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A CT Database for Research, Development and Education: Concept and Potential

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Both in radiology and in surgery, numerous applications are emerging that enable 3D visualization of data from various imaging modalities. In clinical practice, the patient's images are analyzed on work stations in the Radiology Department. For specific preclinical and educational applications, however, data from single patients are insufficient. Instead, similar scans from a number of individuals within a collective must be compiled. The definition of standardized acquisition procedures and archiving formats are prerequisite for subsequent analysis of multiple data sets.

Focusing on bone morphology, we describe our concept of a computer database of 3D human bone models obtained from computed tomography (CT) scans. We further discuss and illustrate deployment areas ranging from prosthesis design, over virtual operation simulation up to 3D anatomy atlases. The database of 3D bone models described in this work, created and maintained by the AO Development Institute, may be accessible to research institutes on request.

KEY WORDS: Bone, biometrics, morphology, computed tomography, database, education

BACKGROUND

Many medical and, in particular, surgical procedures rely heavily on 3D visual information. In orthopedics and trauma surgery, radiological studies (in two orthogonal planes) are the primary source of visual information for decision making and therapy planning. A computed tomography (CT) is appended only when interpretation of bone and fracture morphology in 2D views is ambiguous. In trauma surgery, CT scans are restricted to complex joint fractures. Spatial interpretation is then essential for preoperative planning, as inadequate reduction of fracture fragments inevitably leads to early onset of arthritis. A CT scan is usually confined to the fracture zone, whereas complete CT scans of long bones with shaft fractures are generally not performed, for lack of therapeutic relevance. Occasionally, additional radiograms or CT scout pictures of the healthy limb are employed for comparison with the impaired extremity. However, complete CT scans of intact long bones are clinically rarely acquired.

Despite the lack of direct therapeutic relevance, full-length CT scans of long bones are valuable for various applications in medical research, development and education. These comprise morphological studies of gender-, age-, and race-dependent biometry and analysis of biomechanical

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characteristics deduced from the structure of compact and cancellous bone. Such morphometric data are valuable in designing new implants, resulting in new devices optimized for robustness and ideal fit in a wide population segment. Volume or surface data of entire bone scans can also be employed for virtual simulation of operations on generic bone models and for visualization in intraoperative navigation. Surgeons still plan their operations by using 2D templates superposed onto conventional radiograms. Surgical trainees should, however, from the beginning learn to appreciate physiological and pathological morphologies in a spatial environment. In this context, visualization applications based on generic 3D bone models will become indispensable for surgical education.

We initiated a project to systematically acquire and archive complete CT scans of intact human bones in a comprehensive "bone database." Subsequently, these data can be made available to R&D and educational institutions on request.

METHODS

At the AO Research Institute (Davos, Switzerland), postmortem CT studies of intact bones are taken from specimens dedicated to research projects, compliant with local ethical committee guidelines. The denuded, frozen bones are defrosted about 12 h at room temperature. The CT scans are then performed on a medical spiral CT scanner (Aquilion, Toshiba Medical Systems). Bone extremities are clamped on a radiotranslucent scaffold and the diaphysis (long axis) aligned perpendicular to the CT gantry. Typical scanning parameters include the following: image resolution, 512 × 512 pixels; voltage, 135 kV; charge, 200 mA s; slice distance, 0.5 mm; kernel, soft to middle hard (FC 31). After scanning, the DICOM (digital imaging and communication in medicine) images are postprocessed, using commercially available software, to create virtual 3D models of the bones. The postprocessing of the data goes through three major steps producing bone models in a variety of formats for different applications. These processing steps are shown in Figure 1. At first, segmentation into triangles for outer bone and inner medullary surface is performed by using the "Amira" Software from Mercury Computer Systems Inc. (Chelmsford, MA, USA). The dense bone can be well isolated from soft tissues and inner medullary surface via a semiautomatic labeling process of the Houndsfield units (i.e., the pictures' grayscale values). Nevertheless, experienced designers must often manually correct these automated threshold results. The subsequent triangulation of the surfaces of the different bone materials is completely automatic and the result saved in the stereolithography (STL) file format. Triangulation is the standard method used for 3D representation of surfaces both for screen visualization and rapid prototyping. The surface structure is defined by adjacent small triangles and can be visualized even on common hardware of a desktop PC. Depending on the granularity (i.e., the number of triangles depicted), the amount of data and computation effort, however, increase rapidly.

