Advances in Photogrammetry, Remote Sensing and Spatial Information Sciences:
2008 ISPRS Congress Book – Li, Chen & Baltsavias (eds)
© 2008 Taylor & Francis Group, London, ISBN 978-0-415-47805-2

CHAPTER 31

Medical applications

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ABSTRACT: The wide variety of uses of measurements from imagery to provide spatial information for medicine and human sciences is categorized into three distinct groups. The first category of applications involves surface shape measurement of any part of the body, whether very small or large. It is now commonly undertaken by laser scanning and structured light measurement, and finds uses in plastic surgery, reconstructive medicine, orthopaedics, prosthetics orthodontics and other dentistry, dermatology and cosmetics. The second group involves the recording of the human body in motion, which is widely used predominantly but not solely for studies of walking people. The third group represents the most novel application: the surgical use of real-time measurement to precisely position surgical instruments and prostheses in the operating theatre. The latter two fields are distinguished from the first by being well suited to conventional photogrammetric triangulation using camera imagery in conjunction with the matching of features in the images. This chapter identifies the main challenges in these three groups, specifies the technical features which characterize each, and records some of the applications for purposes involving human beings.

Keywords: Medical photogrammetry, body motion tracking, body surface scanning, surgical procedures

31.1 INTRODUCTION

Photogrammetrists who are interested in applications in human measurement will find that there are many papers in this field, and they are found in both biomedical and photogrammetric journals. They will also find that the authors have a variety of backgrounds, including medical, engineering and photogrammetry. The papers show that some of the photogrammetric systems are intended for short term medical use, others are used over longer terms; some systems emphasize simplicity and low cost while others are more sophisticated. To understand the distinctive characteristics and challenges of medical photogrammetric measurement, it is useful to first recognize some of the more common uses. Motion tracking, typically of the whole body but sometimes of just a part of the body, seems to dominate current applications. There is also a demand for static measurement of certain body regions, the back, the entire head, face, female breast, the hand, arm and foot, undertaken for disease detection, treatment, prosthesis fitting, anatomical research, ergonomic studies and so on. Occasionally, there is a requirement for measuring smaller and very specialized body areas such as the eye, ear, and teeth, or part of the skin in the location of melanoma or wound. Finally, it is important to recognize the current major challenges faced in the dynamics of surgical monitoring in which the goal is to guide the surgeon during surgical interventions.

The aim of medical photogrammetry is to assist in health matters, usually related to a disease and its detection, treatment or monitoring, but perhaps also related to disease avoidance as in the case of sports and ergonomic studies. Medical measurement necessarily involves human beings as subjects for imaging, and humans have certain characteristics that require consideration. Unlike inanimate objects, humans need physical comfort, and do not want to be left in one fixed or unnatural position, especially for an unspecified length of time. Humans also have a range of requirements for mental comfort, including at times the need for privacy and confidentiality.

Although each type of medical measurement faces its own challenges, there are certain distinctive and common photogrammetric characteristics. Body parts are never simple geometric shapes, and the measurement task is generally to define surface shape, and not to detect edges or to locate characteristic points as may be required in industrial measurement, for example.

Also, body surfaces are notoriously free from good natural targets, so that for imaging purposes the surfaces of interest must somehow be given texture. At the photographic stage, the imaging is invariably synchronous, the various cameras being held fixed, and so multiple cameras are needed. Fortunately for the photogrammetrist, accuracy requirements are generally not as high as in other areas of photogrammetry such as industrial measurement.

31.2 SENSORS AND DATA ACQUISITION

31.2.1 *Human motion tracking*

Human motion recording by photogrammetry is used primarily to observe the movement of the entire human body, mostly for gait analysis, but it is also used to record people involved in sporting activity. Less commonly, motion recording by photogrammetry concerns movements of regions less than the entire body. Recording of movement creates severe photographic challenges. In the most common cases, a person, often shrouded with targets, is imaged moving at a relatively high speed while using actions that cause the occlusion of the targets. A stream of confusing imagery may be collected from a number of cameras, so that the subsequent analysis requires photogrammetric systems that are sophisticated, and hence may also be relatively expensive. However, the demand for this type of measurement is high, and a number of advanced photogrammetric systems are available commercially. (The commercial systems also find use in health related, e.g. ergonomic, studies and even in the entertainment industry.)

The extensive commercial involvement in motion recording has meant that reports of applications are widespread but technical details not common. Nor do commercial websites provide the underlying photogrammetric theory and practice, which might interest the photogrammetric reader. In a number of cases, however, technical detail has been reported during a photogrammetric motion recording system's development stage. Consequently, papers reporting the photogrammetric facts can seem to be dated, but they are nevertheless important reports of the developments in that era; see e.g. Ferrigno & Pedotti (1985) and Walton (1990).

Movement recording systems require a number of cameras in order to both ensure patient coverage and to cope with occluded targets. High frame rates are necessary, often rates higher than the 30 images per second typically encountered with common cameras. Targets are normally placed on the subjects, both passive and active targeting being used. The technical features of the many available motion recording systems have been compared by, e.g. Ehara et al. (1995, 1997) and more recently by Richards (1999), who refers to eight systems, which use up to about 30 cameras observing up to 500 targets. The relative accuracies of point measurement are typically 0.1 to 1 mm. Information about the current versions of the systems referred to by Richards are provided by commercial websites: Ariel Dynamics (2008), Charnwood Dynamics Ltd. (2008), BTS SpA (2008), Motion Analysis Corporation (2008), Northern Digital Inc. (2008), Peak Performance (2008), Qualisys AB (2008) and Vicon Motion Systems (2008), while references can be found to yet other systems, e.g. Biogesta (2008) and Phoenix Technologies (2008). It is now relatively rare to find reports of the use of motion analysis systems other than those of commercial origin, but some developments can be noted. A development by Garrido Castro et al. (2006) contrasts with commercial systems referred to above, because the system is intended to be low-cost, with off-line processing involving percentages of manual digitizing. It also aims to be used without wired targets to provide greater versatility, such as outdoors.

Calibration of motion recording systems is a crucial matter, and techniques are included in the comparison by Richards (1999).

31.2.2 *Human body surface scanning*

Laser scanning and structured light projection represent the optical measurement technologies mostly employed for the three-dimensional digitizing of the surface of the human body.

They are both based on the same rule, namely triangulation, in the way that light structures (normally in the form of stripes) are projected onto the human body, with light sensors acquiring the scene; by known geometry of the set-up, 3-D information can then be drawn from the imaged data.

The difference between the two methods resides in the way the light structure is projected and imaged. By laser scanning, laser light sources are used to project on the human body one or multiple thin and sharp stripes (see Fig. 31.1 on the left). To assure the inoffensiveness of the light beam, only eye-safe lasers are employed. A laser scanning unit is composed of the laser light source, the optical system and the light sensor (variations are possible also in the number of employed laser sources and light sensors). The unit is moved across the human body to digitize the surface. The type of movement and the number of employed units can vary depending on the human body parts to be measured. For example, full body scanners are usually composed of three or four scanner units that move vertically synchronously along three or four pillars placed around the person.

The high costs of producing hardware components for laser scanning technology have to be considered as a disadvantage. Additionally to the laser, the light sensor and the optical system, precise electric motors also have to be used for the displacement of the scanner units. Moreover, the complete scanner system has to be calibrated so that the geometrical disposition of all the elements can be determined exactly. A second disadvantage of this method is the time required for the digitizing of large surfaces, as movements and displacements of the person occurring during the scanning process lead to noise and measurement errors in the resulting data. There is no problem for the measurement of extremities such as feet and hands, since these body parts can be kept immobile for some seconds. But in the case of the measurements of head or full body, it is practically impossible to stay immobile for several seconds. Additionally, uncontrolled movements such as breathing or muscle contraction have also to be considered.

