

PHOTOGRAMMETRY IN MEDICAL GAIT ANALYSIS

Baumann, J.U., Meier, G., Schaer A.R.
Motion Analysis Laboratory, Dept. of Orthopedic Surgery,
University of Basel, Felix Platter-Spital, CH-4055 Basel, Switzerland.

Sheffer D.B.
Biostereometrics Laboratory, Dept. of Biomedical Engineering
University of Akron, Akron, Ohio 44325, USA.

ABSTRACT

For understanding the complex dynamics of total body movements of human locomotion, information on shape, dimensions, mass and proportions of the 15 major body segments is needed. In physically handicapped persons, these parameters vary considerably. Evaluation of the individual is feasible using photogrammetry. Graphic presentations of results which are easy to understand are decisive for general acceptance of gait analysis as a useful diagnostic tool. Linking limited measurements to images of the whole person in motion permits local measurements to be incorporated into the general information of total body movements. A pilot study is reported and propositions for cost efficient performance using today's possibilities of electronic imaging technology are discussed.

KEY WORDS: Photogrammetry, 3D Human Motion Analysis, Joint Forces and Moments, Anatomy Based Coordinate Systems, Human Body Deformity.

INTRODUCTION

As a cause for medical consultation, diseases and injuries to the organs of motricity, the neuro-musculo-skeletal system, rank among the most frequent. Long term disabilities affecting independence in daily living as well as working capacity are most often caused by functional insufficiency and pain within the locomotor system. Human beings are three dimensional bodies who to move in space within time. It seems astonishing therefore, that today's methods for recording and measuring the changes in the relative spatial positions of our 15 major body segments are still unsatisfactory. The task is formidable, however. From the standpoint of the photogrammetrist, the systems in practical use for quantitative assessment of such disorders seem inadequate. Better methods at a reasonable price could not only support further improvements in medico-surgical treatment but also help to prevent the development of disabling conditions. This is particularly important in a population reaching much higher ages than only 50 years ago.

A number of commercial systems for gait analysis are available in which output generally consists of the recording of the spatial positions of body segments in space as successive frames or instances of time. Kinematic information describing joint angle changes relative to time and position are represented in stick figures or curves describing the joint movements. These data coupled with the simultaneous recording of ground reaction forces have served as descriptions of the kinematic activities of the human body during ambulation. Continuous development in methodology depending on the advancement of electronic data collection and processing devices has tended to attempt to move the major acquisition protocol from cinematography to that of video based systems such as CINTEL (Winters, 1972), VICON (Macleod et al., 1990), ELITE (Ferrigno 1990). Opto-electronic systems that use position sensitive detectors (SELSPOT, Woltring 1980), or CCD line sensors such as COSTEL (Bianchi et al. 1990) and OPTOTRAK (Crouch et al., 1990). These latter technologies employ non-television based systems of active markers and non-simultaneous sampling of the body segment markers.

We have tried over many years to improve qualitative and quantitative assessment of locomotion in patients and normal persons from their first year of life to old age. Particular focus was centered on disorders of the neural control of movements particularly in children with cerebral palsy, on ligamentous knee injuries in sportive individuals as well as on effects of aging on walking patterns.

Practical experience showed, that photogrammetry and remote sensing using telemetry for some electrical signals are needed to evaluate the movement patterns within the segmented bodies of children and adults under natural conditions of daily life. Body shape and movements in space can thus be recorded and analysed without interference to the phenomena to be measured.

Because orthopedic surgeons should be even more interested in forces and moments occurring at the major joints than in the movements alone, measuring and calculating reactive force actions must be included in many instances. For this purpose, 3D force plates for measuring floor reaction forces to the loading by the feet have proved to be of great help.

During walking, only one leg has floor contact most of the time, while the other three extremities pursue pendular swinging movements. In order to calculate the forces and moments occurring at the hip, knee and ankle joints during walking and running, the segmental masses which make up the pendulums as well as the segmental centers of mass must be known. The total mass of the extremities makes up some 44% of total body mass in a healthy young male. Their rhythmic swinging during walking must have considerable effect, but has so far been largely neglected by measurements in medical movement analysis. Methods and tables for evaluating density distribution within the different body segments are available. Information on translational and angular accelerations of the segmental masses in the 3 dimensions of space is needed to calculate reactive forces and moments at the joints. Because human body proportions change considerably from birth to adulthood and are often highly abnormal in physically impaired person, individual evaluations of segmental mass distribution is frequently required. Photogrammetry seems ideal as a basis for calculating segmental body volumes and marking average

positions of joint axes with related segmental boundaries on images of individual persons. Data acquisition by photogrammetry is fast and bothers the patients but little. Data processing in photogrammetry has long been so laborious that this has prevented regular application to accomplish such tasks. To what degree has this changed by now and how will it develop in the near future?

