.*[56] Camera calibration and surface modelling are discussed in detail. Resolutions of better than 1 mm are obtained. The author suggests applications related to the measurement of the surface area of burns, swelling in arthritis, expansible tumours and for planning of radiation therapy.

Karras and Tympandis[57,58] have also used 3-D measurements to monitor shape variation during pregnancy. Measurements of area and volume of the abdomen, breasts, buttocks and thighs have been made at regular intervals during pregnancy and after delivery.

3 HUMAN SYSTEMS ENGINEERING (ENGINEERING, ANTHROPOMETRY)

Human Systems Engineering is the design of anything that people wear or use and in the ergonomic design and evaluation of the workplace. Most of the large scale anthropometric surveys listed in chapter 1 were conducted for this purpose. They include clothing, anti-g suits, helmets, automobiles, computer keyboards, aeroplanes, workspaces etc. The form, fit and function of these 'human systems' are very dependent upon anthropometry.

3.1 Work enviroment

There is a need to determine body size and shape for the design of protective clothing for use in hostile environments, such as special 'g' suits for military aircraft pilots and for protective clothing for chemical warfare and many hazardous industrial environments. Realistic body shapes are required for architectural models, for use in ergonomics in the evaluation of escape envelopes and for interference checks, fit and integration, assessment of equipment interfaces and manikins for crash research.

'Crew Chief',[59,60] is an interactive computer design 3-D modelling system. As the 3-D modelling system creates a computerised human model that has the correct body size and proportions, it is of particular use in the design of clothing and personal protective equipment. It has 35 segments, which correspond functionally to the human skeleton system and is able to represent the limits of mobility and the physical capacities of the human body.

Another CAD system has been proposed by Yang, Thalmann and Thalmann.[61] Here the skeleton or a simple representation is used to convey size information to the designer to convert the two dimensions to three. This is important for seeing the lay of the fabric over the 3-D shape.

Computerised biomechanical manmodel, COMBIMAN,[62] is an interactive computer graphics human factor evaluation system. It is used to assess the capabilities and the accommodation of the human operator. It represents the geometric and physical properties of an operator, which is useful for the design of car or aircraft control seats.

A critical review of six computerized analogue models including 'Crew Chief' and COMBIMAN can be found in Paquette.[63] One of these models, JACK, has been designed for the evaluation of the space shuttle and the space station. Programs for animation and visual fields analysis are written in C under UNIX and run exclusively on Silicon Graphics workstations. Graphic representation is very good and fast. A second, SAFEWORK, is designed for evaluation of human–machine incompatibilities including safety and health concerns. Positioning of the model and its segments is interactive and a zoom is available for precise positioning. It is a 35-link skeleton and enfleshment is realized using Bezier equations. ACADS uses a totally different approach. Indeed, the U.S. Navy has abandoned man-models for digitized images of living human subjects, but images are static and require some advanced knowledge of the design.

The common difficulty of any model is that traditional anthropometric data were not conceived with the aim of developing man-models. It is only with the more recent U.S. military survey (1988) that measurements were taken for the approximation of segment lengths. A description of that one-year project is given in Symington and Gordon.[64] One hundred and thirty-two measurements were done on 5499 men and 3485 women. The dimensions were chosen to support a wide variety of applications and oversampling was done to provide data for future uses. Additional information was gathered on the head and hand using an automated 3-D head board and a hand photographic system. Biographical data were also included for correlation with occupational groups.

Research to establish the relationship between readily measured body dimensions and mass distribution has been reported.[65–67] Stereophotogrammetry has been used for volume measurements and regression equations on anthropometric data for predicting mass distribution characteristics of the total body and its segments. The two studies used 31 male and 46 female subjects. This photogrammetric system consisted of stereopair cameras integrated in a single coordinate system using control stands as reference planes, for front and back views.

Greiner and Gordon[68] assess long-term changes of the human body shape. The secular trend study is based on 22 variables taken from the 1966 and 1988 U.S. Army surveys. Individuals were grouped by birth year into 12 5-year cohorts that span the years 1911 to 1970. It is observed that, with few exceptions, the greatest relative rates of change were found in dimensions related to soft tissue development rather than skeletal dimensions.

Unique environments such as mines and space have attracted special attention. A list of publications related to space human factors for the period of 1980–90 is given in Dickson.[69] An information retrieval system that provides relevant human factor information related to mining is given in Fowkes and Aiken.[70] It describes 10 mining-related categories, such as biomechanics, work physiology, human error and reliability. Rider and Unger[71] describe a computer model to analyze the human factor aspects in mining machine operator compartments. It is proposed to original equipment manufacturers and mining companies as a tool for the design of new machines in order to improve safety, visibility/illumination and structural design.

3.2 Population anthropology

Imaging tools for population screening are under development in Japan.[72] A full-body optical scanner has been integrated in a mobile unit. The system used by the Research Institute of Human Engineering for a

Quality Life will collect data on 50,000 Japanese subjects. Data will be used to revise Japan's industrial standards and other manufacturing guidelines.

Similar studies are already being carried out by the HUMAG Research Group at Loughborough University, where to-date a databank of over 300 people have been scanned on the LASS system together with appropriate anthropometric measurements. The 3-D data are being interrogated for use in the clothing manufacturing industries and medical applications.[5] The reliabilty and repeatability of 3-D whole-body scanning measurements and anthropometry are reported by Brooke-Wavell *et al.*[73]

Finally, Roebuck[74] gives suggestions for future developments in the fields of anthropometry, computer modelling of the human form and electronic imaging of the human body. The author stresses the importance of measuring the location of joint centers of rotation and the development of standards for dividing up body parts for mass properties of moving segments studies. He suggests a very interesting strategy for compact mathematical data description and storage of electronic images, based on a skeleton reference axis and a cylindrical coordinate system for compact surface data representation.

3.3 Helmets and face masks

Helmets are by far the most used form of personal protection. Types include construction worker safety, motorcycle, football, baseball, diving, welding, riding, fire fighting, protective crash, wrestling, explosive ordinance disposal and flight helmets. Similarly, facemasks are used for cold protection, surgical and medical procedures and anaesthesia. They are used by dentists, sculptors, scuba divers, welders, fire fighters and others.

In the case of an aircraft pilot the helmet is used not only for personal protection but also for interfacing with the aircraft controls and instruments. Hall and Campbell[75] describe the helmet of the future, showing the complexity of the design task and the importance of integration for lightweight design and comfort.

In a report by Robinette,[76] the pilot's head is digitized (using a Cyberware scanner) with and without the helmet to provide information about stability and fitting. The author stresses the need for a new type of anthropometry that takes into consideration the shape of the head and the changes in surface curvature for helmet design and integration. The laser scanning system has been used to digitize over 1000 subjects. Scanning time is about 12 s for 130,000 surface points that have a resolution of about 1 mm. The main advantage of the proposed method is that the helmet axis system can be used to standardize the alignment and define the population variability.

