A DYNAMIC CONTACT-FREE OPTICAL ACQUISITION TECHNIQUE FOR ANATOMICAL STRUCTURES OF THE TRUNK AND LOWER BODY

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Abstract: 3D modelling of the human body has become a common topic recently. The majority of the approaches however do not involve anatomical reconstruction of the inner skeletal configuration of the analyzed patient. In this article a radiation-free measuring technique is presented, reconstructing the inner skeletal configuration starting form topographic measurements of the skin surface. The main application fields are occupational, sports and rehabilitation biomechanics. One of the advantages of this approach is that it offers an alternative to ionizing measuring techniques. The innovative idea is to measure a moving surface in 3D over a time period and to reconstruct the corresponding inner skeletal configuration for each time frame of the measured sequence. Afterwards, different methods are applied to the video rasterstereographic images to detect relevant landmarks which can be related to corresponding bones. Based on the reconstructed skeletal model, a number of relevant clinical parameters can be derived. For example kyphotic and lordotic angles, used in a follow-up study of scoliotic patients. The presented paper gives an overview of the current project status.

Introduction

The objective of the current study is the development of a low-cost objective measurement tool that is able to reconstruct the inner skeletal configuration during patient motion. The system operates contact-free, which also makes it more conformtable to the patient. The ongoing research is focused on the back and the lower limbs, but other applications are possible in the future.

There is a huge number of different musculo-skeletal complaints in the industrialized world. Low back pain for instance, is one of the most compelling problems and one of the main causes of work absenteism. Orthopedic physicians and physiotherapists are required to analyze a variety of movements to diagnose these pathological or abnormal changes.

The presented measuring system provides the medical examiner and/or physiotherapist with clinically relevant data to support the diagnosis and therapy planning in different applications.

There are different applications for this measuring system. The lumbar spine provides the body with mobility and strength. Pain in the lower back can reduce the activity and work ability of a person. Most cases of lower back pain however respond to simple treatments. Nevertheless a correct diagnosis of the problem is important to prevent further damage to the spine. Important parameters to detect are the kyphotic and lordotic angle.

Similar problems are observed near the lower limbs. Complaints such as knee and foot problems are very common. Important parameters to detect are the Mickulicz line for and the Q-angle for diagnosis of varus or valgus knee. Volume analysis can support diagnosis of obesitas or thromboses and patella tracking is able to diagnose abnormal muscular functioning.

Existing systems obtain skeletal information using markers to track anatomic landmarks. This tracking however is influenced by the relative motion of the skin relative to the underlying structures. Also these systems are unable to record surface structures and marker placing should be done by an experienced person.

Additional information about possible damage on bone tissue is then obtained with X-rays, by CT scanning or MRI. The disadvantage is that these measurement techniques are quite static and/or involve potentially harmful ionizing radiation. This techniques can be very expensive and require qualified personnel (radiologists). They also involve a certain form of contact with the subject or some form of immobilization.

The system described in this paper obtains data using a system based on 3D surface measurement. The collected 3D data is used for the detection of anatomical features and landmarks using mathematical tools and biomechanical modelling. As this technique doesn't use ionizing radiation, it can be applied from early childhood to high age or during pregnancy. It opens excellent possibilities especially for routine screening and follow-up studies.

It should be clear from the above that an easy to use and low cost system for diagnosis of musculo-skeletal disorders is highly desirable. The system specification

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will allow that a wide range of clinical practitioners can use the system. Its availability will contribute significantly to the quality of the diagnosis, but also to the quality of the treatment, because it allows for an efficient follow-up of the treatment at regular and frequent time intervals.

Previous Work

As soon as 1981, Frobin and Hierholzer [1,2] developed appropriate hardware for the assessment of a back surface in order to reduce the amount of radiographs for patients with scoliosis. This involved measurements of the back surface and estimation of the vertebral column shape and deformation. All measurements were done in a static environment.

In “4D analysis of muscular dynamics using flexible 3D muscle models”, International Conference on Artificial Reality and Telexistence '99, Suziki et al. Describe a method for constructing a 4D musculo-skeletal model. The method is based on fitting a muscular and skeletal model to MRI results and on measuring movement by a video camera and a set of sensors.

Another approach is that of Douros and Buxton [5] where a full model of the outer body is reconstructed with surface estimation and computation of curvatures. The application field for their approach is seen in the clothing industry, so after the reconstruction of the outer body surface no inner skeletal model is computed, because it is not relevant in this field.