The second technology used extensively for human body measurement is based on the projection of light patterns. It comes closer to the solution of the problems described above. Instead of moving the scanning unit, a light pattern (usually in the form of a bundle of stripes) is projected onto the entire interested area of the human body (see Fig. 31.1 right), where a light sensor (usually a digital camera) acquires the scene. In this case, the scanning device is usually composed of a white light projector and a camera. More complex systems employ multiple light sensors and/or multiple projectors. The measurement process is similar to the method of laser scanning: stripes on the surface are measured singularly by triangulation. The difference is that this happens in a single step allowing the entire surface to be digitized by a single acquisition. For the increment of the resolution, the projected stripes may be shifted and multiple scenes acquired.

The short time of the scanning process (mostly under one second) reduces the problems caused by uncontrolled movements of the person during the measurement process. However, to measure large parts of the human body (e.g. entire head or full body), multiple scanning devices are required. This procedure has the disadvantage that multiple units cannot be used simultaneously since they interfere with each other. In practice, multiple equipment has to be used serially. This implies again an extension of the acquisition time.

Figure 31.1. Left: laser stripe projected onto the human body. Right: structured light in the form of multiple white stripes projected onto the human body. (see colour plate page 515)

Figure 31.2. Example of surface measurement systems employed in medicine (from left to right, top to bottom): InSpeck surface digitizer Mega Capturor II (mounted on a vertical bar), 3Shape dental scanner DentalSCAN, Polhemus hand-held surface digitizer FastSCAN Scorpion, IVB-Jena face scanner gscan.

Which of the two technologies—laser scanning or structured light projection—should be more adequately employed, depends on the measurement task to be performed. This fact is also demonstrated by the multitude of commercial measurement systems based on different methods and technologies available nowadays. Among them, four groups can be identified as the main systems used in the medical field: (1) modular structured light projection systems (multiple units can be combined into a complete system) - for a fast digitizing of body areas; (2) desktop solutions with multi-axial moving platform—for the automatic measurement of small objects (e.g. dental impressions, ear impressions); (3) hand-operated or hand-held laser profilers—for complete freedom during the acquisition; and (4) dedicated systems designed for a specific measurement task—as for example face scanner, foot scanner, full body scanner. Figure 31.2 shows examples of the four groups.

31.3 APPLICATIONS IN MEDICINE

The medical field represents an established group of users of both human body surface scanning and human body motion tracking techniques. In this regard, various applications can be found in biomechanics, plastic surgery, orthopaedics, prosthetics, orthodontics, forensic medicine, dermatology, etc. In the following sections, some examples of applications are briefly described. They represent uniquely a small part of possible exploitations. Nevertheless, they serve to illustrate the potentials of 3-D measurement techniques applied in medicine.

31.3.1 *Dynamic 3-D measurement*

31.3.1.1 *Human motion tracking*

The end uses of human motion tracking are very diverse, and extend beyond anticipated application areas in anatomical and physiological research, sporting studies, rehabilitation and ergonomic planning to applications in the neurological, psychological and anthropological areas. Even a fairly cursory examination of the literature will show the full range of commercial systems being used for the analysis of walking (Whittle & Levine 1999, Troje 2002), running (Krosshaug et al. 2007), in sport (Ford et al. 2003) and also for studies involving the effects of cold exposure on leg muscles (Oksa et al. 1997), cerebral palsy (Meinecke et al. 2006), obesity (Achard de Leluardière et al. 2006) and idiopathic arthritis (Broström et al. 2007), and so on.

Not all studies concern the full body. Puce et al. (2003) and Baroni et al. (1998) observed movements of the face using commercial systems intended for studies of the movement by the entire human. Liu et al. (2007) investigated the measurement of teeth movement, again using a standard commercial system. “Optical motion analysis techniques have been widely used in biomechanics for measuring large-scale motions such as gait, but have not yet been significantly explored for measuring smaller movements such as the tooth displacements under load. In principle, very accurate measurements could be possible and this could provide a valuable tool in many engineering applications”, according to the authors, who, in their evaluation of the “accuracy and repeatability of the Qualisys ProReflex-MCU120 system when measuring small displacements”, noted that system repeatability was less than 0.005 mm, demonstrating “that the system suffices accuracy for measuring tooth displacements and could potentially be useful in many other applications.”

Cases of measurement when the trajectory itself is not relevant but the movement causes an effect, such as a deformation, which is of interest are not strictly motion recording, but we will include them here especially because they often face the same challenges and use similar solutions to pure motion recording. For example, Gao et al. (2000) used a pair of cameras to record the shape of a bioprosthetic heart valve at critical stages during a laboratory experiment to observe the valve’s deformation in an action induced by a mechanical apparatus. The valve surfaces were marked to provide photogrammetric targets. The only medical part of the experiment were the valves, but the issue is still seen here as medical photogrammetry. The experiment faced the interesting challenge that the valve opening and closing could last less than 0.04 seconds, while affordable cameras recorded with a period of 0.03 seconds. The interline transfer cameras recorded two events per frame by stroboscopic illumination, the two images being segregated subsequently.

Photogrammetry is also finding applications in the task of positioning patients for irradiation. While this may not strictly be motion recording, it can be noted that Baroni et al. (2003) used a commercial motion recording system for this purpose, and the challenges of the task can put it into the motion recording category. The benefit of precise patient positioning lies in reducing the radiation that must be allowed to overflow to nearby healthy cells in cases of poor positioning. The obvious tactic is to use targets fixed to the body, but another approach is to mathematical match measured surface shapes to identify whether the relevant part of the patient is in the required location. This is especially suited to positioning distinctive shapes such as the female breasts (e.g. Baroni et al. 2003), but it has also been used for neurosurgery, e.g. Raabe et al. (2002). Bert et al. (2006) refer to the use of a commercial patient positioning system; see Vision RT (2008). Accuracy is obviously a primary concern; Rogus et al. (1999) consider accuracy issues in patient positioning, but high speed measurement and processing are also crucial.

Although recording is of primary interest to the photogrammetrist, the spatial data manipulation and motion analysis is an important adjunct to motion recording to provide information of the sort shown in Figure 31.3. Most commercial photogrammetric motion recording systems are available with linked

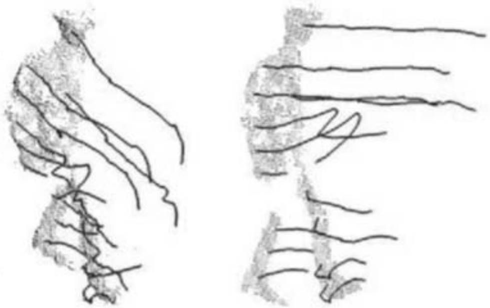


Figure 31.3. Three dimensional trajectories representing human body motion, from D’Apuzzo (2000).

motion analysis software. Occasionally analysis software is available independent of the recording system (e.g. see C-Motion Inc. (2008)).