Case *et al.*[77] report face mask fitting tests to determine the facial characteristics associated with seal breakage. It is observed that there is a significant difference between races and sexes. The authors complain about the lack of anthropometric data available for studying the effects of secular and demographic changes. It is suspected that a substantial overlap exists in the current sizing interval for face masks and a more in-depth fit test could result in the reduction of the total number of sizes.

Oestenstad *et al.*[78] uses fluorescent tracer aerosol at the leaking sites of respirators to study their distributions. Seventy-three subjects are used to link anthropometric data with leaks. Conclusions are that 79% of the leaks occurred at the nose, 73% of leaks approximated the shape of a slit, there is a difference between the sexes, there is a significant association between facial dimensions and leak sites, the amount of leakage is higher through the chin area, and finally, that there is a correlation between facial dimensions and fit factor for three facial dimensions, none of which are used for the design of the respirator.

Hidson[79] describes experiments using CAD/CAM technology for the design of a respirator facepiece. The geometry is constructed using bi-parametric cubic patches and a three-axis NC milling machine cuts the final shape.

For a good review of human factors and safety considerations of instrumented helmets, see Rash *et al.*[80] This paper discusses a helmet equipped with a night vision system for operation in darkness or under adverse weather conditions. A large variety of topics are analyzed, such as sensor inputs, display parameters, temporal characteristics, visual acuity, field of view, environmental considerations and the effects of internal/external sources of information. Accident experiences are also carefully analyzed in the context of an improved process of helmet design.

3.4 Gloves

In industrial as well as in military environments, the realization of ideas and objectives are achieved most of the time by the actions of the hands, through the use of tools and control knobs or grips. Every day we need to use our hands to operate a variety of devices, such as door handles/latches, locking devices, sink/shower controls, appliance controls, vending machines, desk/dresser drawer handles, elevator buttons, telephones, transportation vehicle controls, computer keyboards and remote controls.

Designs related to the hands are of two types: one is the interface shapes (e.g. door handle shapes) which fit most of us, the other is for personal protection (e.g. gloves for chemical protection). Czaja[81] noted that a significant amount of the population falls in the category of people having hand disabilities (~3 million in the U.S.A.). He stressed the importance of gathering anthropometric data, not only for the adult able-bodied population, but also on a variety of users, including children, the elderly and persons with difficulties handling and fingering. Examples of people with hand disabilities are given; they are arthritics, amputees, rheumatoid patients, burn victims and persons with muscular dystrophy, cerebral palsy, multiple sclerosis and Parkinson's disease. Also listed are people with hand size extremes. The authors suggest that more data should be available to designers for the evaluation of hand controls design.

The second type of design related to hand controls is for protection. In that case, the designer has more flexibility. Indeed, various sizes can be designed to conform to the shape of the hands. The main difficulty, though, is that abilities and task performances are substantially affected by the properties of the glove material and the fit of the gloves.[82] In a sense, the user of gloves is closer to the hand-disabled population than the able population. This suggests that a better match between hand controls and a protected hand using gloves could be achieved by improved hand control designs and glove designs.

In Robinette and Annis,[83] a nine size system for chemical defense gloves is described. The program objective is to provide designers of gloves and hand forms with data for men and women in a single system. It is a two-step process: firstly, the number of sizes is established using hand length and circumference as key dimensions; second, 22 hand dimensions and multiple regression equations are used to establish the design parameters of the glove.

Hidson[84] reports a new set of anthropometric dimensions which are suggested for glove design. Fifty dimensions that can be measured by traditional techniques are proposed. The selection of those new measurements is dictated by CAD/CAM requirements. The advantage of the approach is a better match between CAD shapes and hand shapes.

Protective gloves for agricultural workers are studied in Tremblay *et al.*[85] It is observed that anthropometric data for this population of workers differs from that for the military personnel population, on which the gloves manufacturers base their designs. It is also noted that some subjects prefer tight fit while others find it unacceptable. Nineteen hand dimensions were collected on 380 Albertan grain farmers who handle pesticides. Suggested considerations for design are gender, age, ethnic origin and occupation. It is stressed that military needs and requirements often differ significantly from other occupations and that a fitting study must take that parameter into consideration.

Halioua *et al.*,[39] in a paper describing applications of the phase measuring profilometry, briefly review a two-camera system for capturing the shape of hands for the design and manufacture of gloves for astronauts. The dual view system measures the front and the back of a live hand in a single operation, matches the two views and extrapolates for the blind spots by polynomial fit. It is reported that it takes 1·5 s to measure a field of view of 30 cm with a precision of the order of 0·1 mm.

3.5 Clothing

This is the application with the most potential for both military and civilian populations. Two basic strategies have been proposed. The first is based on templates; a measuring system identifies and classes individuals in relation to these templates (interpolation is used to adapt the predefined patterns to the measured data). The second is based on the development of 3-D surfaces to conform to the human shape.

Quattrocollo and Holzer[86] are developing a 2-D template-based system where the individual data input is provided by an orthogonal silhouetting method. Back lighting and TV cameras are used to acquire full body silhouette profiles that are compared with templates. The authors have a global approach about custom clothing and anthropometric data collection for the clothing industry. It is proposed to collect anthropometric data in a cumulative manner in a database and use a computer network to share the information among manufacturers. This would give them a better knowledge about their target populations. Advantages listed are reduction of unsold stock, improvement in stock management, diminution of manufacturing times, smaller retail selling spaces and inventories, and finally, increased client satisfaction.

A 3-D version of that concept is under development in the U.S.,[39] the U.K.,[5,44] and Japan.[72] Structured light is used to digitize the shape of the human body in the context of computer-integrated manufacturing in the textile industry. Many challenges remain, such as the automation of assembly and sewing operations and all importantly, the 3-D design and manufacture of garments.

In terms of data acquisition, it takes from a few seconds to a few minutes to collect the raw 3-D coordinates and the dimensional resolution is typically a few millimetres. Filtering and processing are needed to remove measurement artifacts and to complete the data set for 360° surface description.[87] It is interesting to note that today there are no systems (except tomography) that can digitize the whole surface of the human body. Indeed, the human body shape is so complex that it would take an impractically large number of cameras to prevent any occlusion, even then there are re-entrant areas such as the inside of the arms that are virtually impossible to reveal.

Translation of 3-D data points and surfaces into a pattern is another challenge. Okabe *et al.*[88] discuss the development of a simulator that estimates the 3-D form of a garment put on a body form. The approach involves 2-D to 3-D and 3-D to 2-D processes. Parameters considered are the anisotropy of the mechanical properties of the cloth, contact and friction with the body, geometrical nonlinearity deformation and optical properties for graphic visualization. It is noted that the 3-D to 2-D process is an inverse problem that requires an interactive approach involving the user through a graphic display.

Hinds *et al.*[89] present an analytical approach to the problem of the development of doubly curved forms and examples related to the definition of 3-D form of garments. Approximations are used to reduce the complexity of patterns and strategies are proposed to optimize the design process by user feedback, again using graphic display.

