

USE OF TOMODENSITOMETRIC IMAGERY FOR PROSTHESES OF HUMAN KNEE

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Commission V

ABSTRACT

X-ray tomodensitometry is being used more and more for medical diagnoses. A new method of calibrating the tomodensitometric system and generating 3-D data developed at Laval University is described. Subsequent to the calibration, a series of parallel consecutive images obtained in this system for a human knee is digitized. These computer assisted three-dimensional numerical data are used in simulating articular movements and in designing personalized knee prostheses. The obtained results indicate a standard error of less than ± 0.3 mm in each of three dimensions.

RÉSUMÉ

On a de plus en plus recours à la technique d'imagerie-tomographie densitométrique pour préciser un diagnostic médical. Voici la présentation d'une nouvelle technique développée à l'Université Laval permettant à la fois de calibrer tout le système concerné et de fournir des informations tridimensionnelles précises. Par la technique de conception assistée par ordinateur (CAO) on peut générer une représentation tridimensionnelle du genou humain grâce à une série de coupes tomographiques (bi-dimensionnelles) digitalisée. On utilise ces informations pour simuler des mouvements d'articulation et ainsi créer la prothèse personnalisée. On établit par les résultats obtenus que l'erreur standard sur chacune des trois coordonnées est inférieure à ± 0.3 mm.

INTRODUCTION

A growing interest in the World on studies of human body movements (i.e., biomechanics) has been noted. This is due to a great variety of uses of human limbs often involving complex articulations in activities like sports and athletics. The human knee is one of such limbs vulnerable to stress and strain.

In the field of medicine various procedures are currently used, such as arthrography and arthroscopy, whose primary objectives are diagnostic and therapeutic. These, however, do not permit quantitative and dimensional measurements as would be necessary for personalized prostheses.

This study was aimed at developing a new method of obtaining three-dimensional numerical data of knees in-vivo by using tomodensitometric images. Such data would permit the simulation of articulatory movements of the limb with a view to designing and producing personalized prostheses.

DENSITOMETRIC TOMOGRAPHY

In this case, Densitometric Tomography is the data acquisition technique. The technique is based on density calculation on the X-ray of one cross-section of the limb by using mathematically assembled measurements of rays transmitted from different directions.

The installation of "EMI Brain Scanner" at Atkinson Morleys Hospital, Wimbledon, UK in 1971 (Robb, 1985) introduced for the first time such an equipment known in general terms as tomodensitometer. The principal components of the equipment system used in this study (see General Electric, 1982 and Fig. 1) are:

1. The rotating gantry which supports the X-ray source and detectors;
2. The subject table or "couch";
3. The X-ray source and collimation assembly (with associated power supply and cooling system);
4. The detection/collimation system (including electronic amplifiers);
5. The Computer system (including the analog-to-digital convertor); and
6. The display and analysis console;.

To these can be added two other components also:

7. The diagnostic or independent console; and
8. The multiformat camera.

The detector and the computer are the most important elements in an X-ray CT. The magnitude of the detector opening determines the contrast resolution. The computer is the brain of the system and it distinguishes this form of imaging as being different from other forms of conventional radiography (Figs 2 and 3).

The tomodensitometry procedure is based on density calculations of X-rays on a cross-section of the particular part of the body and the integration of such densities on the same cross-section caused by X-ray transmissions from several directions. The final (integrated) density distribution can, with the help of a computer, illustrate an image of various anatomical details in the cross-section. This technique is thus free from the loss of details caused by X-ray shadows in conventional radiography.

The X-rays travel in rectilinear paths. The transmitted rays are registered in accordance with their difference of absorption and diffusion. This property of the body matter is expressed by its "coefficient of linear attenuation". Even though most of the tissues of the body matters are composed primarily of water, they are sufficiently diverse to give significantly different attenuations.

