Comparison of Image Processing Techniques (Magnetic Resonance Imaging, Computed Tomography Scan and Ultrasound) for 3D Modeling and Analysis of the Human Bones

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Magnetic resonance imaging (MRI), computed tomography scanning (CT scan), and ultrasound imaging techniques (UI) were used for data acquisition to construct/develop a 3D solid model of the human tibia, femur, and skull. CT scan was found to be an acceptable technique for cadavers. CT scans are harmful to the human body in large doses, while MRIs and ultrasound are known to be safe. However, MRIs form a better tool in performing this image generation task for living beings because of its high resolution capacity when compared with images obtained using ultrasound techniques. High resolution poses to be a very important factor, as the consideration of various material properties of the bones was part of the emphasis of this research. MRIs have the capacity of displaying a distinct boundary between the muscles and the bone, in addition to the boundary between the cortical and the cancellous region within the bone. Ultrasound was found to be the cheapest technique and gave reasonably good results for just the outside boundaries of the bone. The models of the human bones were generated on a Computer Aided Design (CAD) system. The cross-sections obtained from (MRI, CT, or UI) were scanned into the computer. Image processing software was used to detect the boundaries of the bones. A C + + program was used to read the coordinates of the edges and construct a B-spline curve on the CAD system. The curves were converted to a B-rep solid using skinning. The solid models were meshed, constrained, and material properties were assigned to different regions of the models for Finite Element Analysis (FEM).

KEY WORDS: 3-D, Modeling, FEM, biomechanics, MRI, CT scan, ultrasound.

STATISTICS FROM the National Safety Council[1] confirm that vehicle accidents are a major cause of death in this country. The goal is to make all crashes survivable. The goal is very optimistic, but at least the crash worthiness design of aircraft and vehicles to be improved, are definitely justifiable and warranted. The effect of the head injury problem can be gauged from some statistical data collected during the mid 60s in the US. Approximately 58 million persons are injured per year. Of these, 3.5 to 3.8 million occur in motor vehicle accidents. In about 70% of these, the head is involved. Many of these are minor or nondangerous, involving lacerations, contusions, and even brief unconsciousness. Yet of the 45,000 to 50,000 annual fatalities resulting from motor vehicle accidents, about 62% or 30,000 can be directly attributed to head injury. Thus, the total number of fatalities in the country due to cranial trauma can be expected at a level of about 100,000 per year.

Recent research in the field of automotive crash analysis and its effect on the human body has brought us to a point where injury to the upper human body has been reduced to a certain extent. This has been achieved mainly by designing cars incorporated with air bags. In the event of a car crash, it has now been discovered that the human lower leg is another part of the human body that is severely effected. It is the tendency of the driver of the vehicle to suppress the brake pedal, just before impact, involving two automobiles. This action results in the lower leg taking on most of the impact. This research was aimed at developing 3D models of the skull, tibia, and the femur using the best available imaging technique and to determine the stresses developed while subjecting each one of them to various loading conditions.

The most widely used techniques to capture images of the human skeletal system are x-ray (computed tomography [CT scan]), ultrasound, and magnetic resonance imaging (MRI). All of these techniques differ mainly in the degree of resolution that can be achieved and their capacities to penetrate bones and tissues. X-rays have excellent resolution and can differentiate bone boundaries extremely efficiently, but are in a way harmful to the human body if used in large doses.

The major advantages of ultrasound scanners are low operation costs, portability, and most important of all, its use of nonionizing radiation. Ultrasound makes use of sound waves that have a frequency

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beyond the human audible range, which is between 20 to 20,000 hertz (Hz). In medical applications, a range of 1 to 10 megahertz (MHz) is used to produce ultrasound waves. A clinical ultrasound image is obtained from the echoes that occur at organ and tissue interfaces within the human body. The ultrasound technique is very good when images of organs or tissues are required. However, it does not do a good job when it comes to images of the skeletal system. Ultrasound does not have the capability to penetrate air and bone regions. The images of the tibia obtained through the ultrasound technique were studied and a distinct boundary between the muscles and the bones in the lower leg was not observed. Moreover, because ultrasound does not have the capability of penetrating bone, a boundary between the cortical and the cancellous regions of bone was not evident.