Development of sizing systems based on anthropometric data has been studied by Robinette *et al.*[90] for navy women's uniforms. It is found that the main source of proportional differences in the navy women population is with black and white women. As an example, blacks require longer sleeves and pant legs for the same torso sizes than whites. The solution was to have garment lengths based on torso-to-height proportions rather than just on the height and to provide longer sleeves and leg lengths.

In Zehner *et al.*[91] a fit evaluation of an armour vest was done on 37 females. Here again the idea was to correlate anthropometric data with fitting parameters. Observations are made on subjects standing, sitting and moving around in various ways (bending and twisting). Such investigations show the importance of measurements and testing at the designing stage. Compromises must be made and it is within the context of the specific use of the garments that decisions must be taken.

Custom shoe manufacturing has also been described in Lord[92] and Lord and Travis.[93] The concept is to digitize the foot, model its shape and modify it for manufacturing. It is observed that for optimal fit the surface shape needs higher resolution in the area of high curvature around the heel. An optical scanner is used to capture 1000 x,y,z coordinates from each single view. About 2000 points are taken out of multiple views to reconstruct the entire surface of the foot. One of the features of the modelling process is to allow the user to change the position of the foot to conform to a new heel height. The modelled shape is then modified into an appropriate last shape for manufacturing.

4 COMPARATIVE MORPHOLOGY

4.1 Human morphology

The study of human morphology has the potential of improving early diagnosis of a large variety of diseases. Such an undertaking requires tools that are not yet widely available. Indeed, to build a database for the interpretation, analysis and classification of normal and abnormal morphological trends will require large-scale studies.

A good review of the evolution of tools for the study of the human morphology can be found in Sheffer and Herron.[94] Subjects treated cover data acquisition, reduction and analysis.

Smith *et al.*[95] describe a new tool in the study of human body composition. In their study they examined the usefulness of the LASS system[44] for calculating human body volume and hence density and found it correlated well ($r = 0{\cdot}97$) to the same measures by underwater weighting.

Lele and Richtsmeier[96,97] proposed a mathematical approach for comparing biological shapes using landmarks. A unique feature of the approach is the fact that it is coordinate-free.[98] An extension of the method to surface data (using surface curvature) is likely to produce interesting developments. More recently, Jones *et al.*,[87] describe a data format which can be used for description, averaging and comparision of 3-D body shapes. The same authors describe a mathematical approach to the generation of 3-D body shapes from simple anthropometric measurements.

4.2 Anthropology

Richtsmeier[99] claims that the study of forms is central to evolutionary research. Three main fields of studies are discussed: growth, speciation and sexual dimorphism. It is also shown that 3-D measurements can monitor shape variations due to dentition and puberty. Research activities are directed at the analysis of normal and abnormal growth in order to predict and diagnose malformations.

Computer tools have been developed to reconstruct human fossils.[100] It is shown, for example, that mirror imaging is very useful for matching and positioning fragments when a set is incomplete. The authors note that geometric modelling and computer visualisation provide anthropologists with both quantifiable computer-based generic (CAD) models and physical plastic reconstruction of fossils. Savara *et al.*[101] stress the importance of 3-D imaging in preserving the morphology of fossil specimens. This reduces the problem of lost specimens and makes the data available to researchers throughout the world.

4.3 Human motion analysis

Dynamic studies have been done since the invention of photography more than 100 years ago, but it is only recently that such studies have used 3-D measurements. In Allard *et al.*[102] the dynamic characteristics of the ankle are studied using stereophotogrammetry and mathematical modelling. Accuracy of 0·4 mm is reported.

Knee motion studies using 3-D measurements are also reported in Huiskes *et al.*,[103] Bougoss and Ghosh,[104] and Costigan *et al.*[105] Applications cover articular cartilage biomechanics, analysis of joint contact regions, artificial joint design and anthropometric measurements. It is noted that the studies of such anatomic–physiologic movements are essential for the therapeutical and surgical treatments so frequently needed to treat athletic injuries.

Human motion analysis has also proved useful to plan intra- and extra-vehicular space activities.[106] Stereovideo sequences are analyzed to extract 3-D coordinates of joint centers. The digitized sequence provides joint velocities and accelerations. Tests are done in an on-gravity laboratory environment, neutral buoyancy and in zero gravity on board the KC-135 jet. It is interesting to note that work on 3-D measurements of body and limb volume changes during extended space missions using photogrammetry was reported as early as 1970.[107]

4.4 Forensic imaging

Amongst the most fundamental human abilities is face recognition. This aptitude is used frequently for criminal investigation and suspect or victim identification. Nagamine *et al.*[108] report a 3-D imaging approach for automatic matching of the human face using horizontal, vertical and circular sections. Three-dimensional data images of 256 pixels × 240 pixels are obtained by a laser range finder at a resolution of 1 mm. In Russell[109] faces of missing children are computer aged in order to facilitate recognition. Although the process involves 2-D imaging, it is noted that an ideal system should allow the possibility of rotating images, a feature that 3-D imaging provides.

In a paper by Vanezis *et al.*[110] 3-D facial or skull reconstruction are realised. Two techniques are compared: a sculpting technique using clay and a 3-D computer graphics technique using a laser digitizer to input the skull shape within the computer environment. In this research, the authors want to reconstruct the appearance of a subject from an unidentified skull. Conclusions are that computer reconstruction has the advantage of allowing the generation of several faces compatible with the underlying skull and that one of the present limitations is the lack of detailed facial thickness measurements. Facial expression synthesis is also foreseen to be very important for identification.

4.5 Hearing studies

Decraemer *et al.*[111] report the use of 3-D imaging techniques to study the human tympanic membrane, especially the coupling of acoustic sound pressure in the external ear canal to the motion of the middle ear ossicle. This paper is particularly interesting for the modelling techniques used in the analysis of physical properties. The same approach could be applied to a variety of other dynamic studies related to human motion. Resolutions reported are in the order of 40 μm along the x and y axes and 5 μm along the z-axis.

5 VIRTUAL REALITY AND COMMUNICATIONS

5.1 Three-dimensional portraits

The 3-D reproduction of the human face and body dates back to very ancient times, but it is only in the last century that artists and engineers have attempted to mechanize the process. One of these processes, known as Photo Sculpture,[112] drew a lot of attention in the 1860s. The technique, invented by Francois Willéme, is reported by Newhall,[112] to replicate the human form uses 24 cameras taking pictures all around the subject. The physical reproduction process was based on projections of individual photographs and the use of a pantograph to 'sculpt' a piece of clay. Studios opened in Paris, London and New York and were in operation between 1863 to 1867. Unfortunately, the process was found to be no more easy or economical than the traditional way of making sculptures and was eventually abandoned.