The coefficient of linear attenuation (also known as CT Number) is determined by the following expression (Harrison, 1981):

$$H = \frac{\mu(\text{tissue}) - \mu(\text{water})}{\mu(\text{water})} \times 1000$$

where H = coefficient of linear attenuation;
and μ = coefficient of attenuation.

In practice, H for air is considered as -1000 while H for water is +1000.

When a section of the human body is scanned by X-rays from several directions and integrated, this section (slice) can be subdivided into tiny square blocks as "voxels" (Volume elements; Robb, 1985). In short, the coefficient of linear attenuation is proportional to the average relative attenuation in a voxel. The image (2-D) displayed through the use of the computer corresponds to a matrix of tiny squares with each square having an uniform tone of gray proportional to the attenuation coefficient of the corresponding voxel. These two-dimensional tiny squares are called "pixels" (picture elements) - similar to those used in Remote Sensing. Several such sections (tomographs) can be obtained by simply displacing the couch inside the gantry (Fig. 1). Each of these tomographs can be assumed to liken a parallel projection (Fig. 4). Scale and distortion considerations can relate to such a form of projection. The calibration technique discussed below is based on this concept.

DATA ACQUISITION

- The tomographic system used for the acquisition of images used in this study was a CT Scanner by General Electric (Fig. 1). This is a III generation system (GE Medical System, 1982) having the following characteristics (Bougouss, 1987):

- . Resolution: 0.5 mm
- . Scan time: 1.3 sec (partial scan); 2, 3, 4 and 8 sec (360° scans)
- . Slice thickness: 1.5, 3, 5 and 10 mm
- . Data collection rate: 980 views/sec
- . Detection system: X-3 xenon detection with 742 elements
- . Image reconstruction matrix: 256², 320², 512²
- . Gantry inclination: -20° to +20°.

- The computer for acquisition and reconstruction of the tomographic image is of the type Data General S/140 furnished with a Winchester disc of 354 mega bits.

- A Multiformat camera, controlled with an independent console. The images can be recorded on 3 different film sizes: 8" x 10", 11" x 14" or 14" x 17". Two image formats are available: 3.89" x 3.75" or 5.97" x 5.75". The image dimension is controlled by the change of the image format at the monitor and not by the optical system.

- The Cube for calibration (Fig. 5) is made of plexiglass sheets, of size 23 x 23 x 20 cm, giving two open ends of 23 x 23 cm through which a human limb like an arm or a knee can be inserted. The cube contains parallel and diagonal threads of lead embedded on the outer surface. The metal lead is used due to its opacity to X-rays. These threads (lines) provide certain points whose positions (X, Y) on each tomograph are known. The diameter of each such point is approximately 0.3 mm. The maximum positional error of these points (due to possible imperfections in their placement) is estimated to be ± 0.1 mm. The diagonal lines provide points which can be utilized to determine the distances between successive tomographs, or in other words, to establish the Z (constant for each section) coordinate.

- The photogrammetric measuring instruments are Wild Stereocomparator STK-1 (for off-line processing of data) and Wild Analytical Plotter BC-1 (for on-line use).

- A terminal TEKTRONIX 4016-1 connected to a VAX computer (for STK-1 data) and the NOVA computer which is an integral part of the BC-1.

Instead of unnecessarily exposing a living person, for the preliminary experiments a knee-bone (femur) taken from a cadaver was used. The bone was introduced in the plexiglass cube for the calibration studies. The plane of the gantry being vertical (Fig. 1) a series of 25 tomographs (25 parallel sections) were taken. The interval between sections was 5 mm except for the head of the bone where, in view of rapidly changing surface topography, it was 3 mm. Each tomograph contains a matrix of 512 x 512 pixels, the size of each pixel being 0.94 x 0.94 mm, corresponding to each voxel size of 0.94 x 0.94 x 0.5 mm.

After the image is viewed and verified on the console, it is recorded with a multifomat camera on Kodak film of NMC (Nuclear Medicine on Clear) base in which the resolving power varies, depending on the contrast, between 50 and 200 lines/mm (Eastman Kodak, 1982).