Materials and Methods

Reconstruction is done in several steps: first the surface is measured and the data collected. Then the information is processed mathematically. After that, the obtained surfaces are processed to detect anatomical landmarks and structures. Biomechanical models are used to support these detection algorithms. Finally, the underlying skeletal structure is reconstructed.

Measurement setup: The surface of the subject is measured dynamically using a technique based on raster line triangulation. This technique enables scanning of 3D objects by projecting raster lines on its surface and by capturing these lines under a known and fixed angle with a camera. The spatial coordinates of all raster points are computed using triangulation algorithms. The result of this operation is a dense point cloud which is converted to a regular grid using cubic spline interpolation. This technique is able to grab a surface in a very short time interval (< 1/100s) with a high resolution (<1mm) along the lines and a distance of less than 10mm between two consecutive stripes. This requires no more than a standard commercially available personal computer or laptop. The projected lines can either be white light (WLRT) or split laser beam light (SLBLRT). The advantage of split laser beam light over white light is the better spatial resolution and superb accuracy. The current measurement frequency varies currently between 12Hz and 30Hz. The chosen measurement setup depends on the type of measurement. Back surface measuring is done, using a single projector-camera combination. For measuring the shoulder complex, an additional camera for detecting the acromion is needed. For the lower limbs, a synchronised 4 projector-camera combination is developed to measure the full 4D (3D + time) surface. The latter setup is shown in Fig. 1.

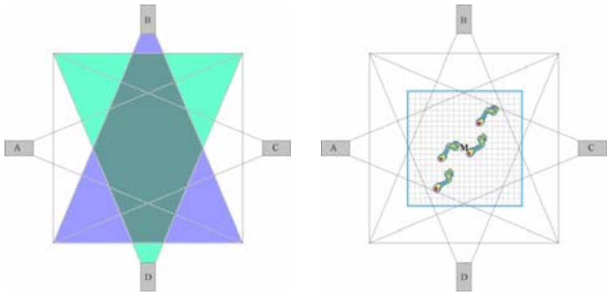

Figure 1: The measurement environment with the force plate and the 4 camera/laser projectors

The measurement area in the 4 camera setup is a 1.2x1.2x1.2m cube. Lasers with different wavelengths and filters are used to avoid interference. Also a synchronised force plate is integrated for pressure distribution measurement in later dynamical analysis.

Image Reconstruction: The capturing is done in real time (online). The processing however, is done afterwards in different steps. The spatial coordinates of all raster points are calculated for each camera, based on triangulation algorithms. This results in a dense point cloud of randomly distributed points, describing the measured surface in every sequence step. To simplify further analysis, this set of data points is transformed into a regular grid by using interpolation. If there are multiple cameras in the setup, the different point clouds are stitched together to form one model of the surface.

The image data is then further analyzed in two different ways: each image frame is processed separately but also information from the complete movement is obtained.

Mathematical Surface Processing: The collected data is mathematically processed for analysis of surface properties, which are related to the underlying anatomical structures. Different surface properties are processed. This can be seen in figure 2.

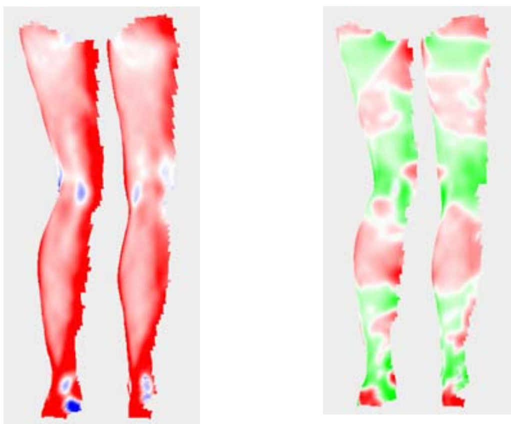

Figure 2: lower limbs captured from behind, mean (left) & Gaussian curvature (right)

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First of all, mean and Gaussian curvature in each data point is calculated. As a consequence, every group of points corresponds to a certain curvature profile. This can be related to the underlying anatomical structures. Second to that, also texture and normal vector orientation is extracted from the images.

Also the complete movement is used for kinematic reconstruction and smoothing of the landmark motion in time. If necessary, it is possible to extend this information with texture information or the like.