31.3.1.2 *Surgical navigation systems*

Optical measurement systems are an established facet of surgical procedures using computer aided assistance. The importance of these systems has grown with the increasing popularity of minimally invasive procedures, which are associated with a reduction in operative field visibility. These measurement systems are mostly based on stereo photogrammetry and are usually composed of stereo camera acquisition units and surgical instrumentations marked with signalized target points. Figure 31.4 shows a typical example: the infra-red photogrammetric measurement system Cambar of the company Axios 3D Services (2008). Recent studies (Broers & Jansing 2007) evaluated positively the reliability and precision of such stereo measurement systems for the overall success rate of surgical navigation.

The stereo photogrammetric measurement system is uniquely a component of the surgical navigation system. In fact, complete solutions for computer assisted surgery also include real-time navigation and real-time computer assisting software solutions. Moreover, medical imaging data acquired pre-operatively (as for example by computer tomography or by magnetic resonance imaging) has also to be integrated into the navigation system and has to be aligned with the photogrammetrically acquired data. This is required both for planning and for executing the surgical intervention.

Various solutions are available commercially and dedicated solutions have been implemented for typical interventions, as for example knee replacement or spinal surgery. Figure 31.5 shows snapshots of different parts of a complete navigation system for total knee replacement: VectorVision Knee of BrainLAB AG (2008). The complete navigation solution enables knee replacement surgery with great precision and control. The system helps the surgeon, in real-time and with on-screen information, in the different phases during the intervention, from the bone cuts execution to the precise insertion of the knee replacement components in the bone. The surgeon also has the option to make individual modifications of the treatment plan, including the size, position and orientation of the implant. Surgical instruments are continuously tracked by the navigation system to judge their precise position and alignment relative to the operated parts and in accordance with the planned and

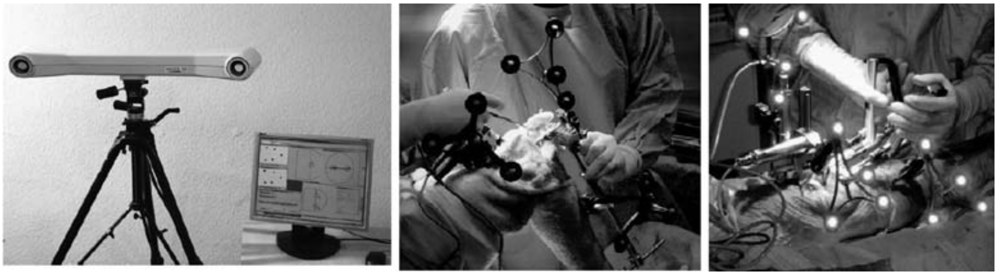
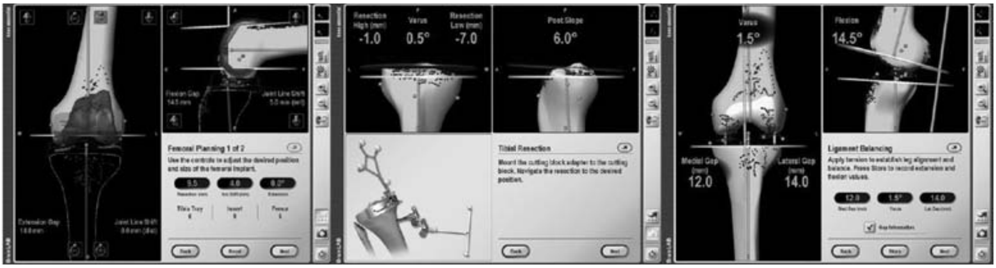


Figure 31.4. Axios3D Cambar photogrammetric measurement system and surgical instrumentation with signalized targets. (see colour plate page 516)



Femoral Planning 1 of 2

Use the controls to adjust the desired position and size of the femoral implant.

Tibial Resection

Mount the cutting block adapter to the cutting block. Navigate the resection to the desired position.

Ligament Balancing

Apply tension to establish leg alignment and balance. Press Store to record extension and flexion values.

Figure 31.5. Snapshots of VectoVision Knee of BrainLAB (2008). Initial planning and alignment of the implant position (left), real-time bone cut navigation and verification (centre), kinematical analysis for optimal leg alignment balance (right). (see colour plate page 516)

executed treatment. This provides the surgeon with comprehensive real-time information, which allows the surgeon to make decisions for greater control over the surgical outcomes.

31.3.2 *Human body surface measurement*

31.3.2.1 *Plastic surgery, reconstructive medicine*

Even though, at first sight, plastic surgery will be thought as an ideal field of application of human surface measurement techniques, in practice this is not the case. Commercial systems dedicated to the measurement of various parts of the human body and especially developed for surgical applications are available. Two examples are shown in Figures 31.6 and 31.7: the breast and face digitizer of InSpeck (2008) and the portable face and body scanner by GFMesstechnik (Benderoth 2005).

Advantages of using such systems in combination with analysis and measurement software could be manifold, e.g. for the planning of surgical interventions, for the comparison between pre- and post-operative shape, or for a better interface between patient and surgeon. Other software solutions go even further by simulating the effects of surgical interventions in a virtual environment. Regardless of all these available solutions, resistance is still present from the surgeons for their use in actual practice. Nevertheless, interest begins to arise especially if advantages can be demonstrated, as in the case of the two examples described in the following paragraphs.

The first regards a study on the simulation of surgical intervention done by Buskirk et al. (2005). In their work, they describe a project aimed at collecting and comparing standard body contouring data from 3-D scanners and from manual anthropometric measurements. Additionally, forecasted models of prospective body contouring procedures were mathematically implemented for the purpose of generating 3-D views of multiple predictive outcomes of surgical interventions. The special case of breast implant surgery was considered.

The scanning system employed for the study, Novaptus Systems Scanner Suite (Novaptus 2008), is based on structured light pattern projection and is able to rapidly produce a three-dimensional surface model of the entire body of a patient. From the scan data, the system extracts automatically relevant measures, such as suprasternal-notch-to-nipple and nipple-to-nipple linear lengths and bust, contoured-bust, under-bust, waist, hip, abdomen, thigh and knee circumferences. These findings were compared to manual anthropometric measurements taken on more than 70 patients. In this way, it could be demonstrated that digital scanning was as accurate as classical anthropometric measurement techniques.

Figure 31.6. InSpeck Breast and Facial Digitizer BFD 1300 and measurement software EM-Measurement. (see colour plate page 516)

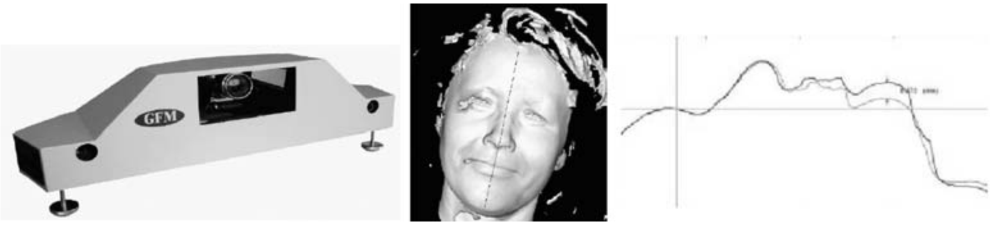


Figure 31.7. PRIMOS body II—portable 3D face and body scanner, 3-D scan data and comparison (colours code the difference ranges), 2-D cross sections showing difference between pre- and post-operative 3-D scan data. (see colour plate page 517)

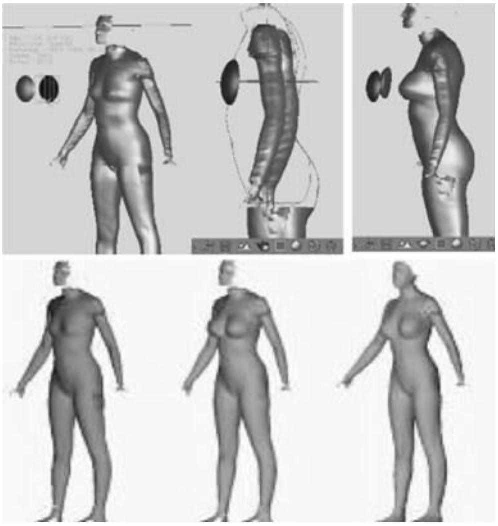


Figure 31.8. Top: placing the virtual breast implants on the pre-operative scan and the resulting forecasted 3-D model. Bottom: comparison of breast augmentation pre-operative subject's 3-D scan image, forecasted 3-D model and seven month post-operative subject scan.