In a second step, based on this surface triangulation, the "Geomagic Studio 7" software from Raindrop Geomagic Inc. (Research Triangle Park, NC, USA) is used for a semiautomatic reverse engineering process. The triangulated surfaces of outer bone shape and inner medullary region are converted into nonuniform rational B-spline (NURBS) surfaces. These mathematically describe consistent surface areas that can be employed in 3D computer-aided design (CAD) systems. The NURBS surfaces are

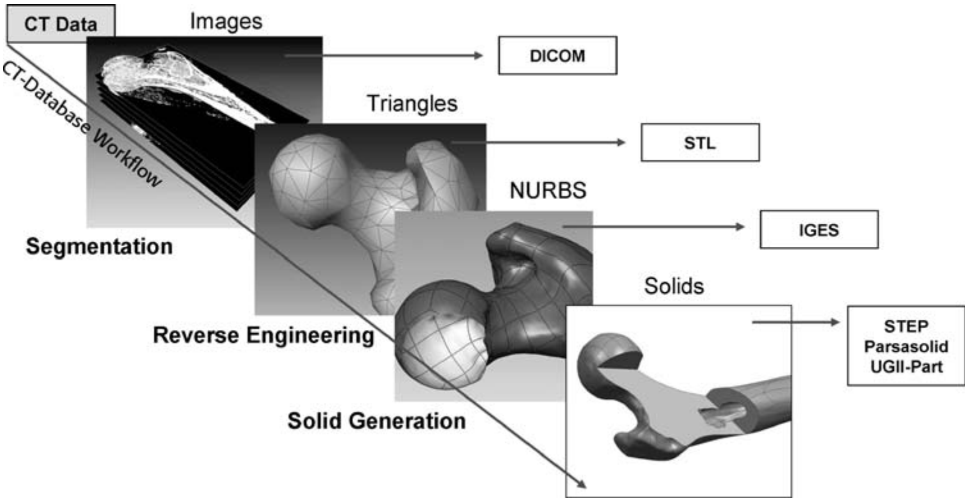

Fig 1. Conversion process of DICOM CT slices. In a simple triangulated surface model, consistent surfaces can be mathematically described by nonuniform rational B-splines (NURBs). Finally, a solid model serves biomechanical studies better than mere surface representations.

saved in the compact International Graphics Exchange Standard (IGES) file format. IGES files are typically 20–30 times smaller than the corresponding STL Files.

Finally, in a third step, solid models are produced employing the CAD software "Unigraphics NX" (Unigraphics Solutions GmbH, Cologne, Germany). These are currently used for implant design and optimization. Additionally, solid models are necessary for potential operation simulation and for biomechanical evaluation using finite element analysis. The solid models can be saved in STEP (Standardized Exchange of Product), PRT (CADKEY Partfile printer), and X_T (Parasolid CAD) file formats.

RESULTS

We created a computer database of full-length models of human bones. The database is continuously increasing; to date, it includes 367 scanned bones (Fig 2). Anonymous patient data are available for about 70% of the bones. The mean age of the bone collective is 69.5 years (10.8–95.9) with 47.9% females. The average body size is 1.62 m (1.45–1.93) and weight 66 kg (29.0–170.0). A summary of acquired data sets is shown in Table 1. The surface and volume conversion is being performed in an ongoing process. As of July 2005, 189 bones were converted. The metadata is stored in tables containing anonymous patient data, scan parameters, and relevant processing details. The DICOM images and the derived CAD files are not stored as actual records, but as separate files on a special file server. These files are referenced from the database tables.

Besides creating the database, we have also begun demonstrating deployment of the database in prototype. Some aspects of our ongoing work are detailed in the next section.

Table 1. Number of CT scans of entire intact bones acquired to date

Bone	Scanned	Processed to date
Tibia	114	38
Femur	90	50
Humerus	47	47
Fibula	37	13
Forearm	18	17
Mandibula	17	16
Foot	14	2
Pelvis	6	1
Clavicula	6	4
Cranium	17	0
Scapula	1	1
Total	367	189