Anatomical landmarks and structures: Depending on the application, a different approach is required to allow diagnostic measurement under dynamic conditions. Because the detection of landmarks is less reliable than detecting markers in the existing systems, additional information is required. This information is either provided by the image or by a biomechanical model.

The detection of landmarks and anatomical structures is done on three different levels. There is the detection of surface landmarks, the detection of geometrical axes and the kinematic reconstruction of mechanical landmarks.

Landmarks that lie near the skin surface can be detected by the way they change the surface curvature for a certain pose or during a certain motion. This is also true for certain structures (i.e. the tibia line). By defining surface curvature properties around a landmark in a catalogue, it can be tracked during a measuring sequence.

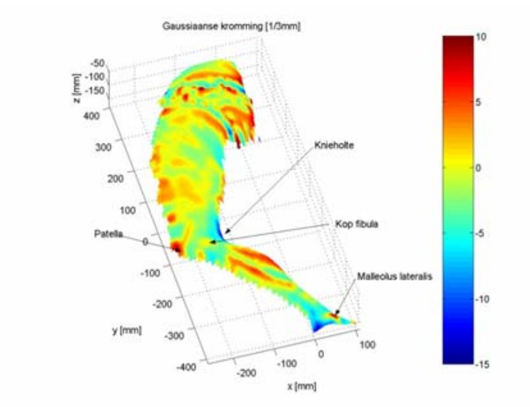

Figure 3: Gaussian curvatures with detected anatomical landmarks.

For analysis of the spinal chord e.g. , the aim is to obtain the spinal midline. This is solved by using a technique based on active contours [3,4], also known as "snakes". Starting from an intial estimation, the objective is to iteratively move the contour on the image until the cost is minimized and appropriate contour properties are achieved. External and internal costs are defined. The external cost is connected to the surface properties. The internal cost describes the internal behaviour of the contour itself.

The external cost consists of two parts. The first is the *surface curvature cost*: a combination of the mean and the Gaussian curvature, related to the surface properties induced by the underlying landmarks. To increase the robustness of landmark detection *active shape models (ASM)* are introduced in the method. An ASM can be seen as a "smart snake" that is only able to deform in ways characteristic of the class of objects it represents. It is built by learning patterns variability form a training set of correctly labelled points on images. By examining the statistics of these labelled points a distribution model can be derived. The model gives the average positions of the points and has a number of parameters that control the main modes of variation found in the training set. The major external cost of the active contour is the *symmetry cost*: an asymmetry function, which calculates the minimal asymmetry point in each horizontal cross section. This relates to the case of healthy people, where the medial sagital plane is a symmetry plane in the upright standing position. To improve this estimation, also the mean curvature (with less weight) is added. When the measurement is not done in an upright standing position, the mean curvature will increase weight to compensate for the loss of symmetry.

The internal cost also contains different parts. A bending and a torsion cost avoid clinically or biomechanically impossible results. At last other additional costs are added, such as the relation between the lateral deviations and the axial rotations of the vertebrae.[4] Another internal cost forces the snake points to be equidistant. This prevents the snake points from grouping on a single position on the spinal midline.

The surface analysis process is then done as following. First the sacrum point, the vertebra prominens (being the begin and the end point of the line through the spinous processes) as well as the posterior superior iliac spines on the pelvic bones are located. Then the active contour is calculated in an optimization algorithm combining all the above mentioned cost functions with their weighting factors. The goal is to minimize the total cost. The result is shown in figure 4

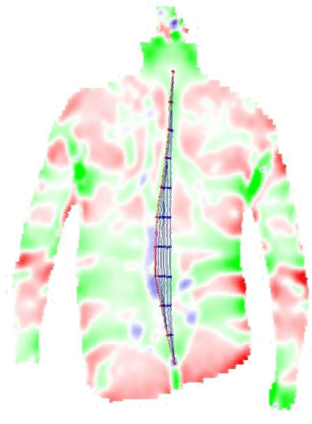

Figure 4: using active contours to find the spinal midline

Finally, the internal model of the subject is reconstructed based on the time-dependant information of the body surface. The matching of the frames takes place with the obtained model from the previous step. In order to make a maximal use of the information of successive images, a combination of mathematical and statistical methodes is used, e.g. a Kalman filter, which is a set of mathematical equations that provides an

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efficient computational solution of the least-squares method.