Each piece of 14" x 17" size film having a single layer of emulsion is placed in a cassette as in the case of conventional radiography. Each film contains 12 tomographs (photos) of size 3.89" x 3.75". Approximate scale of each photograph is 1:4.

All the 25 photos are next observed to obtain all necessary photo coordinates at the Wild STK-1 stereocomparator (used in the mono-mode) connected with an IBM-PC computer having RS-32 interface, to record the x, y coordinates directly on discs. Each control point is observed twice. For the current experimental studies only the external surface of the bone was considered, where a point was observed at every 0.5 mm (in the scale of photograph).

CALIBRATION

The calibration is based on the consideration that the projection geometry of each tomograph is assumed to be "parallel". The automatic integration of X-ray scanning from all around the object being done in producing a tomograph would corroborate this premise of parallel projection. The

calibration is realized by a Least Squares adjustment based on the following transformation polynomials (for each tomograph):

$$X = a_1 + a_2x + a_3y + a_4x^2 + a_5y^2 + a_6xy + a_7x^3 + a_8y^3 + a_9x^2y + a_{10}xy^2$$

$$Y = b_1 + b_2x + b_3y + b_4x^2 + b_5y^2 + b_6xy + b_7x^3 + b_8y^3 + b_9x^2y + b_{10}xy^2$$

where X, Y are the coordinates of object points used in calibration;
 x, y are their photo-coordinates (observed);
 and a's and b's are the error coefficients of the mathematical model.

This transformation considers scale affinity as would be expected in the system. Once the polynomial coefficients are determined, their values are used to transform all object points. This being done for all the 25 tomographs. One can get an idea of the results as presented in the following table:

Table 1: Calibration Results (samples)

Photo No.	Scale factor		σ_X (mm)	σ_Y (mm)
	in X	in Y		
1	4.20	3.96	0.11	0.08
5	4.20	3.96	0.11	0.08
9	4.19	3.95	0.09	0.07
13	4.20	3.96	0.11	0.07
18	4.21	3.95	0.12	0.09
24	4.21	3.97	0.10	0.07
25	4.19	3.96	0.09	0.08
Average of all 25	4.19	3.96	0.10	0.07

With regard to the Z coordinates, after establishing the datum at the first section (Z_1) the Z values of other sections are obtainable by considering a simple relationship based on linear proportionality:

$$Z = Z_1 (\underline{1} / \underline{1}_2)$$

where $\underline{1}_2$ is the distance measured on the first section and $\underline{1}$ is the distance corresponding to $\underline{1}_2$ on the section concerned. The standard error in Z coordinate determination in the current studies is estimated to be ± 0.14 mm.

GRAPHICAL REPRESENTATION

The three-dimensional graphical representation is performed by using numerical (digital) data. It permits to envisage a part or details of various parts of the object by means of perspective diagramming (Fig. 6) in consideration of its shape, volume, surface and specific cross-sections. Furthermore, it can be extended into deriving ideas on its weight, moment of inertia, etc. It also offers various other possibilities like shifting or rotating the object and finally manufacturing (reproducing) the object replica by using a digitally controlled machine (Matra Datavision, 1984) after the program known as EUCLID.

The equipment comprises: (1) a high resolution graphic terminal TEKTRONIX 4016-1 connected to a printer, HP 7580 B; (2) a computer, VAX 785 with two disc units; and (3) an alphanumeric screen, VT-240 with its keyboard.

The tomographic data cannot be used directly by the "EUCLID" because the number of points digitized per section is not constant as also the difference (distance) between successive sections may not be the same. Therefore, certain extra points may have to be generated by way of interpolation of observed points in order to create a grid network around the object. This is done with a Fortran 77 program developed for this purpose. This program can determine new points as necessary by non linear regression of the form (Howard, 1977), which gives the best results:

$$Z = a_1 + a_2X^2 + a_3Y^2$$

where the a's are coefficients of the polynomial.

This program requires a 5 meg memory.