MRI is one of the latest technologies employed in 3D medical imaging. It is also known as nuclear magnetic resonance (NMR). Hydrogen is one of the elements that is found in abundance in the human body. MRI uses the proton density of the hydrogen atom and the radio frequency response of the spinning nuclei to magnetic fields and radio waves to generate an image. The human body is first subjected to a strong magnetic field and then is exposed to radio-frequency waves. Each atom in the human body acts as a small magnet when exposed to an external magnetic field. Once a radio-frequency wave is passed through the body, some atoms are affected. Upon switching off the radio-frequency wave, these atoms generate a radio-frequency wave, which is picked up by an antenna and used to display an image. Each material within the human body has a different radio-frequency response and hence produces the required contrast in images.

Computed axial tomography (CAT) is an x-ray imaging method that produces images of selected planes or slices through the patient's body. In conventional x-ray imaging (radiography and fluoroscopy), an image is formed by projecting a large-area x-ray beam through the body and, in principle, casting shadows of internal body structures. In CAT, the formation of the image is a distinct two-step process. In the first step, a very thin x-ray beam is passed through the edges of the slice while the beam is rotated around the body. During the scanning process, no image is actually formed; however, the amount of radiation that penetrates the body section is measured, and the data is stored in computer memory. Then the computer creates, or reconstructs, the image in the second step. The image reconstruction is a mathematical process of converting x-ray penetration data into a numerical or digital image. It is the computer reconstruction of an image of the selected slice of tissue that gives CAT its unique characteristics.

The major advantage that CAT has over conventional radiography and fluoroscopy is a much higher contrast sensitivity. Computed tomography is capable of producing visible contrast (different shades of grey) in images between various soft tissues. There are various factors that contribute to its high contrast sensitivity. The notable factor is all the tissues within a slice are viewed directly, as it is a tomographic imaging method. Also, a relatively thin x-ray beam used in CAT produces much less scattered radiation than the large-area beam used in radiography. This also improves contrast sensitivity. This high contrast sensitivity of CAT makes it a valuable imaging method for displaying soft tissues.

IMAGE ANALYSIS/PROCESSING USING CT SCAN (HUMAN SKULL)

It was found that CAT[2] was the best available technique to obtain images of the various cross sections of the Homo sapiens skull under the available resources. Each cross-sectional image was taken at a fixed distance from the previous one. The CAT scanner facility at the O'Bleness Hospital in Athens, OH was used to obtain the images of the skull. The skull was positioned vertically (supero-inferior) on the scanner table. CAT has proven to be one of the most reliable imaging techniques to obtain 2D scans of an object. It also provides a precise image of regions within the object being scanned. 14 cross-sectional scans of the skull were taken, each at a distance of 13 mm from the next. To extract the x, y, z coordinates of the scans, the CAT scans were fixed to a plate below which a light source was placed, to enable a camera to pick up the image. The camera was totally automatic and was positioned directly above the scans. The camera was connected to a color monitor, which was also connected to a personal computer (PC). Thus the image of each scan was reproduced via the camera on the color monitor and stored to a disk in some raster format. A software called OPTIMUS (Bioscan Inc, Edmonds, WA), which runs on a PC was used to acquire the coordinates of the various cross-sectional images. B-splines curves were generated on the CAD system using a C + + program. The curves were converted into a B-rep solid using skinning. Features for the eyes and nose were added to the solid and boolean operations were performed to obtain an anatomically correct model of the skull (Fig 1).

The different finite element packages used in this investigation are I/FEM and MSC/PATRAN for pre- and postprocessing and ABAQUS for nonlinear analysis.[3,4,6] Skull bone is assumed to be elastic, homogeneous, and the spinal fluid is assumed to undergo viscoelastic response. A prony series distribution is used to define its viscoelastic material response. An equivalent load in the range of 2,650 to 4,000 lbs taken from experimental investigation of National Highway Traffic Safety Administration (NHTSA) is applied for the frontal nodes in the y-direction or in anteposterior direction as in frontal impact. The load applied in the head impact analysis is made to vary as a haversian sine-function. The model is analyzed for different boundary conditions like considering both head-neck joint and skull alone. For the skull boundary conditions, the nodes on the opposite side of the direction of load are fixed in all directions or constrained to move in a plane perpendicular to load application. For the head-neck joint model is modified to include lumbar spine until the sixth vertebra. Static, dynamic analysis with implicit method using automatic time integration technique