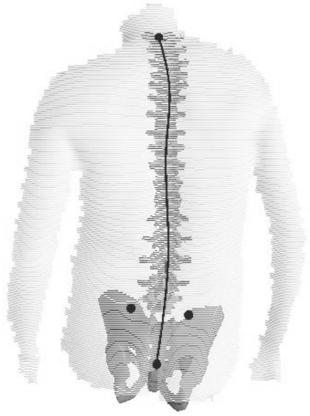

Figure 5: using active contours to find the spinal midline

The skeletal components of the models are based on templates of the bones, which are scaled, rotated and translated according to the obtained information from the back surface analysis. Both the full vertebral column and the pelvis are reconstructed currently (figure 5).

For the analysis of the lower limbs a kinematic model of the lower limbs has been developed. Comparing to the spinal chord analysis, also volumetric information and geometrical axis orientation are interesting parameters, as described in the introduction. Volumes are computed from surface information. Geometrical axes are calculated iteratively using a slicing algorithm. Some important landmarks are not available at the surface, but can be detected by kinematic reconstruction of the sequence. The hip joint rotation centre for example can be found by tracing the instant centre of rotation during the measurement sequence, based on the known kinematic properties of the hip. (figure 6)

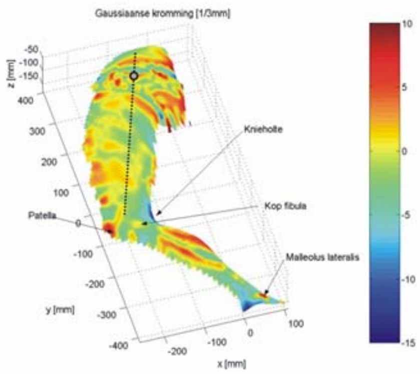

Figure 6: Geometrical axis of the femur and kinematic reconstruction of the hip joint rotation center

Results

Raster line triangulation visualizes surfaces in an accurate (+/- 0.5mm) and repeatable way, without detrimental effects, and without making contact to the human body. Both measurement time and analyzing time are short. The measurement technique is used in different applications. For analysis of the spine and the pelvis, the system is able to accurately detect the landmarks in most cases and different kinds of movements. Compared to radiographic scans, the positions of the geometrical centres of the vertebrae in a frontal projection can be reconstructed with a root mean square deviation of 4.6mm. The main causes for this error are noise in the video images and the algorithmic estimation of the line through the processi spinosi and the vertebral rotations. Nevertheless, the error is acceptable for the intended application.

To evaluate the reliability and accuracy of the active contour approach, the method is compared to the methodology of Drerup and Hierholzer, which is specifically developed for scoliosis. Raster stereographs of 33 scoliotic patients were taken. The data of nine patients was used as a training set to derive appropriate weight factors for each cost term. The additional costs are not implied to firmly, because of interindividual scatter and since external costs are relatively more important. The data of the remaining 24 patients were used to compare spinal midline estimations of Drerup and Hierholzer with the active contour method. A mean r.m.s. error of 0.9mm for the lateral deviation and 0.4º for the axial rotation in between the curves was found.

In the ongoing research for the lower limbs, the system is able to describe a complete dynamic biomechanical volume-model of the lower limbs, including landmarks, bony structures, kinetic and kinematic data. Now the relevant clinical parameters have to be extracted from the data and – according to the clinical task at hand – analyzed on laboratory scale. The correct detection of the biological surface landmarks then has to be verified on a statistically sufficient population of dynamical models. This will happen based on clinical correlation studies, using X-Ray, MRI or active markers.

In the future, soft tissue, ligaments and tendons may be layered on the skeletal elements.

Currently it is not possible to investigate very fast motions yet. Increasing the frequency would mean an increase of data to be stored and of analyzing time. This must be considered.

Discussion and Conclusions

The main advantages of the project output are the equipment’s ability to reconstruct kinematics, kinetics and dynamics of the musculo-skeletal system of the lower body, without the use of potentially harmful and/or relatively expensive equipment, as well as its ability to indicate and quantify pathological changes or abnormalities, both at an early stage and in connection with diagnosis. Additionally, basic clinical parameters will be covered as well: volumetric analysis (volume differences, areas, distances, angels, …), as well as “standard” kinematic features (axes of the lower extremities, acceleration and velocity parameters, …).

Clinical correlation studies using other verifying methods, as X-ray, MRI or active markers, have to be realized both in the biomechanical laboratories and in strictly clinical surroundings.

Acknowledgements

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