In order to evaluate the feasibility of obtaining individual body parameters by photogrammetry for subsequent inclusion in high quality kinetic gait analysis, a pilot study was performed on a collaborative basis including the Biostereometrics Laboratory of the University of Akron, Ohio, a photogrammetry laboratory at the University of Illinois in Champaign-Urbana, the Bioengineering Centre of the University of Strathclyde in Glasgow and our Institution.

METHODS

10 normal individuals age 8 - 18 years as well as 10 age and sex matched patients with spastic diplegia have been examined in brief swim wear. For **data acquisition**, orthopedic medical examination was followed by weighing and by marking 107 anatomical sites with stick-on reflective markers defining joint locations, segmental boundaries and other landmarks.

For evaluation of Human Segmental Body Volumes and Inertial Properties using stereophotogrammetry, data were collected by means of stereophotogrammetry for the determination of segmental body volumes and their respective inertial tensors. The methods of simultaneous recording of front and rear stereopairs requires the use of two pairs of stereometric cameras linked together by electro-mechanical shutter releases. Stroboscopic flashlamps illuminate the subjects and are used to project a random pattern onto the surface of the subjects to increase the surface contrast necessary for data reduction. For the purposes of this investigation, wide angle stereometric cameras (Hasselblad Superwiede Angle) were used. The cameras are equipped with Biogon lenses having a focal length of 38 mm. The cameras were modified for glass plates using film planes containing fiducial markers. All subjects were photographed while standing in a control reference frame which provided spatial information to enable the linkage of front and rear stereomodels and to provide proper scaling information for the data analysis.

Following development and enlargement of the exposed stereopairs, the data were reduced using a modified Kern PG-2 stereoplotter. The plotter allowed the operator to obtain coordinate triplets for a series of points on the surface of the subject's photographic image. The methodology used has been comprehensively described by Herron et al. (1974, 1975). To insure ease in computation of the volumetric information, the points representing the body surface were collected in parallel crosssections approximately 2.0 cm apart and lying perpendicular to the long axis (cranial-caudal) of the body. In addition to the crosssection data used to describe the shape of each body segment for computation of volume, further coordinates were collected to provide planes of segmentation for separating (analytically) major body parts such as the thigh, shank or foot. These extra landmark coordinates were used to describe anatomical axis systems necessary for translation and transformation of coordinate systems in the kinetic data analysis phase of the study.

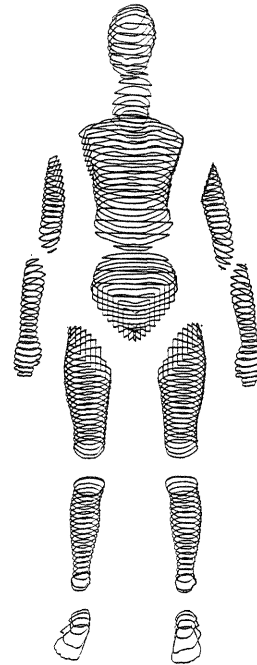


Fig.1: 13 segment model, photogrammetric reconstruction from 2 cm slices.

Resistance to the change in angular velocity depends upon the mass of the body and its distribution about the centers of rotation. This resistance is referred to as the mass moment of inertia (I). The geometric properties, hence shape or volume distribution, determine the extent to which each particle of mass contributes to the moment of inertia. The mass moment of inertia about an axis greatly determines the dynamics of the body segment undergoing simple rotation. Because the body is three dimensional an inertial tensor is produced to describe the moments of inertia about the three orthogonal axes. Because only one inertial tensor exists for a non-symmetric body in which the off diagonal elements are zero, we can describe this entity as containing the principal moments of inertia, which greatly enhance the comparison of the mechanical properties of motion from one subject to another. Based upon a uniform density assumption, the segmental mass and center of gravity could be determined and therefore enable a comprehensive joint kinetic analysis to complement the traditional gait analysis techniques.

Data evaluation and processing of the static tests consisted in constructing a 13 segment body model for each of the 20 test persons with calculation of segmental volumes, segmental masses and mass centers from the two pairs of stereophotographs. A pair of 16 mm film images with DLT calibration served to link 3D body marker positions obtained in the global axis system with the laboratory space coordinate system as used for gait recordings. Marker positions were manually digitized from projected film images.