Virtual predictive modelling, to forecast post-operative results, was also performed during the study. In this case, the scanner was employed in conjunction with a predictive software tool, Novaptus Virtual Surgery Suite (Novaptus 2008), allowing the surgeon to volumetrically manipulate the subject's pre-operative contour to virtually model it into the desired shape (see Fig. 31.8). Real surgical interventions such as breast augmentation, breast reduction and abdominoplasty, performed during the study, demonstrated that both pre- and post-operative measurements were concordant with the simulated results.

In the cases where a patient has lost part of their faces (as eyes, ears or nose), plastic surgery commonly uses the method of generating an artificial replacement (called "epithesis") for the missing part. 3-D scanning technologies can be very useful in these situations.

A project at the Institute of Production Engineering of the Technical University of Dresden aims at the use of face scanning and rapid prototyping technologies for the design and production of epitheses (Stelzer et al. 2006).

A face scanner based on white light projection, gscan of IVB-Jena (2008), is used to measure three-dimensionally the face of patients. Modelling software is then employed to virtually design and model in 3-D the replacement of the missing part. In the cases where the missing parts are still present on the face of the patient as mirrored parts (as eye or ear), the missing part can be modelled by mirroring the existing part. In the case of a missing nose, the artificial replacement can be chosen from an extensive 3-D database of virtual noses and visualized in 3-D over the digitized face. The accurate 3-D modelling of the artificial replacement is completely performed in a virtual environment using commercial modelling software. The obtained CAD model is then converted into a physical model with rapid prototyping techniques. The model is first generated on 3-D printers in a polymer material and then used as master for the production of the final epithesis from silicone. Figure 31.9 shows an example of 3-D scan data and the modelled epithesis (to protect the privacy of the patient, a 3-D point cloud of the face is shown; in the real situations fully textured surface models are visualized).

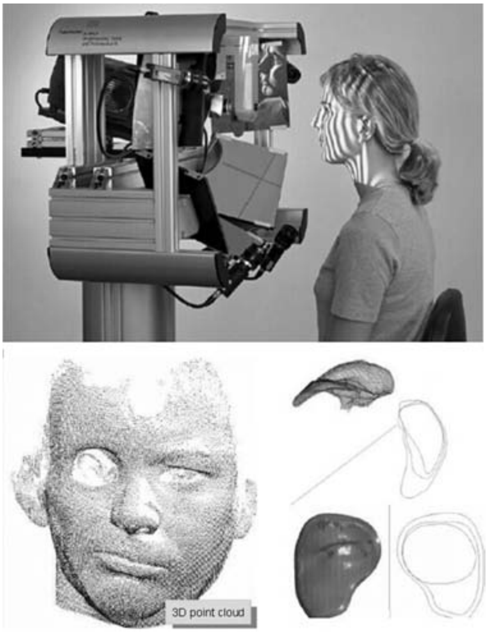


Figure 31.9. Human face scanner gscan (left), 3-D point cloud of patient with missing eye (centre), digital design of the missing part (right).

31.3.2.2 *Orthopaedics, prosthetics*

The peculiarity of orthopaedics and prosthetics is that measurements of the interested body part are always required. In a large proportion of the cases, in order to build best fit ortheses and/or prostheses, negatives of the human body part are required; these are usually obtained by casting. For these reasons, 3-D scanning technologies have the best presuppositions to become replacements of classical methods. In the next paragraphs, two typical cases are described where optical

3-D measurement techniques are already successfully employed instead of classic measurement methods (negative of the human body part by casting).

A good example of how 3-D surface scanning can be successfully employed in the field of prosthetics is well described by the work of Bonacini et al. (2007) and regards the design process of lower limb prostheses. An important aspect concerns the reconstruction of the 3-D digital model of the stump, which replaces a plaster cast. The work of Bonacini et al. (2007) goes even further by combining optical 3-D measurement techniques for the external surface of the limb and computer tomography (CT) and magnetic resonance imaging (MRI) for the inner structure (bone structure, muscle tissue, soft tissue and dermis). With the integration of external surface and internal components, it is possible to obtain a complete digital model of the residual limb, which permits the simulation of the behaviour and interaction of a designed socket with the stump.

For the acquisition of the external surface of the stump, a laser scanner, Minolta Vivid 9i, was used. This system is normally employed for industrial applications and it is not particularly suited for the measurement of human body parts. Nevertheless, it was suitable for the preliminary studies of the project. The principal problems occurring during acquisition were caused by noise generated by downy skin on the stump, and by uncontrolled muscular contractions. The first problem could be solved with a preparation of the skin of the stump whereas for the second problem a more suitable measurement system should be adopted.

After the acquisition of the inner structure of the stump by CT and MRI and after alignment of the different datasets, a complete 3-D digital integrated stump was obtained using commercial modelling software. In order to guarantee an alignment of the data acquired by the three different technologies, fixed markers were placed on the stump (lead shots for laser and CT, vitamin E for MRI). Figure 31.10 shows the 3-D surface model, the inner bones structure and the obtained combined result.

The obtained 3-D model of the stump can then be used for the design and production of a customized socket in a CAD/CAM environment.

A proof of the utility of the described process is given by the presence in the market of commercial CAD/CAM solutions especially dedicated to the design of lower limb sockets, based on 3-D scan models of the stump.

An example is shown in Figure 31.11, the CANFIT-PLUS P&O System from the Canadian company Vorum Research Corporation (2008). In this specific case, a hand-help laser scanner is employed for the 3-D acquisition of the external surface. Dedicated software tools are then employed for the accurate modelling of prostheses on the base of the scanned data.