CONCLUSION

The obtained results are very satisfactory. Firstly the calibration process indicates the existence of certain scale affinity in the tomographs. Secondly, the final precision depends on the polynomial used in the calibration process. The third order polynomial with 20 unknowns gives a standard error of less than ± 0.12 mm whereas its simplified version (first order polynomial with 6 unknowns) gives a standard error of less than ± 0.28 mm, which may be acceptable in most applications. From this one may draw the conclusion that a two-dimensional affine transformation requiring four points on each tomograph may be sufficient for the calibration.

Prostheses are possible by knowing the mass volume and the configurations. One can digitize the muscles and tendons to study biomechanic movements. The developed technique can also be utilized in transplantation of most limbs/organs of a human body.

In order to make the technique more cost-effective, it would be better to minimize the time necessary for observation and computation i.e., to adapt it to be "on-line" at an economical analytical photogrammetric equipment system.

Such digital 3-D data have the advantage of being able to develop "mirror reversed" models. For example, a prosthesis can be developed for a completely damaged left leg of a patient by using tomographs of his right leg.

Stereograms can also be prepared of such perspective diagrams for better visual appreciation of the object as has been done by Bougouss (1987).

Organ transplantations (heart, lung, kidney, etc.) would become easier with a developed data bank towards matching the donor and the receiver for their shapes and sizes.

ACKNOWLEDGEMENT

The Natural Sciences and Engineering Research Council (NSERC) of Canada provided support for some portion of the related research through their Grant N° A-1177. The Laval Foundation of Radiology at the Hôpital de l'Enfant-Jésus, Quebec, permitted their facilities for obtaining all necessary tomographs in this study. This involved the assistance of Dr. Gaston Paradis, Mr. Pierre Cantin, Mme Céline Bédard and Mme Ginette Blouin, all of this hospital staff. Dr. M. Richard of the Department of Mechanical Engineering of Laval University assisted in providing the calibration cube. Mr. François St-Onge of the General Electric Company of Canada and Ms Sylvie Rochon of Kodak, Canada provided further useful information. These are all gratefully appreciated.

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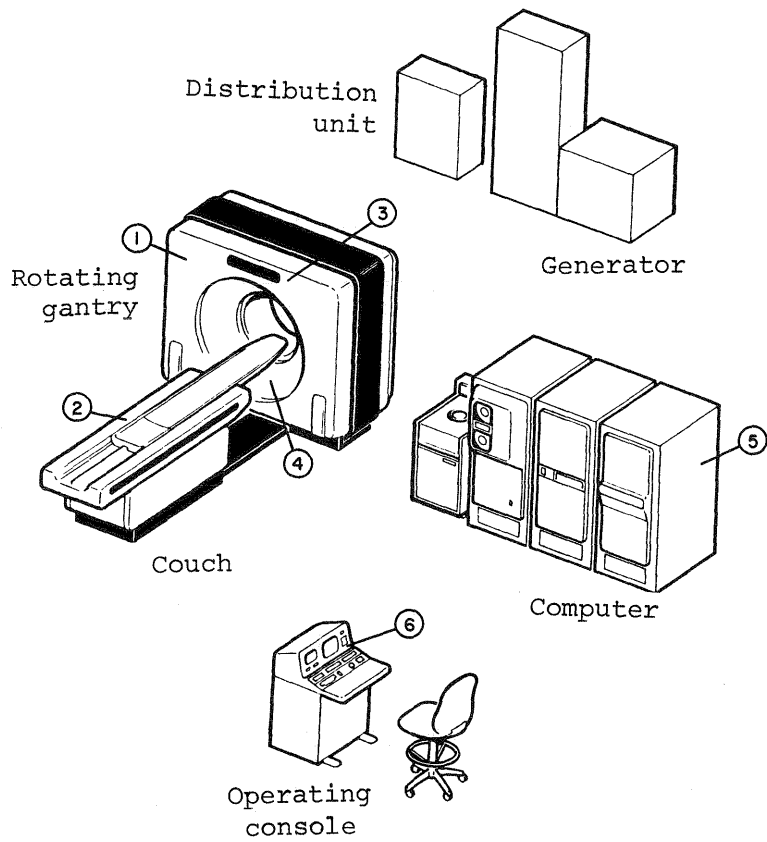