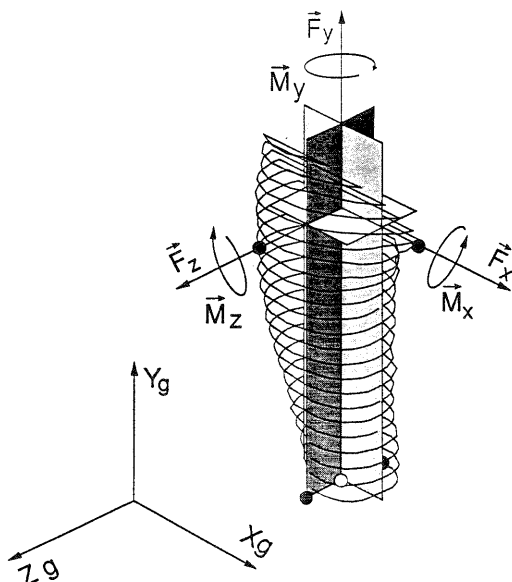


Fig. 2: Anatomy based coordinate system of right thigh.

For evaluation of the dynamics of the right lower extremity during walking, one typical gait cycle of each person was chosen for manual digitization of 3D marker positions from paired synchronous images with real time in milliseconds marked on each 16mm filmframe. Translational and angular velocities and accelerations of the right thigh and shank-foot segments in space were calculated. The reactive forces and moments occurring at the hip and knee were obtained from the prevalently gravitational loading of the force measuring platforms and the effects of segmental mass accelerations produced by muscle activity during swing and stance phase of the steps. For these calculations the inverse dynamic approach was used. (Schär et al. 1989).

RESULTS

The usefulness of data from gait analysis for medical purposes depends on the reliability of measurements, their linking to accustomed anatomical knowledge and presentations permitting rapid appraisal. Graphic reports are therefore obligatory. The ability shown here to extract measurements from images of the whole person in motion and to link other data from electronic transducers to them, allows data to be shown within the context of these total body images. This permits the observer to link measured phenomena with large sets of information gathered rapidly from body proportions and the actual position of hundreds of large and small joints during the particular phase of the movement. The evaluation of the relative value of results from limited measurements in the context of a highly complex situation is thus greatly facilitated. This may be decisive to the widespread acceptance of motion analysis as a diagnostic medical tool.

The biostereometrics approach has proven to be ideal as a technique for producing inertial body segment information for handicapped subjects for two reasons. The subject time involved is greatly reduced for that necessary to collect anthropometric data used in prediction equations of segmental parameters. Secondly, the photogrammetric technique is in a sense a customized estimation process not hampered by

contralateral body asymmetry often seen in CP patients. This research project has clearly demonstrated the ability to combine two different and independent analyses, through the use of common reference points which could be used for axis systems definition necessary for both the gait analysis and the body segment parameter computation.

The addition of the segmental mass distribution, parameters provided information for the kinetic evaluation of the two groups of subjects. These data were used in calculating external forces and moments at the knee and hip in the anatomical axis systems. Several examples of the analysis follow:

a. **Hip Forces:** A rapid and strong force acting to push the femoral head forward and thus favouring the increase of its anteversion was observed in the antero-posterior hip force during weight acceptance of the CP patients. In the extreme case, this force was more than twice the average normal value and in several patients this net anterior hip force continued throughout the entire stance phase.

b. **Knee Moments:** In comparison to the normal subjects, a much stronger and more prolonged reactive abduction moment was seen following the initial ground contact of the spastic diplegic subjects. Perhaps this phenomenon was explained by abductor muscle spasticity. Even more important to the gait analysis was the finding that the flexion-extension knee moment coinciding with the early and late swing phases was twice the value of the normal subjects.

c. **Hip Moments:** Typically seen were increased adduction and abduction moments (due to the increased moment of the shank-foot) during the swing phase of the stiff appearing spastic gait. A strong flexion moment of twice the normal intensity was observed in the late swing phase of the CP patients.

The spastic diplegic patients demonstrated a more powerful and longer lasting flexion moment after initial ground contact which lasted throughout the stance phase. In summary, all of these increased moments and forces quite simply contribute to a decrease in the efficiency of the energy utilization of the child with spastic diplegia. The results of our study are consistent with the clinical observations of both the normal and pathological gait patterns observed. However, the quantification of the contributions of the inertial properties allows comparison of groups of subjects throughout the various portions of the gait cycle. By normalizing the gait cycles, the moments and forces can be compared for subjects of differing sizes and weights.