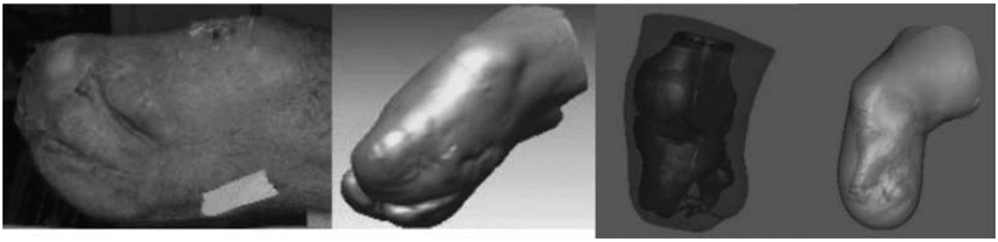


Figure 31.10. From left to right: stump image (note the signalized landmarks on the top), 3-D laser scanning model, CT skin-bone model, integrated laser/bone model (right). (see colour plate page 517)

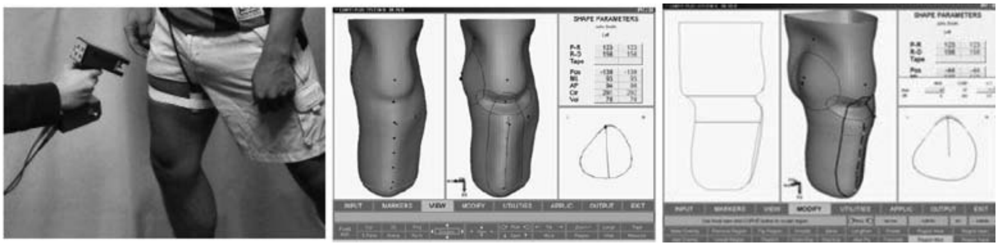


Figure 31.11. Lower limb socket design system CANFIT PLUS P&O: hand-held laser scanner and snapshots of the CAD/CAM solution. (see colour plate page 517)

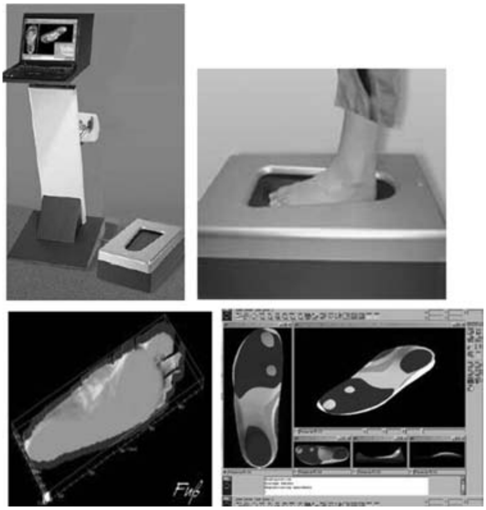


Figure 31.12. 3-D scanning system of pedcad (2008), acquired 3-D data and designed 3-D sole.

The second example of application of 3-D scanning technologies in the orthopaedic field regards the design and production of customized orthopaedic soles. The classical method consists also in this case of first getting an imprint of the foot (i.e. a negative of the foot plantar) and then building the shoe sole according to it. The advantages of using modern 3-D scanning technologies to acquire the shape of the foot are manifold compared to the classic foot imprint method. The design of customized shoe soles can in fact be completely performed in CAD/CAM solutions starting from 3-D scan data of the plantar of the feet of a person.

Various commercial systems have been developed especially for this purpose. Inexpensive scanning solutions are available, as the measurement task is relatively simple. For these reasons, this application became commercially more interesting.

Figure 31.12 shows an example of a complete solution from the German manufacturer pedcad Orthopaedieprodukte (2008). The scanning system is based on the structured light projection method and acquires the shape of the plantar of the foot in a very short time. The integrated software solution allows for the analysis of the scan data and for the complete design process of customized orthopaedic shoe soles in a CAD/CAM environment. The generated data can be sent directly to milling machines for the production. Also in this case, the integration of 3-D scanning systems with CAD/CAM solutions serves for a smoother and simplified design and production.

31.3.2.3 *Orthodontics, dentistry*

In dentistry and orthodontics, the advantages of employing optical 3-D digitizing techniques can be as straightforward as for orthopaedics and prosthetics. In fact, already available for many years are CAD/CAM solutions for the 3-D scanning of dental cast impressions for archiving and for a simplified design of orthodontical restoration, as well as dedicated intra-oral 3-D scanners for a direct 3-D measurement of teeth without the need for taking dental impressions. Clinical studies and basic reviews were published assessing positively the employment of CAD/CAM technologies both in dental restoration laboratories (Williams et al. 2006), as well as in dental practices (Christensen 2006). Moreover, manufacturers of CAD/CAM dental solutions constantly improve their products in order to increase the acceptance from potential users (i.e. dentists and dental laboratories) and in order to increase the penetration in the specific market. However, dentists' acceptance of 3-D technologies and CAD/CAM solutions still varies from excellent to poor. The cost of the investments involved and the technical know-how required to operate the systems are the significant deterrents. Dentists have to examine various factors in order to determine if the purchase of CAD/CAM technology is financially and clinically advantageous for their practice (Trost et al. 2006). Nevertheless, CAD/CAM dental solutions have been a reality for several years and are successfully exploited by thousands of dental laboratories and dental practices (Christensen 2006).

A typical example of solutions for modern design and production of dental restorations starting from 3-D scans of dental cast impressions is the given by the products of the company LaserDenta (Blumenschein 2006), which cover all the process steps: 3-D scanning, 3-D processing, 3-D visualization, 3-D virtual planning of restorations (see Fig. 31.13). For this purpose, a desktop laser scanning solution was especially designed and developed to automatically scan dental impressions with complete automation and with high precision (absolute accuracy of 0.02 mm, value given by the manufacturer). The scanning system employs a 5-axis (2 rotations and 3 translations) moving platform in combination with a laser profiler in order to scan entirely a dental cast impression. A complete jaw dental cast impression can be scanned fully automatically in about 5–8 minutes. The scanning equipment (scanner and control software) is designed to be easily used by non experts, so that the scanning process can be performed by unqualified (inexpensive) staff.

The data resulting from the scanning process will then be used by the dentist and/or dental laboratories to directly plan and design dental restorations (e.g. bridges, ceramic inlays, crowns, etc.) in a virtual environment. The virtually designed components of a restoration can then be produced in a fast and accurate

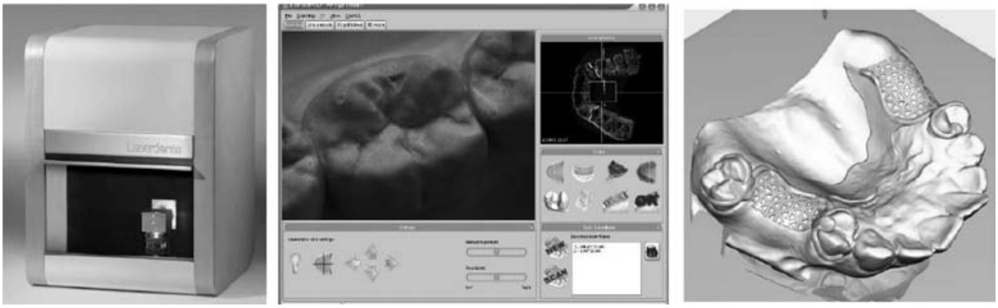


Figure 31.13. Dental solution of LaserDenta (Blumenschein 2006): desktop dental cast laser scanner (left), snapshot of the scanning control software (centre), virtual planning of a complex dental restoration (right). (see colour plate page 517)

Figure 31.14. The intra-oral scanner E4D Dentist of D4D Technologies (2008): the hand held miniaturized scanner (left), surface scanning by multiple lines projection (centre), real-time scanning control visualization (right). (see colour plate page 518)

way by modern rapid prototyping technologies: metal and ceramic parts can be produced automatically by CAM solutions starting from CAD data.

The employment of 3-D scanning technologies and modern CAD/CAM solutions in the dental domain can increase the efficiency and at the same time reduce the costs of the design and production of the different parts (in ceramic and/or metal) required by a dental restoration. For this reason, these technologies have a great potential for expansion in the dental domain.