With the advent of computers and electronic cameras, the process regained interest in the 1980s. Cyberware developed a 360° rotating laser profiling system and computer controlled milling for the reproduction of head and bust. The system has also been successfully used for special effects in Hollywood science fiction movies.

Vision 3D in France has pioneered a similar digitizing arrangement using laser beam profiling and Cencit[113] developed a multi-camera incoherent light projection system reminiscent of the early work of Willéme. Posing times were in the order of a few minutes in the 1860s, they are now in the order of a few seconds for a resolution of typically 1 mm. It is interesting to note that the process still requires substantial human interaction for styling and finishing.

5.2 Computer animation of human models

Visual communications are dominated by the visualisation of the human face movements and expressions. Researchers in this field of activity are developing computer graphic tools for the synthesis of expressive faces.[114–117] Applications range from low bandwidth teleconferencing, synthetic speaker and actor and human behaviour simulation.

Realism is increasing rapidly as the process is refined. Typically, a physical model is created. It contains parameters for the definition of the physical and geometrical properties of skin and muscles. The physical model is deformable[118] so it can be adapted to a 3-D digital image, including colour texture of a real individual. In Williams,[119,120] software tools are developed for digital editing and painting of 3-D images. The aim of this research is to create consistent unified methods for computer-assisted drawing, painting, modelling and animation for artists.

Mase and co–workers[121,122] describe a realtime head motion detection system for various man-machine interactions, such as virtual environment feedback and medical aids for disabled persons. The NTT Human Interface Laboratories and the ATR (Advanced Telecommunications Research Institute) in Japan are developing 2-D and 3-D facial image processing techniques for visual telecommunications.[123,124] Various deformable physically based models and digitizing techniques are proposed.[125]

6 ISSUES

6.1 Spatial definition requirements

The above review of applications of digital imaging of the human body shows clearly that spatial definition requirements are mainly related to the size of the body segments to be digitized. Scanning the shape of the cornea or the surface of a tooth necessitates sampling densities much higher than the surface of the trunk or of a leg.

Because most body segments are fairly smooth and regular in shape, we can expect that changes in surface normals are the best way to specify spatial definitions. Essentially this means that each body segment (defined in its simplest form) needs approximately the same number of samples to define its shape. As an example, a finger segment would require for its definition about the same number of samples as a leg segment or an arm segment. On the other hand, one can expect to need a higher number of samples if the head is considered as a unique segment. This is due to the very different topology of the surface of the human face as compared to other body segments.

6.2 Limitations of human subjects

The human body is a living organism in constant motion. It is subjected to variations in shape from external (gravity) and internal factors. Shape variations of a subject are induced by changes in facial expression, sway, respiration, body fluid distribution, shifts in pose, pulsation of the blood and motor reflex correction for control of postural stability. Occlusion is another limitation imposed by the complexity of whole-body topology and the large number of degrees of freedom of its segments.

Skin pigmentation and scattering properties also limit the accuracy of measurement. Because the human skin is quite transparent (especially in the red portion of the visible spectrum), most optical sensing techniques will underestimate skin elevation. Studies of optical propagation in biological tissues can be found in Grossweiner *et al.*,[126] Arnfield *et al.*,[127] Yoon *et al.*,[128] and Bolin *et al.*[129]

Lastly, hair interference is likely to be the most difficult challenge in automating body surface anthropometric measurements. The distribution and density of hair is difficult to predict, dark pigmentation demands very high dynamic range optical sensing and sampling density requirements for shape description are much too coarse to allow its resolution.

6.3 Camera limitations

Speed is presently one of the most limiting factors for human body imaging. Few approaches are able to digitize the full body at a resolution appropriate for anthropometric studies. Typically, the acquisition time is more than 10 s, which is long enough to be susceptible to most of the subject's shape variations mentioned above.

Portable devices would be ideal, especially for large population database collection, but with the exception of the NKK mobile unit, there is no easy way to transport most of the full body 3-D imaging systems described in this review.

Laser-based systems have the advantage of depth of field, but they pose eye hazards, which necessitate either protection or proper camera design. For a brief review of laser radiation hazards see Henderson.[130] Eye-safety is achievable if the laser wavelength is selected in the 1·5 μm range,[131] but the costs associated with the laser source and the optical sensing element are presently prohibitive.

Generally speaking, the technology available to digitize the human body is difficult to operate, necessitates frequent calibration and requires skilled operators to maintain performances.

7 CONCLUSIONS

From the survey of applications related to the measurement of the human body we find that at least three levels of resolution are needed: high resolution (10–100 μm) for shapes in the size range of teeth, medium resolution (100 μm–1 mm) for the face, hand and foot and low resolution (1–5 mm) for the trunk and limbs.

Many researchers complain about the lack of a database of normal and abnormal human shape measurements; this lack is seen as an impediment to the development of applications. From various sources, it is estimated that traditional anthropometric measurements cost between $50 and $500 per subject, depending on various factors such as the number of parameters measured, the number of sites visited, the constraint on time and the sample size. There is no need to explain why large scale-surveys are almost non-existent. Databases are sometimes collected by people having very little training in the proper use of the equipment and appropriate research methods. In some cases improper equipment is used impairing the reliability of the data collected. It has been also documented that there are large inter- and intra-observer variations between anthropometrists[73] when taking tradional measurements. A cost analysis using surface imaging may be appropriate at this time. We must establish it for the size of the sample and also for the number of parameters to be collected and interrogated. With a fully automated system, it may be more cost effective to measure thousands of individuals rather than hundreds.

We also find that some applications require only a single view recording, such as in the study of the back in spinal disorders, in the fitting of face masks and in a number of prosthetic interface fittings. However, most applications would benefit from multiple views with a minimum of a front and a back view. For more surface coverage, three or more views may be needed. Moreover, it is clear that no current surface imaging system will be able to digitize 100% of the body's surface, especially in cases where the user wants to make recordings with the subject in different postures. The human shape is too complex and possesses too many degrees of freedom to devise a practical 100% surface collection digitizing system.

Nevertheless, it is abundantly clear that 3D imaging can produce useful information, extending way beyond that which can be derived using earlier simple anthropometric techniques, for a multitude of differing applications.