Figure 1: Components of Tomodensitometry system

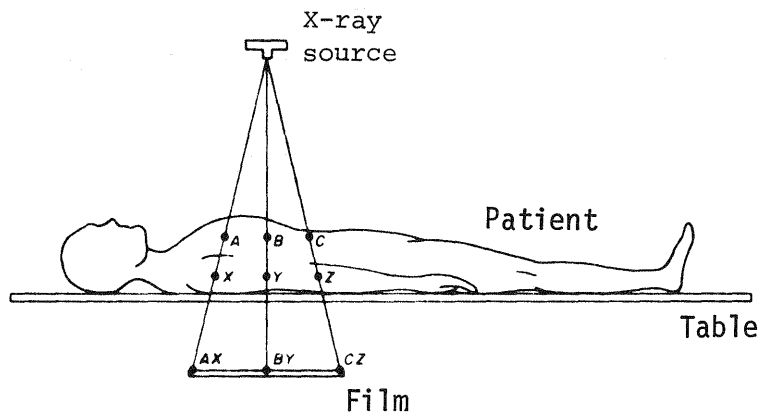


Figure 2: Conventional technique of radiography

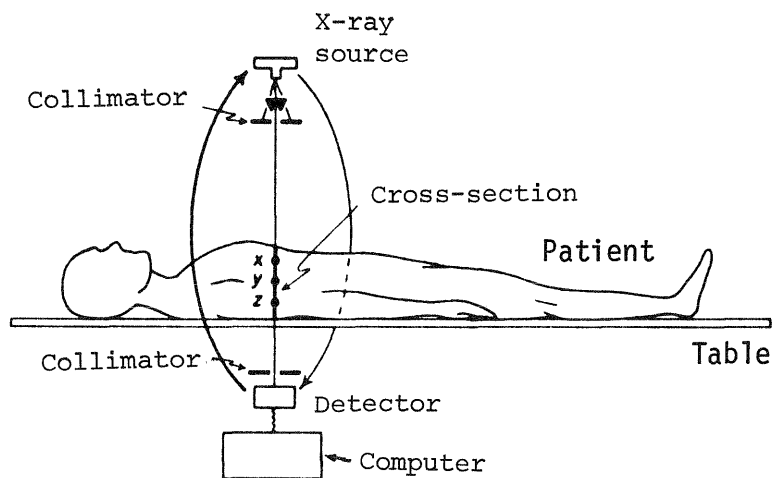


Figure 3: Tomodensitometric technique

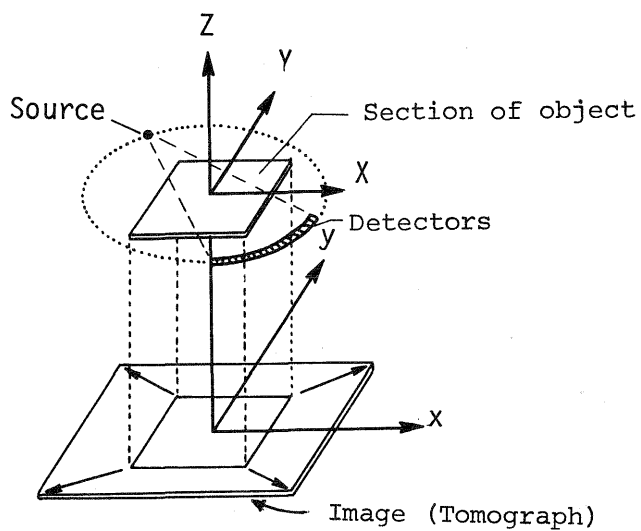


Figure 4: Parallel projection (Schematic)