A step further to simplify the entire process for the design and production of dental restorations is given by the intra-oral scanners. Various companies offer solutions for a direct scanning of teeth inside the oral cavity, i.e. without the need to first take an impression of the teeth and after to digitize it with a desktop scanner (as described above). Figure 31.14 shows an example of such a device from the company D4D Technologies (2008). The hand-held 3-D scanning system is so miniaturized that it can be placed inside the mouth of a patient to accurately record the 3-D shape of the teeth.

The main advantage resulting from the use of intra-oral scanners is the immediate generation of a 3-D surface model of teeth, thus allowing an immediate and direct design and planning of dental restorations in a virtual environment. In some simple cases (e.g. ceramic inlays), the entire procedure can be performed during the same session, i.e. without the need of have the patient leave. In fact, 3-D intra-oral scanning systems are usually accompanied by virtual restoration planning software, as well as with small milling machines for the production of ceramic parts directly from the generated 3-D data.

31.3.2.4 *Forensic medicine*

Documentation of morphological findings on and in the living and deceased is essential in forensic medicine. Nowadays, most of the documentation of forensic relevant medical findings is limited mainly to traditional 2-D photography, 2-D radiographs, sketches and verbal descriptions. More and more forensic institutes begin however to employ modern 3-D acquisition techniques, such as photogrammetry, laser scanning and surface scanning for the documentation and analysis processes. Among them, the Institute of Forensic Medicine at the University of Bern (Switzerland) represents a pioneer. Within the research project Virtopsy (Naether et al. 2007, Thali et al. 2005), 3-D optical surface digitizing and cross-sectional radiological modalities were introduced for documentation and reconstruction of the internal and

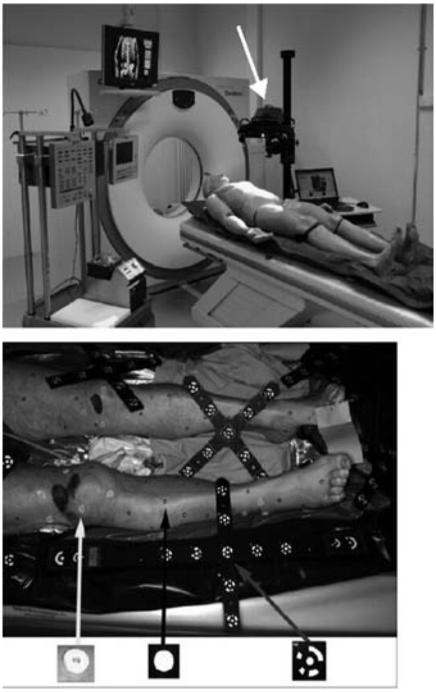


Figure 31.15. Left: Computer tomograph Siemens Emotion 6 and 3-D surface scanner GOM ATOS III (arrow). Right: different markers used for the measurement with GOM TRITOP. (see colour plate page 518)

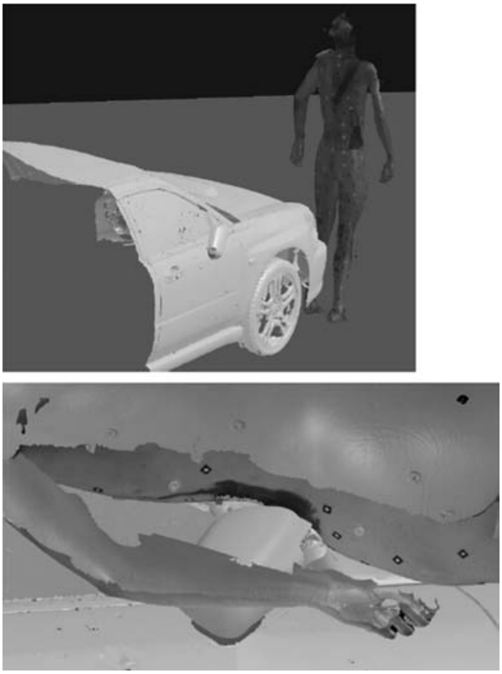


Figure 31.16. Top: 3-D model of involved vehicle and 3-D model of the injured pedestrian. Bottom: 3-D models of the injured corpse and the injury-causing instrument, the broken mirror of the car.

external body morphology of living or deceased persons, as well as of objects involved in the case (e.g. vehicles, weapons).

For the digitizing of the external body morphology, the forensic institute is using the structured light based surface scanning system ATOS III and the photogrammetric measurement system TRITOP, both of GOM (2008). The combined TRITOP/ATOS III system has the advantage that it can be used for surface documentation ranging from fine detailed structures, as skin lesion or fine instrument structures, to overview documentation, as whole body or entire vehicles. Additionally, the obtained 3-D models are fully coloured. Such a complete and detailed documentation could not previously be efficiently performed, in terms of time and quality, using classical approaches. Moreover, with the precise 3-D measurement of markers placed on the corpse, 3-D data acquired optically can be aligned and merged with the internal body morphology digitally documented using medical imaging systems such as multi-slice computed tomography (MSCT) and magnetic resonance imaging (MRI). Figure 31.15 shows the employed computer tomograph and the optical acquisition system.

The integration of the radiological data and the 3-D body surface data allow for a complete and detailed analysis of injuries. Figure 31.16 shows for example the 3-D surface model of the whole body of an injured pedestrian and the 3-D model of the involved vehicle. The 3-D human body model is completed with the internal body structure (bones, muscles, soft tissues, etc.) and the comprehensive injured damages. Both the 3-D surface model of the vehicle and the 3-D complete model of the corpse are very useful to determine the causes of the injury. In fact, the documented geometric findings (on and in the body, and involved objects) can be animated step by step or even by movie clips. Using data merging methods and animation, it is possible to answer reconstructive questions of the dynamic development of patterned injuries (i.e. morphologic imprints). In Figure 31.16, for example, the results achieved by the analysis of the case can be seen: the broken mirror of the involved vehicle was the cause of the fatal injury.

This example serves to illustrate how modern technologies of three-dimensional documentation can open new possibilities for forensic reconstruction by bringing added values and real quality improvements into forensic science. Moreover, they enable real data based 3-D reconstructions at any time, without the need for storage of the bodies, vehicles and instruments. By bringing the body into a virtual 3-D accident or crime scene, further information about the course of events can be delivered than in the conventional way. This is path-breaking for accident and crime scene analyses in the future.

31.3.2.5 *Dermatology, cosmetics*

Dermatology and cosmetics represent medical fields where optical 3-D measurement techniques can be successfully employed. For this reason, manufacturers of 3-D scanning equipment have developed products especially dedicated to the 3-D measurement of the human skin, as for example the handheld 3-D skin scanner PRIMOS compact portable of GFMesstechnik GmbH (Benderoth 2005). This optical measuring system, shown in Figure 31.17, is based on digital fringe projection technology and is designed to measure with extremely high resolution (about 60 microns in the plane and 6 microns in the vertical direction) in order to acquire the fine structures of the human skin. The main fields of application of such devices are, in fact, the 3-D measurement of wounds, scars, wrinkles, melanoma, naevi, birthmarks, etc. By means of analysis software, the received skin profile can then be evaluated in terms of all parameters of interest such as roughness, volumes of wrinkles or scars or, respectively, their geometrical dimensions.

An interesting application of 3-D skin measurement in dermatology is presented by the work of Smalls (2005). In this case, cooperation between private companies and medical universities has resulted in the implementation of a laser surface scanning system of Cyberware (2008) along with analysis software in order to quantify gynoid lipodystrophy, more commonly known as cellulite. Cellulite affects 85% of post-adolescent women and is for this reason of chief interest to the pharmaceutical and cosmetic industry. The distinctive surface morphology is believed to result when subcutaneous adipose tissue protrudes into the lower reticular dermis, thereby creating irregularities at the surface.