REFERENCES

1. Borelli, G. A., *De Motu Animalium*. Lugduni Batvorum, 1680–1.
2. Martin, R., *Lehrbuch der Anthropologie*, 2nd edn, Vol. 3. Fischer, Jena, 1928.
3. Sheldon, W. H., Stevens, S. S. & Tucker, W. B., *The Varieties of Human Physique: An Introduction to Constitutional Psychology*. Hafner, New York, 1940.
4. Lovesey, E. J., A method of determining facial contours by shadow projection. Royal Aircraft Establishment Technical Report no. 66192, 1966.
5. Jones, P. R. M., West, G. M. & Brooke-Wavell, K. F., Interrogation of 3D body data for applications in manufacturing industries. In *Application of Computers to Manufacturing Engineering, Directorate of the Science and Engineering Research Council, Research Conf. Proc.*, Sheffield University, 1993, pp. 20–25.
6. Meaney, F. J. & Farrer, L. A., Clinical anthropometry and medical genetics: A compilation of body measurements in genetic and congenital disorders. *Am. J. Med. Genet.*, **25**(2) (1986) 343–359.
7. Hiritz, R. J., Thomas, T. T. & Merchant, R. K., Delineation of craniofacial abnormalities of the fetal alcohol syndrome by close range photogrammetry. *Proc. American Society for Photogrammetry and Remote Sensing*, 1986, pp. 101–109.
8. Takamoto, T. & Schwartz, B., Biostereometrics in ophthalmology: topographic analysis of the optic disc cup in glaucoma. *SPIE Proc. Biostereometrics*, **602** (1985) 219–227.
9. Laurendeau, D., Guimond, L. & Poussart, D., A computer-vision technique for the acquisition and processing of 3-D profiles of dental imprints: an application in orthodontics. *IEEE Trans. Med. Imaging*, **10**(3) (1991) 453–461.
10. Côté, J., Laurendeau, D. & Poussart, D., A multi-operator approach for the segmentation of 3-D images of dental imprints. *Proc. Vision Interface* '91, Calgary, Alberta, 1991, pp. 189–196.
11. Craxford, A. D., Rutherford, A. & Evans, M. S., Stereophotogrammetry and relief photography in assessment of foot disorders. *Ann. Rheumatic Dis.*, **40**(1) (1981) 83–86.
12. Houghton, G. R., Jefferson, R. J., Thomas, D. C., Harris, J. D. &

Turner-Smith, A. R., Effects of scoliosis surgery on back shape. *Surface Topography and Spinal Deformity: Proc. 4th Int. Symp.*, eds I. A. F. Stokes, J. R. Pekelsky & M. S. Moreland, Mont Sainte Marie, Québec. Fischer, Stuttgart, 1987, pp. 29–34.

13. Vannier, M. W., Pilgram, T., Bhatia, G. & Brunsden, B., Facial surface scanner. *IEEE Comput. Graphics Appl.*, **11**(6) (1991) 72–80.
14. Linney, A. D., Grindrod, S. R., Arridge, S. R. & Moss, J. P., Three-dimensional visualisation of computerized tomography and laser scan data for the simulation of maxillo-facial surgery. *Med. Informatics*, **14**(2) (1989) 109–121.
15. Linney, A. D., Tan, A. C. Richards, R., Coombes, A. M., Gardener, J. & Lees, W. R., The acquisition, visualisation and applications of three-dimensional data on the human body. *Proc. Electronic Imaging of the Human Body Workshop*, Dayton, Ohio, 1992, pp. 38–48.
16. Moss, J. P., Grindrod, S. R., Linney, A. D., Arridge, S. R. & James, D., A computer system for the interactive planning of maxillofacial surgery. *Am. J. Orthodontics Dentofacial Orthopedics*, **94**(6) (1988) 469–475.
17. Coombes, A. M., Moss, J. P., Linney, A. D., Richards, R. & James, D. R., A mathematical method for the comparison of three-dimensional changes in the facial surface. *Eur. J. Orthodontics*, **13** (1991) 95–110.
18. Meadows, D. M., Johnson, W. O. & Allen, J., Generation of surface contours by Moiré patterns. *Appl. Opt.*, **9** (1970) 942–947.
19. Turner-Smith, A. R., Television scanning technique for topographic body measurements. *SPIE Proc. Biosteriometrics*, **361** (1982) 1–5.
20. Schofield, J., Mapping the human curve. *Comput. Guardian*, **7 April** (1988).
21. Moreland, M. S., Pope, M. H. & Armstrong, G. W. D., eds, *Moire Fringe Topography and Spinal Deformity: Proc. Int. Symp.* Pergamon Press, Oxford, 1981.
22. Drerup, B., Frobin, W. & Hierholzer, E., eds, *Moiré Fringe Topography and Spinal Deformity: Proc. 2nd Int. Symp.*, Münster, West Germany, 1983. Fischer, Stuttgart.
23. Harris, J. D. & Turner-Smith, A. R., eds, *Surface Topography and Spinal Deformity: Proc. 3rd Int. Symp.*, Oxford. Fischer, Stuttgart, 1986.
24. Stokes, I. A. F., Pekelsky, J. R. & Moreland, M. S., eds, *Surface Topography and Spinal Deformity: Proc. 4th Int. Symp.*, Mont Sainte Marie, Québec. Fischer, Stuttgart, 1987.
25. Neugebauer, H. & Windischbauer, G., eds, *Surface Topography and Spinal Deformity: Proc. 5th Int. Symp.*, Wein. Fischer, Stuttgart, 1990.
26. Halioua, M., Liu, H. C., Chin, A. & Bowins, T. S., Automated topography of human forms by phase measuring profilometry and modal analysis. *Surface Topography and Spinal Deformity: Proc. 5th Int. Symp.*, Wein, eds H. Neugebauer & G. Windischbauer. Fischer, Stuttgart, 1990, pp. 91–100.
27. Swain, I. D., Daunt, S.O-N., Robertson, J. C. & Isherwood, P. A., Dynamic moire topography for the determination of postural asymmetry. *Surface Topography and Spinal Deformity: Proc. 3rd Int. Symp.*, Oxford. J. D. Harris & A. R. Turner-Smith eds. Fischer, Stuttgart, 1986, pp. 77–83.
28. Kováts, F. Jr, Böszörményi-Nagy, G., Nagy, G. G. & Ôrdîg, L., Morphometry upright trunk during breathing. *SPIE Proc., Biostereometrics*, **1030** (1988) 255–262.