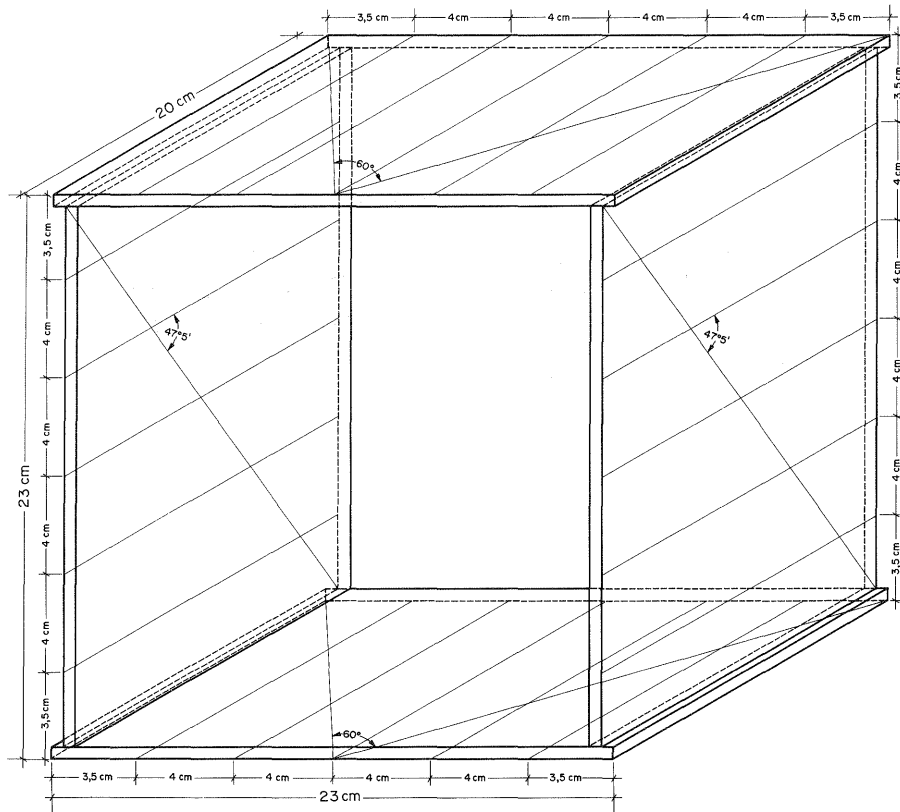


Figure 5: The calibration cube (plexiglass, indicating location of embedded threads of lead)

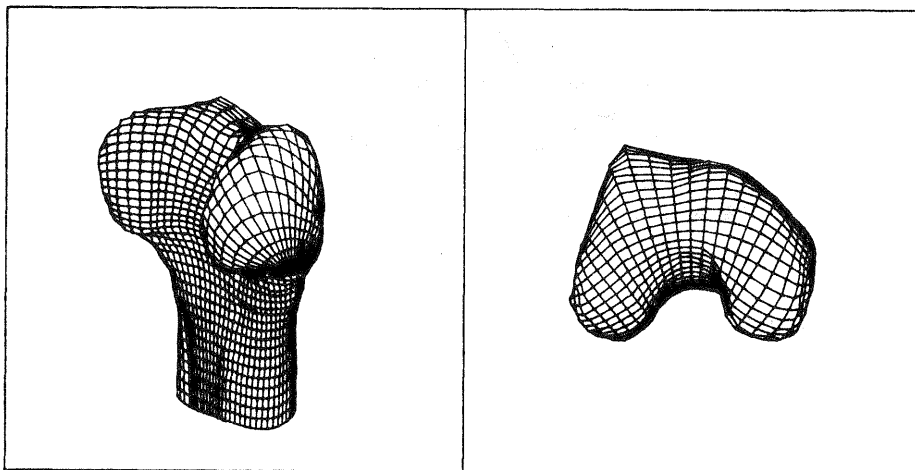


Figure 6: Perspective diagrams (samples)