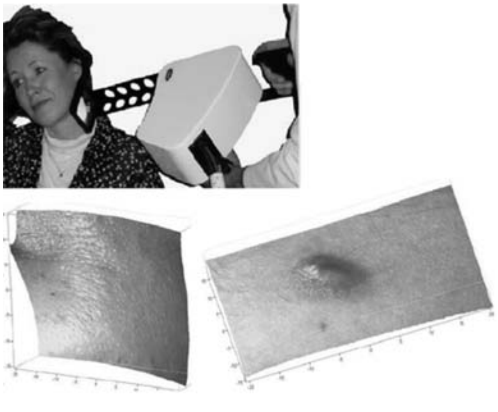


Figure 31.17. 3-D data acquisition by PRIMOS compact portable and 3-D data examples: wrinkle around the eye and wound measurements.

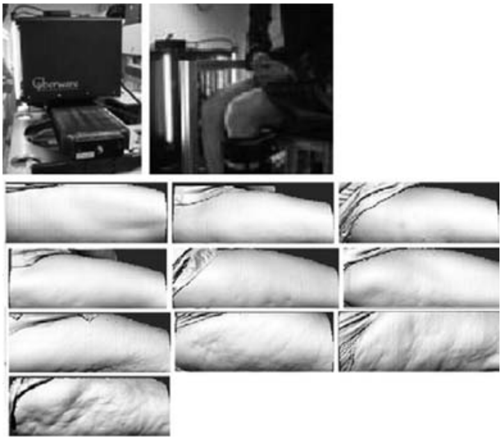


Figure 31.18. Top: the 3-D laser scanning system. Bottom: 3-D scan images arranged with increasing cellulite severity grades.

The three-dimensional laser scanning system was employed in order to objectively characterize and quantify the three-dimensional features of the skin surface for this specific work. The scanner was used to capture surface data of cellulite-affected thigh sites in women with varying degrees of cellulite, as well as subjects exhibiting non cellulite. Three-dimensional skin surface data were captured by using a customized laser scanning solution of Cyberware (2008): a laser scanning head situated on a linear platform, with user defined platform speed and scanner resolution. The outer aspects of both thighs were scanned while subjects were seated on a level surface, with knees bent at a 90° angle, as shown in Figure 31.18.

The acquired surface data were analysed to quantify the skin surface morphology and to determine specific roughness values. Customized software solutions were employed to firstly remove features not associated with cellulite, including thigh curvature, noise, hair, varicose veins. The edited 3-D data were finally processed in order to calculate the surface roughness parameters for the region of interest. A comparison of the roughness parameters extracted from the 3-D scan data, with the grades (on a scale from 0 to 9) established by an expert by visual analysis, proved the correctness of the method.

In Figure 31.18, on the bottom are shSown details of the acquired 3-D surface of the thighs skin arranged by increasing grade of cellulite.

31.4 FINAL REMARKS AND CONCLUSIONS

This study of the applications of image measurement for purposes involving human beings shows that they are not restricted to simple static measurement of body parts. In fact, the more common usage and the more exciting applications involve the relatively complex challenges caused by movement, whether for studies of the human body in motion or in the exciting area of surgical navigation. It can also be discerned from this review of medical measurement that among the various application areas there is a range of levels of acceptance of the use of spatial data from image measurement. It is more noticeable that many commercial organisations are involved in developing and marketing imaging systems, which have medical or other related human applications.

Overall, medical measurement is not a field that is solely the field of study of conventional measurement specialists as it is a field that involves a variety of scientists and engineers who presumably wish to contribute to bettering the lives of people. For the future, the surgical field in particular would seem to offer opportunities for further development, as it is clearly work that has not reached its ultimate objective.

REFERENCES

Achard de Leluardière, F., Hajri, L., Lacouture, P., Duboy, J., Frelut, M. & Peres, G. 2006. Validation and influence of anthropometric and kinematic models of obese teenagers in vertical jump performance and mechanical internal energy expenditure. *Gait and Posture* 23(2): 149–158.

Ariel Dynamics Inc. 2008. http://www.arielnet.com. Accessed 21.02.2008.

Axios 3D Services GmbH. 2008. Complete solution for 3D surgical navigation systems. http://www.axios3d.de. Accessed 21.02.2008.

Baroni, G., Ferrigno, G. & Pedotti, A. 1998. Implementation and application of real-time motion analysis based on passive markers. *Medical and Biological Enginering and Computing* 36: 693–703.

Baroni, G., Troia, A., Riboldi, M., Orecchia, R., Ferrigno, G. & Pedotti, A. 2003. Evaluation of methods for opto-electronic body surface sensing applied to patient position control in breast radiation therapy. *Medical and Biological Enginering and Computing* 41: 679–688.

Benderoth, C. 2005. PRIMOS handheld and PRIMOS body II: New products from GFM—Germany and applications in maxillofacial surgery. In N. D'Apuzzo (ed.), *Human Body Measurement Newsletter, Vol.1 No.2.* Zurich, Switzerland. http://www.hometrica.ch/en/newsletter.html. Accessed 21.02.2008.

Bert, C., Metheany, K.G., Doppke, K.P., Taghian, A.G., Powell, S.N. & Chen, G.T.Y. 2006. Clinical experience with a 3-D surface patient setup system for alignment of partial-breast irradiation patients. *International Journal of Radiation Oncology, Biology and Physics* 64: 1265–1274.

Biogesta. 2008. http://www.biogesta.fr. Accessed 21.02.2008.

Blumenschein, P. 2006. State of the art of the 3-D scanning devices used for dental applications: open or closed systems. *3-D Modelling, Proceedings of Conference, June 13–14, 2006, Paris, France*.

Bonacini, D., Corradini, C. & Magrassi, G. 2007. 3-D Digital Model Reconstruction: Residual Limb Analysis to Improve Prosthesis Design. In A. Gruen & H. Kahmen (eds.), *Optical 3-D Measurement Techniques VIII*. Zurich, Switzerland.

BrainLAB AG. 2008. *VectorVision Knee*. http://www.brainlab.com Accessed 21.02.2008.

Broers, H. & Jansing, N. 2007. How precise is navigation for minimally invasive surgery? *International Orthopaedics* 31(1).

Broström, E., Örtqvist, M., Haglund-Åkerlind, Y., Stefan Hagelberg, S. & Gutierrez-Farewik, E. 2007. Trunk and center of mass movements during gait in children with juvenile idiopathic arthritis. *Human Movement Science* 26(2): 296–305.

BTS SpA. 2008. http://www.bts.it Accessed 21.02.2008.

Buskirk, T.D. et al. 2005. 3D Body Scanner: an aid in planning body contouring surgery. *Proc. of Plastic Surgery 2005, September 24–28, Chicago, USA.*

Charnwood Dynamics Ltd. 2008. http://www.charndyn.com Accessed 21.02.2008.

Christensen, G.J. 2006. Is now the time to purchase an in-office CAD/CAM device? *Journal of the American Dental Association* 137: 235–238.

C-Motion Inc. 2008. http://www.c-motion.com Accessed 21.02.2008.

Cyberware Inc. 2008. http://www.cyberware.com Accessed 21.02.2008.