Knee Moments

Normal

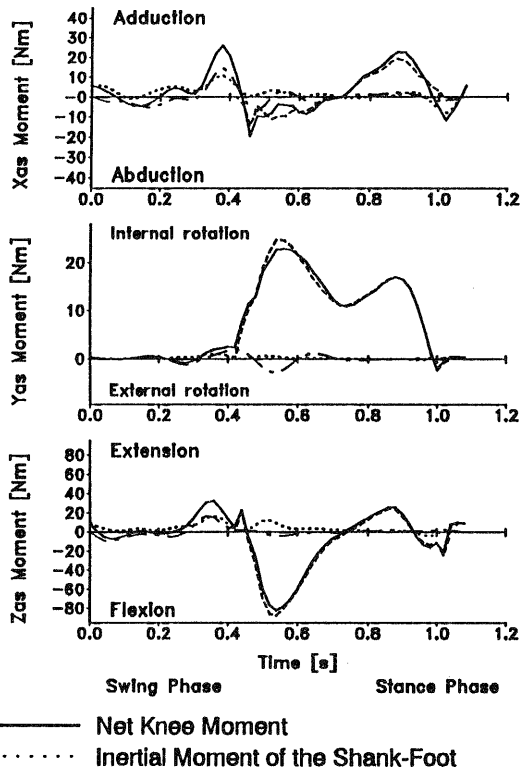


Fig. 3: Reactive knee moments (normal) calculated from ground reaction, inertial properties of thigh and shank-foot segments as well as from rotational and translational acceleration.

DISCUSSION

Two recommendations for further studies became readily apparent following this pilot study. The customized analysis of body shape leading to the mass distribution parametric description is extremely desirable, but nevertheless, very operator intensive. To have these data available, the reduction of the stereometric data must be greatly optimized. Promising developments are seen in the field of image analysis, but the image matching techniques still fall short of satisfactory levels of accuracy when applied to the surface of the human body, because of its monochromatic characteristics of low contrast and structural differences. For the kinematic analysis, the tracking algorithms of marker identification must be improved to include large numbers of markers to increase the accuracy of the three-dimensional motion recording. Finally, the kinematic and kinetic analysis of gait should be expanded to include the study of both legs simultaneously in order to include the influence that the contralateral body has on the entire gait cycle. The total gait analysis should include the contributions of the upper extremities to the locomotion of individuals with pathologic gait.

Spastic Diplegia

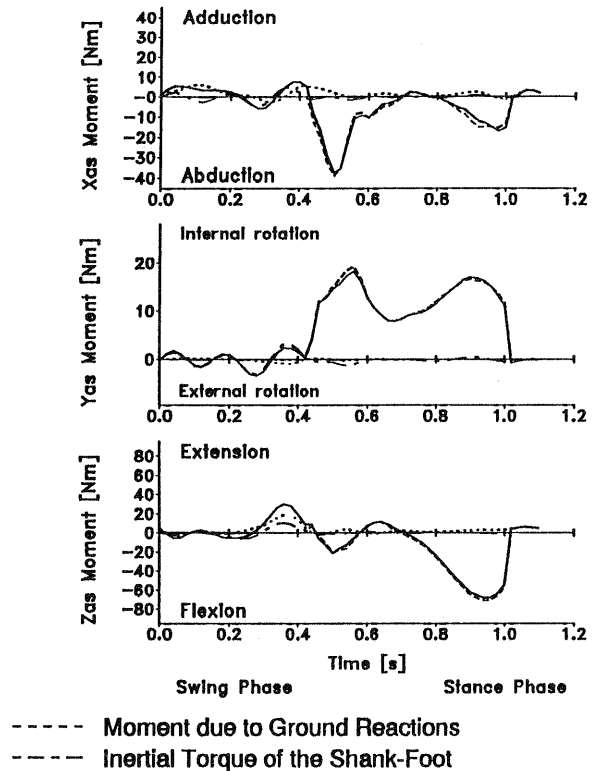


Fig. 4: Reactive knee moments (spastic diplegia) calculated as in Fig. 3.

The usefulness of gait analysis to orthopedic surgery and rehabilitation would be enhanced, if forces and moments at the hip and knee were regularly measurable. This requires the transfer of kinematic measurements in laboratory space to anatomical coordinate systems. In many instances, individual determination of segmental body volume and mass with segmental mass center location is required to calculate the dynamic components of such reactive forces and moments in addition to information from dynamic 3D force plates. Photogrammetry using information from CCD still and movie-video cameras together with digital image processing could deliver the required information in a fast and economically acceptable manner. In addition it would permit graphic demonstration of the results of measurements within the context of particular phases of total body movements, thus enhancing much needed understandability. The pilot study on 20 test persons presented here was performed with conventional film and photogrammetric equipment. The results have provided medically valuable new information on joint forces and moments at the hip and knee during walking in presence of spastic cerebral palsy and normal subjects. The results provide better understanding of the development of secondary bone and joint deformities such as femoral anteversion, loss of acetabular sphericity and deformities around the knee joints in presence of spastic musculature. They are of help to decide on the most suitable plan for treatment.

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