29. Lewis, J. R. T. & Sopwith, T., Three-dimensional surface measurement by computer. *Image Vision Comput.*, **4 August** (1986) 3.
30. Kováts, F. Jr., Age and chest-wall physiology. *SPIE Proc., Biostereometrics*, **602** (1985) 257–261.
31. Adams, L. P., Rüther, H. & Klein, M., Development of a PC-based near real time photogrammetry system for evaluating regional body surface motion during breathing. *SPIE Proc., Biostereometrics*, **1030** (1988) 352–360.
32. Gourlay, A. R., Kaye, G., Dennison, D. M., Peacock, A. J. & Morgan, M. D. L., Analysis of an optical mapping technique for lung function studies. *Comput. Biol. Med.*, **14**(1) (1984) 47–58.
33. Duret, F. & Blouin, J.-L., De l'empreinte optique à la conception et la fabrication assistées par ordinateur d'une couronne dentaire. *J. Dentaire Québec*, **XXIII** (1986) 177–180.
34. Yeung, M., Wu, C. J., Liontas, H., Chartier, P., Orban, P., Lavelle, C., Jordan, R., Domey, J. & Rioux, M., An automated posterior dental restoration system—preliminary results. *The Canadian Medical and Biological Engineering Society Conf. Proc.*, Winnipeg, Manitoba, 1990, pp. 117–118.
35. Siemens, 1989.
36. Altschuler, B. R., Remote 3-D laser topographic mapping with dental application. *SPIE Proc., Biostereometric Technol. Appl.*, **1380** (1990) 238–247.
37. Saunders, C. G., Reconstruction of anatomical shapes from moire contourographs. *SPIE Proc., Biostereometrics* '82, **361** (1982) 99–106.
38. Duncan, J. P., Anatomical definition and modelling. *Engng Med.*, **15**(3) (1986) 109–116.
39. Halioua, M., Liu, H. C., Bowins, T. S. & Shih, J. K., Automated topography of human forms by phase-measuring profilometry. *Surface Topography and Spinal Deformity: Proc. 6th Int. Symp.*, Estoril, eds A. Alberti, B. Drerup, & E. Hierholzer. Fischer, Stuttgart, 1992, pp. 6–16.
40. Pho, R. H. W., Lim, S. Y. E. & Pereira, B. P., Computer Applications in Orthopaedics, *Ann. Acad. of Med.*, Singapore, **19**(5) (1990) 691–698.
41. Bok, S. H., Bhattacharjee, A., Nee, A. Y., Pho, R. W., Teoh, S. H. & Lim, S. Y., Computer aided design and computer-aided manufacture (CAD-CAM) applications in cosmetic below-elbow prostheses. *Ann. Acad. Med., Singapore*, **19**(5) (1990) 699–705.
42. Sheffer, D. B., Herron, R. E., Morek, W. M. & Proietti-Orlandi, F., Stereophotogrammetric method for breast cancer detection. *SPIE Proc., Biostereometrics*, **361** (1982) 120–124.
43. Sheffer, D. B., Price, T. E. Jr & Loughry, C. W., Reliability of a photogrammetric determination breast-thorax boundary. *SPIE Proc., Biostereometrics*, **602** (1985) 196–203.
44. Jones, P. R. M., West, G. M., Harris, D. H. & Read, J. B., The Loughborough anthropometric shadow scanner LASS. *Endeavour*, **13**(4) (1989) 162–168.
45. Neugebauer, H. & Windischbauer, G., School screening: A new pilot study in Vienna. *Surface Topography and Spinal Deformity: Proc. 4th Int. Symp.*, eds I. A. F. Stokes, J. R. Pekelsky & M. S. Moreland Mont Sainte Marie, Québec. Fischer, New York, 1987, pp. 177–186.

46. Batouche, M., A knowledge based system for diagnosing spinal deformations: Moiré pattern analysis and interpretation. *Proc. 11th IAPR Int. Conf. Pattern Recognition. Conf. A: Computer Vision and Applications*, The Hague, The Netherlands. Vol. I, 1992, pp. 591–594.
47. Mehta, M. H., Moire topography and associated asymmetries in scoliosis. *Moire Fringe Topography and Spinal Deformity: Proc. Int. Symp.*, eds M. S. Moreland, M. H. Pope & G. W. D. Armstrong. Pergamon Press, Oxford, 1981, pp. 198–189.
48. Jensen, R. K. & Nassas, G., A mixed longitudinal description of body shape growth. *SPIE Proc., Biostereometrics* '85, **602** (1985) 130–135.
49. Jensen, R. K., Body segment mass, radius, and radius of gyration proportions of children. *J. Biomech.*, **19**(5) (1986) 359–368.
50. Jensen, R. K., The growth of children's moment of inertia. *Med. Sci. Sports Exercise*, **18**(4) (1986) 440–445.
51. Jensen, R. K., Growth of estimated segment mass between four and sixteen years. *Human Biol.*, **59** (1987) 173–189.
52. Richtsmeier, J. T., Beyond morphing: visualization to predict a child's skull growth. *Adv. Imaging*, **24 July** (1993) 26–27.
53. Moss, J. P., Linney, A. D., Grindrod, S. R. & Mosse, C. A., A laser scanning system for the measurement of facial surface morphology. *Opt. Lasers Engng*, **10** (1989) 179–190.
54. Jones, P. R. M., Baker, A. J., Hardy, C. J. & Mowat, A. P., Measurement of body surface area in children with liver disease by a novel 3-D body scanning device. *Eur. J. Appl. Physiol.*, **68** (1994) 514–518.
55. Haycock, G. B., Schwartz, G. J. & Wisotsky, D. H., Geometric methods of measuring body surface area: a height–weight formula validated in infants, children and adults. *J. Pediatrics*, **93** (1978) 62–66.
56. Dunn, S. M., Keizer, R. L. & Yu, J., Measuring the area and volume of the human body with structured light. *IEEE Trans. Sys. Man Cybernetics*, **19** (1989) 1350–1364.
57. Karras, G. E. & Tympanidis, K. N., Studying abdomen size and shape variations during pregnancy: an application of moire topography. *SPIE Proc., Biostereometrics*, **361** (1982) 89–91.
58. Karras, G. E. & Tympandis, K. N., Measuring changes in posture during pregnancy. *Surface Topography and Spinal Deformity: Proc. 4th Int. Symp.*, eds I. A. F. Stokes, J. R. Pekelsky & M. S. Moreland, Mont Sainte Marie, Québec. Fischer, Stuttgart, 1987, pp. 131–138.
59. Easterly, J. A., Crew Chief: a model of a maintenance technician. Report AFHRL-TP-90-18, National Technical Information Service. U.S. Dept of Commerce, 1990.
60. McDaniel, J. W. & Askren, W. B., Computer-aided design models to support ergonomics. Report AAMRL-TR-85-075, National Technical Information Service, Springfield, Virginia, 1985.
61. Yang, Thalmann & Thalmann 3D garment design and animation—a new design tool for the garment industry. *Comput. Ind.*, **19** (1992) 185–191.
62. Bapu, P., Korna, M. & McDaniel, J., User's guide for combiman programs (COMputerized Biomechanical MAN-Model), Version 6. Report UDR-TR-83-51, AFAMRL-TR-83-097, National Technical Information Service, U.S. Dept of Commerce, 1983.