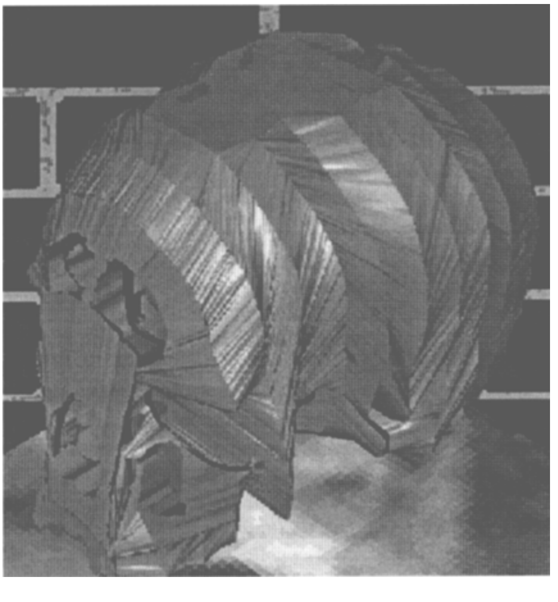

Fig 1. Solid model of the human skull using CT scans.

and modal dynamic analysis are performed on this model for different time steps and for different material properties. Even though these models are slightly approximated, the results obtained have given substantial insight into the head injury phenomenon. The models have confirmed the theory of countercoup mechanism as proposed by Anzelius.[4] It is observed that with the increase in the complexity of the model, the inflection area or the maximum stress concentration area is increasing and varying in position. It can be concluded that the membranes play a significant role in determining the accurate frequency response of the skull.

IMAGE PROCESSING USING MRI AND ULTRASOUND (HUMAN TIBIA AND FEMUR)

A 3D model of the human tibia and the fibula, with a length of 443.5 mm was developed. MRIs and ultrasound images were used to extract two dimensional coordinates of the cortical and cancellous regions in both the tibia and the fibula. A total of 23 sections were taken at varying distances along the length of the lower leg, with the frequency increasing in the regions of the knee and the ankle. This was done to attain greater accuracy while capturing geometric characteristics of the tibia and the fibula. OPTIMUS, was used to digitize the images to extract the coordinates. The resolution from ultrasound imaging was very poor and the edge detection and model creation was very difficult and tedious. The model generated using ultrasound looked anatomically incorrect compared with the model generated using MRI and some textbook models. The outside boundary in each scan was easier to detect in the ultrasound images compared with the boundary for the cortical and cancellous bones.

The solid model of the tibia and fibula[5,7] was developed using the x, y, z coordinates and the skinning command on the CAD system (Fig 2). A 3D finite element model of the tibia was then developed using PATRAN. An equally distributed load of 2450 N was applied over an area where the lateral and medial condyles of the femur came into contact with the tibia. This was load experienced by the tibia during normal gait in the stance phase at full extension. The model was made up of three materials, namely, the articular cartilage, cortical region, and a cancellous region. The articular cartilage was found to deflect by a total of 7 mm. Moreover, up to a distance of 90 mm from the proximal end of the tibia, the maximum compres-

Fig 2. Solid model of the human tibia and fibula using MRI.

sive stresses was found to be 23.1 N/mm^2. However, a maximum compressive stress of 43.5 N/mm^2 developed in the medial region, about 70 mm from the distal end of the tibia. This result could be associated with the geometric characteristic of the tibia. The shape of the tibia could also be the result of the increase in deflection by 2 mm of articular cartilage, when compared with studies performed by other researchers. This proves the importance of consideration of the whole tibia for modeling and stress analysis.[5]

A 3D solid model of human femur was constructed using MRI, image processing software, OPTIMUS, and solid modeling system. Finite element analysis was performed using P3/PATRAN and ABAQUS to evaluate stresses, and displacements developed under static and dynamic loads and to study the effect of varying material properties on them. Loading conditions and material properties were taken from literature. Finite element models with seven mesh densities were constructed to determine the optimum mesh. For the rest of the research, linear static and dynamic analysis was then performed on two and three material models to calculate the stresses and displacements. The results were compared with the ultimate strength of the different materials. The distribution of the deflection and stress values developed compared well within the limits of those existing in literature. A optimum mesh density of 0.31 was obtained and the Von-Misses stresses for one and two material property was 5.63 N/mm^2 and 12.25 N/mm^2. These values were far below the ultimate strength of the materials. Nodal displacements of up to 1 mm was obtained, which compared well within displacement range obtained by past researchers. The maximum Von-Misses stress was found along the weakest cross section nearly 150 mm from the posterior end. The principal stress at this cross-section was maximum.

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