D'Apuzzo, N. 2000. Motion capture by least squares matching tracking algorithm. In *AVATARS'2000 Workshop, November 30–December 1, 2000, Lausanne, Switzerland*. *IFIP Conference Proceedings*: 196. Kluwer. ISBN 0-7923-7446-0.

D4D Technologies L.P. 2008. *E4D intraolar 3D dental surface digitizer.* http://www.d4dtech.com Accessed 21.02.2008.

Ehara, Y., Fujimoto, H., Miyazaki, S., Tanaka, S. & Yamamoto, S. 1995. Comparison of the performance of 3-D camera systems. *Gait and Posture* 3: 166–169.

Ehara, Y. Ehara, Y., Fujimoto, H., Miyazaki, S., Mochimaru, M., Tanaka, S. & Yamamoto, S. 1997. Comparison of the performance of 3-D camera systems II. *Gait and Posture* 5: 251–255.

Ferrigno, G. & Pedotti, A. 1985. ELITE: a digital dedicated hardware system for movement analysis via TV signal processing. *IEEE Transaction Biomedical Engineering* BME-32: 943–950.

Ford, K.R., Myer, G.D. & Hewett, T.E. 2003. Valgus Knee Motion during Landing in High School Female and Male Basketball Players. *Medicine and Science in Sports and Exercise* 35(10): 1745–1750.

Gao, Z., Pandya, S., Arana, C. & Hwang, N.H.C. 2000. Bioprosthetic heart valve leaflet motion monitored by dual camera stereo photogrammetry. *Journal of Biomechanics* 33(2): 199–207.

Garrido Castro, J.L., Medina-Carnicer, R. & Galisteo, A.M. 2006. Design and evaluation of a new three-dimensional motion capture system based on video. *Gait and Posture* 24(1): 126–129.

GOM mbH. 2008. http://www.gom.com Accessed 21.02.2008.

Hoyer, K., Holzner, M., Guala, M. & Kinzelbach,W. 2006. Simultaneous 3D-flow field and compliant wall measurements in a abdominal aortic aneurysm flow using scanning-PTV. ISPRS *Commission V Symposium, September 25–27. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXVI, Part 5.

InSpeck Inc. 2008. *Breast and Facial Digitizer BFD 1300.* http://www.inspeck.com/products/PlasticSurgery/PlasticSurfery.asp Accessed 21.02.2008.

IVB Jena GmbH. 2008. *GSCAN 3D Body Scanner*. http://www.ivb-jena.de Accessed 21.02.2008.

Krosshaug, T., Nakamae, A., Boden, A., Engebretsen, L., Smith, G., Slauterbeck, J., Hewett, T.E. & Bahr, R. 2007. Estimating 3D joint kinematics from video sequences of running and cutting maneuvers—assessing the accuracy of simple visual inspection. *Gait and Posture* 26(3): 378–385.

Liu, H., Holt, C. & Evans, S. 2007. Accuracy and repeatability of an optical motion analysis system for measuring small deformations of biological tissues. *Journal of Biomechanics* 40(1): 210–214.

Meinecke, L., Breitbach-Faller, N., Bartz, C., Damen, R., Rau G. & Disselhorst-Klug, C. 2006. Movement analysis in the early detection of newborns at risk for developing spasticity due to infantile cerebral palsy. *Human Movement Science* 25(2): 125–144.

Motion Analysis Corporation. 2008. http://www.motionanalysis.com Accessed 21.02.2008.

Naether S., Buck U. & Thali J.M. 2007. Virtopsy—Scientific 3-D Documentation of Human Bodies in Forensic Medicine: with High Resolution Surface Scanning Radiological MSCT/MRI Scanning. In A. Gruen & H. Kahmen (eds.), *Optical 3-D Measurement Techniques VIII*. Zurich, Switzerland.

Northern Digital Inc. 2008. http://www.ndigital.com Accessed 21.02.2008.

Novaptus Systems, Inc. 2008, *Novaptus Systems Scanner Suite and Novaptus Virtual Surgery Suite*. http://www.navaptus.com Accessed 21.02.2008.

Oksa, J., Rintama, H. & Rissanen, S. 1997. Muscle performance and electromyogram activity of the lower leg muscles with different levels of cold exposure. *European Journal of Applied Physiology* 75: 484–490.

Peak Performance Technologies, Inc. 2008. http://www.vicon.com/company Accessed 21.02.2008.

pedcad Orthopaedieprodukte GmbH. 2008. *PedCad scanning system.* http://www.pedcad.de Accessed 21.02.2008.

Phoenix Technologies Inc. 2008. http://www.ptiphoenix.com Accessed 21.02.2008.

Puce, A., Syngeniotis, A., Thompson, J.C., Abbott, D.F., Wheaton, K.J. & Castielloc, U. 2003. The human temporal lobe integrates facial form and motion: evidence from fMRI and ERP studies. *NeuroImage* 19: 861–869.

Qualisys AB. 2008. http://www.qualisys.se Accessed 21.02.2008.

Richards, J.G. 1999. The measurement of human motion: A comparison of commercially available systems. *Human Movement Science* 18(5): 589–602.

Rogus, R.D., Stern, R.L. & Kubo, H.D. 1999. Accuracy of a photogrammetry-based patient positioning and monitoring system for radiation therapy. *Medical Physics* 26(5): 721–728.

Raabe, A., Krishnan, R., Wolff, R., Hermann, E., Zimmermann, M. & Seifert, V. 2002. Laser Surface Scanning for Patient Registration in Intracranial Image-guided Surgery. *Neurosurgery* 50(4):797–803.

Stelzer, S., Schreiber, S. & Schoene, C. 2006. Utilisation of 3D Face Scanner in Medical Faculty. *3D Modelling, Proceedings of Conference, June 13–14, 2006, Paris, France.*

Smalls, L.R.K. 2005. Development of quantitative models for the investigation of gynoid lipodystrophy (cellulite). PhD Thesis, University of Cincinnati, USA, April 2005.

Thali, J.M. & Aghayev, E. 2005.Virtopsy research project, documentation of the internal and external body morphology in forensic medicine. In N. D'Apuzzo (ed.), *Human Body Measurement Newsletter, Vol.1 No.2*. Zurich, Switzerland. http://www.hometrica.ch/en/newsletter.html Accessed 21.02.2008.

Troje, N.F. 2002. Decomposing biological motion: A framework for analysis and synthesis of human gait patterns. *Journal of Vision* 2(5)2: 371–387.

Trost, L., Stines, S. & Burt, L. 2006. Making informed decisions about incorporating a CAD/CAM system into dental practice. *Journal of the American Dental Association* 137: 32s–36s.

Vicon Motion Systems. 2008. http://www.vicon.com Accessed 21.02.2008.

Vision RT Ltd. 2008. http://www.visionrt.com Accessed 21.02.2008.

Vorum Research Corporation. 2008. *CANFIT-PLUS P&O System.* http://www.vorum.com Accessed 21.02.2008.

Walton, J.S. (ed.). 1990. *Image-based motion measurement, Proc. of Symposium, University of California, San Diego*. Bellingham, USA: International Society for Optical Engineering, SPIE.

Whittle, M.W. & Levine, D. 1999. Three-dimensional relationships between the movements of the pelvis and lumbar spine during normal gait. *Human Movement Science* 18(5): 681–692.

Williams, R.J., Bibb, R., Eggbeer, D. & Collis, J. 2006. Use of CAD/CAM technology to fabricate a removable partial denture framework. *Journal of Prosthetic Dentistry* 96: 96–99.