63. Paquette, S. P., Human analogue models for computer-aided design and engineering applications. Report NATICK/TR/90/054, National Technical Information Service, U.S. Dept of Commerce, 1990.
64. Symington, L. E. & Gordon, C. C., 1989. Applied MANPRINT research: The 1988 US Army Anthropometric Survey (ANSUR). *Proc. Ergonomics Society's* 1989 *Annual Conf.*, ed. E. D. Megaw, Reading, England, pp. 326–329.
65. McConville, J. T., & Clauser, C. E., An anthropometric data bank, its hidden dimensions. In *Anthropometry and Biomechanics, Theory and Applications*, eds R. Easterby, K. H. E. Kroemer, & D. B. Chaffin. Plenum Press, New York, 1980, pp. 35–42.
66. McConville, J. T., Clauser, C. E., Churchill, T. D., Cuzzi, J. & Kaleps, I., Anthropometric relationships of body and body segment moments of inertia. Final report AFAMRL-TR-80-119, National Technical Information Service, U.S. Dept of Commerce, 1980.
67. Young, J. W., Chandler, R. F., Snow, C. C., Robinette, K. M., Zehner, G. F. & Lofberg, M. S., Anthropometric and mass distribution characteristics adult female. Report FAA-AM-83-16, National Technical Information Service, U.S. Dept of Commerce, 1983.
68. Greiner, T. M. & Gordon, C. C., Assessment of long-term changes in anthropometric dimensions: secular trends of U.S. army males. Report NATICK/TR-91/006, National Technical Information Service, U.S. Dept of Commerce, 1990.
69. Dickson, K. J., Space human factors publications: 1980–1990. Report NAS1.26:4351; NASA-CR-4351, National Technical Information Service, U.S. Dept of Commerce, 1991.
70. Fowkes, R. S. & Aiken, E. G., Human factors in mining search system. Report BUMINES-IC-9243, National Technical Information Service, U.S. Dept of Commerce, 1990.
71. Rider, J. P. & Unger R. L., Human factors model concerning the man-machine interface of mining crewstations. *Proc. NASA Conf. Space Telerobotics*, Vol. 1, 1989, pp. 119–127.
72. Uesugi, M., Three-dimensional curved shape measuring system using image encoder. *J. Robotics Mechatronics*, **3**(3) (1991) 190–195.
73. Brooke-Wavell, K. F., Jones, P. R. M. & West, G. M., Reliability and repeatability of 3-D body scanner (LASS) measurements compared to anthropometry. *Ann. Human Biol.*, **21**(6) (1994) 571–577.
74. Roebuck, J. A., Calibration, validation, and evaluation of scanning systems: anthropometric issues and recommendations for electronic imaging. *Proc. Electronic Imaging Human Body Workshop*, Dayton, Ohio, 1992, pp. 131–146.
75. Hall, P. S. & Campbell, B. L., Helmet-mounted systems technology planning for the future. *SPIE Proc.*, **1695** (1992) 2–8.
76. Robinette, K. M., Anthropometry for HMD design. *SPIE Proc.*, **1695** (1992) 138–145.
77. Case, H., Erving, C. & Robinette, K. M., Anthropometry of a fit test sample used in evaluating the current and improved MCU-2/P masks, Report AAMRL-TR-89-009, National Technical Information Service, U.S. Dept of Commerce, 1989.

78. Oestenstad, R. K., Dillon, H. K. & Perkins, L. L., Distribution of faceseal leak sites on half-Mask respirators and their association with facial dimensions. National Institue for Occupational Safety and Health, Cincinnati, Ohio, 1990.
79. Hidson, D. J., Computer-aided design of a respirator facepiece model. Report DREO-902, National Technical Information Service, U.S. Dept of Commerce, 1984.
80. Rash, C. E., Verona, R. W. & Crowley, J. S., Human factors and safety considerations of night vision systems flight using thermal imaging systems. *SPIE Proc.*, **1290** (1990) 142–164.
81. Czaja, S., Hand anthropometrics. Technical paper with comments, PC A04/MF A01, National Technical Information Service, U.S. Dept of Commerce, 1983.
82. Robinette, K. M., Ervin, C. & Zehner, G. F., Dexterity testing of chemical defense gloves. Report AAMRL-TR-86-021, National Technical Information Service, U.S. Dept of Commerce, 1986.
83. Robinette, K. M. & Annis, J. F., Nine-size system for chemical defense gloves. Report AAMRL-TR-86-029, National Technical Information Service, U.S. Dept of Commerce, 1986.
84. Hidson, D., Development of a standard anthropometric dimension set for use in computer-aided glove design. Technical Report DREO-TN-9122, National Technical Information Service, U.S. Dept of Commerce, 1991.
85. Tremblay, J. F., Crown, E. M. & Rigakis, K. B., Anthropometric analysis of fit problems in chemical protective gloves. In *Performance of Protective Clothing*, Vol. 4, ASTM Special Technical Publication no. 1133, eds J. P. McBriarty & N. W. Henry. American Society for Testing and Materials, Philadelphia, PA, 1992, pp. 634–650.
86. Quattrocolo, S. & Holzer, K., Calibration, validation, and evaluation of scanning systems: Project MIDA anthropometrical identification machine. *Proc. Electronic Imaging Human Body Workshop*, Dayton, Ohio, 1992, pp. 124–130.
87. Jones, P. R. M., Li, P., Brooke-Wavell, K. F. & West, G. M., Format for human body modelling from 3-D scanning. *Int. J. Clothing Sci. Technol.*, **71** (1995) 514–518.
88. Okabe, H., Imaoka, H., Tomiha, T. & Niwaya, H., Three-dimensional apparel CAD system. *Comput. Graphics*, **26**(2) (1992) 105–110.
89. Hinds, B. K., McCartney, J. & Woods, G., Pattern development for 3D surfaces. *Comput.-Aided Des.*, **23**(8) (1991) 583–592.
90. Robinette, K. M., Mellian, S. A. & Ervin, C. A., Development of sizing systems for navy women's uniforms. Report NCTRF-TR-183, National Technical Information Service, U.S. Dept of Commerce, 1990.
91. Zehner, G. F., Ervin, C., Robinette, K. M. & Daziens, P., Fit Evaluation of female body armor. Report AAMRL-TR-87-046, National Technical Information Service, U.S. Dept of Commerce, 1987.
92. Lord, M., Foot shape representation for a CAD application. *Surface Topography and Spinal Deformity*: *Proc. 4th Int. Symp.*, eds I. A. F. Stokes, J. R. Pekelsky & M. S. Moreland, Mont Sainte Marie, Québec. Fischer, Stuttgart, 1987, pp. 293–300.
93. Lord, M. & Travis, R. P., Surface modelling the foot from OSIRIS scans.

Surface Topography and Spinal Deformity: *Proc.* 5*th Int. Symp.*, eds H. Neugebauer & G. Windischbauer, Wein. Fischer, Stuttgart, 1990, pp. 227–230.

94. Sheffer, D. B. & Herron, R. E., Biostereometrics. In *Non-topographic Photogrammetry*, 1989, pp. 359–366.
95. Smith, S. H., Jones, P. R. M. & West, G. M., 3-D scanning: a new tool in the study of human body composition. *Ann. Human Biol.*, **17**(4) (1990) 340.
96. Lele, S. & Richtsmeier, J. T., Euclidean distance matrix analysis: a coordinate-free approach for comparing biological shapes using landmark data. *Am. J. Phys. Anthropology*, **86** (1991) 415–427.
97. Lele, S. & Richtsmeier, J. T., On comparing biological shapes: detection of influential landmarks. *Am. J. Phys. Anthropology*, **87** (1992) 49–65.
98. Richtsmeier, J. T. & Lele, S., A coordinate-free approach to the analysis of growth patterns: models and theoretical considerations. *Biol. Rev.*, **68** (1993) 381–411.
99. Richtsmeier, J. T. Applications of finite-element scaling analysis in primatology. *Folia Primatol.*, **53** (1989) 50–64.
100. Kalvin, A. D., Dean, D., Hublin, J.-J. & Braun, M., Visualization in anthropology: reconstruction of human fossils from multiple pieces. *Proc. of Visualization* '92, Boston, MA, 1992, pp. 404–410.
101. Savara, B. S., Steen, J. C. & Vannier, M. W., Applications of biostereometrics to biomedical and anthropological research. *SPIE Proc., Biostereometrics*, **602** (1985) 148–153.
102. Allard, P., Nagata, S. D., Duhaime, M., Labelle, H. & Murphy, N., Ankle kinematics described by means of stereophotogrammetry and mathematical modelling. *SPIE Proc., Biostereometrics*, **602** (1985) 187–194.
103. Huiskes, R., Kremers, J., de Lange, A., Woltring, H. J., Selvik, G. & van Rens, Th. J. G., Analytical stereophotogrammetric determination of three-dimensional knee-joint geometry. *J. Biomech.*, **18**(8) (1985) 559–570.
104. Bougoss, M. & Ghosh, S. K., A study of human knee by using close-range photogrammetry. *SPIE Proc., Biostereometrics*, **602** (1985) 179–186.
105. Costigan, P. A., Wyss, U. P., Deluzio, K. J. & Li, J., Semiautomatic three-dimensional knee motion assessment system. *Med. Biol. Engng Comput.*, **30** (1992) 343–350.
106. Probe, J. D., Quantitative assessment of human motion using video motion analysis. *Proc. Third Annual Workshop on Space Operations Automation and Robotics* (*SOAR* 1989), NASA, Lyndon B. Johnson Space Center, 1990, pp. 155–157.
107. Herron, R. E., Cuzzi, J., Bender, M. J. & Hugg, J. E., Stereometric measurement of body and limb volume changes during extended space missions. *Soc. Franc. Photogram. Paris*, **40** (1970) 45–50.
108. Nagamine, T., Uemura, T. & Masuda, I., 3D facial image analysis for human identification. *Proc.* 11*th IAPR Int. Conf. Pattern Recognition. Conf. A*: *Computer Vision and Applications*, The Hague, The Netherlands. Vol. I, 1992, pp. 324–327.
109. Russell, P. D., Image processing offers hope in the search for missing children. *Adv. Imaging*, **5**(11) (1990) 46–68.
110. Vanezis, P., Blowes, R. W., Linney, A. D., Tan, A. C., Richards, R. & Neave, R., Application of 3-D computer graphics for facial reconstruction

and comparison with sculpting techniques. *Forensic Sci. Int.*, **42** (1989) 69–84.
111. Decraemer, W. F., Dirckx, J. J. J. & Funnell, W. R. J., Shape and derived geometrical parameters adult, human tympanic membrane measured with a phase-shift moiré interferometer. *Hearing Res.*, **51** (1991) 107–122.
112. Newhall, B., Photosculpture. *Image*, **7**(5) (1958) 100–105.
113. Grindon, J. R., Non-contact 3-D surface digitization human head. *NCGA* '89, Vol. I. Philadelphia, PA, 1989, pp. 132–141.
114. Waters, K. & Terzopoulos, D., The computer synthesis of expressive faces. *Phil. Trans. R. Soc. Lond. B*, **335** (1992) 87–93.
115. Terzopoulos, D. & Waters, K., Physically-based facial modelling, analysis, and animation. *J. Visualization Comput. Animation*, **1**(2) (1990) 73–80.
116. Terzopoulos, D. & Waters, K., Analysis of facial images using physical and anatomical models. *Proc. Third Int. Conf. Computer Vision*, Osaka, Japan, 1990, pp. 7270–7232.
117. Carignan, M., Yang, Y., Magnenat Thalmann, N. & Thalmann, D. Dressing animated synthetic actors with complex deformable clothes. *Comput. Graphics*, **26**(2) (1992) 99–104.
118. Lee, Y., Terzopoulos, D. & Waters, K., Constructing physics-based facial models of individuals. *Proc. Graphics Interface* '93, Toronto, Ontario, 1993, pp. 1–8.
119. Williams, L., 3D paint. Report ACM D89 791-351-5/001/0003/0225, 1990, pp. 225–233.
120. Williams, L., Performance-driven facial animation. *Comput. Graphics*, **24**(4) (1900) 235–244.
121. Mase, K., Suenaga, Y. & Akimoto, T., Head reader: a head motion understanding system for better man-machine interaction. *Proc. IEEE Int. Conf. Systems, Man, and Cybernetics*, Vol. 3, 1987, pp. 970–974.
122. Mase, K., Watanabe, Y. & Suenaga, Y., A realtime head motion detection system. *SPIE Proc.*, **1260** (1990) 262–269.
123. Zheng, J. Y. & Kishino, F., 3D models from contours: further identification of unexposed areas. *Proc. 11th IAPR Int. Conf. Pattern Recognition. Conf. A: Computer Vision and Applications*, The Hague, The Netherlands, Vol.I, 1992, pp. 349–353.
124. Delingette, H., Watanabe, Y. & Suenaga, Y., Simplex based animation. In N. Thalmann and D. Thalmann, editors, *Models and Techniques in Computer Animation* (*Computer Animation* '93), pp. 13–28. Springer-Verlag, May 1993.
125. Advanced Telecommunications Research Institute International Artificial Intelligence Department 1991–92 Annual Report, 1992.
126. Grossweiner, L. I., Karagiannes, J. L., Johnson, P. W. & Zhang, Z., Gaussian beam spread in biological tissues. *Appl. Opt.*, **29**(3) (1990) 379–383.
127. Arnfield, M. R., Tulip, J. & McPhee, M. S., Optical propagation in tissue with anisotropic scattering. *IEEE Trans. Biomed. Engng*, **35**(5) (1988) 372–381.
128. Yoon, G., Welch, A. J., Motamedi, M. & van Gemert, M. C. J., Development and application of three-dimensional light distribution model for laser irradiated tissue. *IEEE J. Quantum Electronics*, **QE-23**(10) (1987) 1721–1733.

129. Bolin, F. P., Preuss, L. E., Taylor, R. C. & Sandu, T. S., A study of the three-dimensional distribution of light (632·8 nm) in tissue. *IEEE J. Quantum Electronics*, **QE-23**(10) (1987) 1734–1738.
130. Henderson, A. R., Laser radiation hazards. *Opt. Laser Technol.*, **April** (1984) 75–80.
131. Rioux, M., Beraldin, J. A., O'Sullivan, M. & Cournoyer, L., Eye-safe laser scanner for range imaging. *Appl. Opt.*, **30**(16) (1991) 2219–2223.