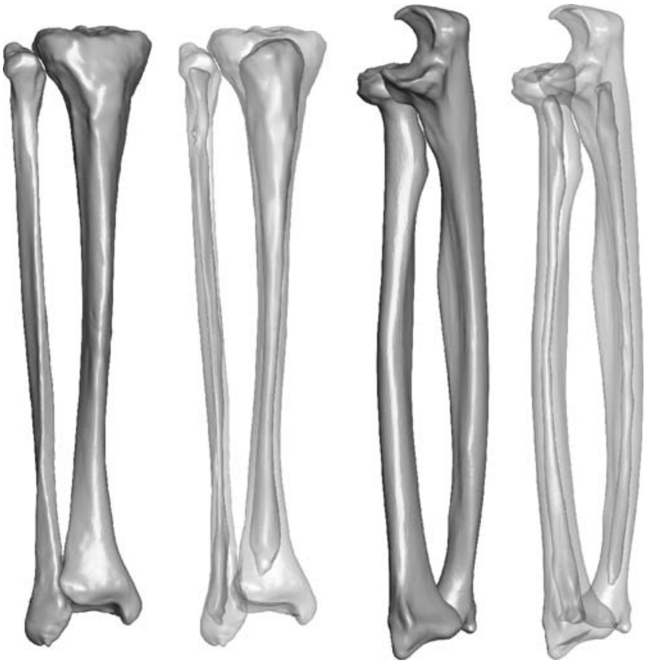

Fig 2. Examples of scans from the CT database: Full-length CT scans of tibia, fibula, radius, and ulna converted to solid models. In the semitransparent view, the medullary cavity is visible.

DISCUSSION

When required for clinical use, CT scans are confined to the region of interest containing the pathology to be examined. Seldom are bones scanned in full length routinely. Systematically building a database of full-length CT scans of physiological human bones, as performed by the AO Development Institute and described above, is a novelty.

Most CT consoles nowadays enable visualization of scanned bones in a pseudo-3D mode. Such reconstructions primarily display the bone's surface topography. Morphological scrutiny of the digital data is possible by using criteria that were previously defined during macroanatomical studies of specimens. However, the bone scan contains much more information than mere surface-bound topography. The interior structure of the bone can also be analyzed on reconstructed CT planes. The cross sections of the medullary canal can be therein described, e.g., as shape, inner and outer circumference, and surface area at various diaphyseal heights. Using digital analysis methods, the bone morphology can be characterized as a set of such morphometric parameters. This data is directly available for repeated electronic processing. Necessity for anatomical dissection of specimens is thus drastically reduced.

In the visual human project, just two individuals were sliced and soft tissues and bones manually segmented to demonstrate an exemplary human body. Acquiring entire series of comparable CT scans takes digital anatomy analysis a step further. Typical bone characteristics can be deduced and a "standard bone" computed out of the series. More important than merely determining an average bone is assessing the biological variability and physiological extremes within a population. Biometric criteria that are gender, age, and race dependent can be examined from multiple individuals. Craniofacial CT scans have been examined in a similar manner, and recently remarkable results published in anthropological studies.[1] We envisage comparable studies for long bones, too.

Current prosthesis and implant development relies on macroanatomical morphological studies, often dating back to mid 20th century. Influenced by nutritional, life-style, and demographic factors, the current population's physiognomy might not anymore be comparable. Obvious racial differences prevail, and implant manufacturers have started designing specific implants, e.g., for eastern societies.[2] Although acquisition of pertinent morphological data from present populations is essential, large anatomical dissection studies are no longer feasible. Hence, systematically collecting CT scans of intact bones gains importance. Moreover, CT data not only reveal morphological aspects but also contain information on biomechanical properties. These can be derived from cortical bone thickness or density of cancellous bone by finite element analysis.[3] Such biomechanical data, together with morphometric parameters, can significantly contribute to the development of new prosthesis and implants, which account for both morphological diversity and biomechanical aspects. Currently, our database contains bones of Caucasian individuals. We intend enhancing our database to comprise scans from various races, e.g., Asian, African. Data from cultural subsets can then enter the process of designing custom implants for specific populations. We also plan to

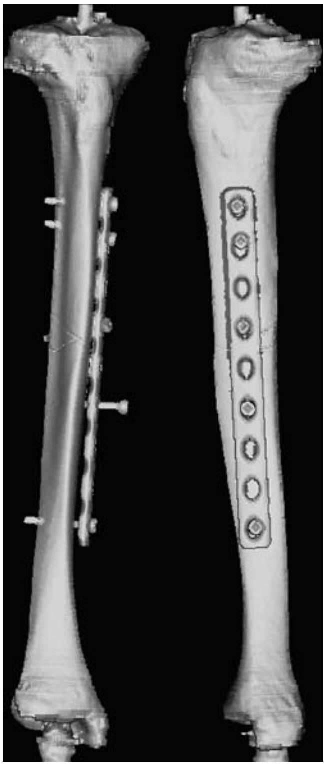

Fig 3. Simulation of osteosynthesis using full-length digital bone models. To date, traditional practical training still relies on plastic bone prototypes.

diversify the age groups when selecting further specimens.

Development of new implants is not the only benefit of the bone database. We also envisage entirely new operation methods, which can be digitally planned and tested by virtual simulation, using volume data of generic bones. The off-line conceptual planning and testing can be enhanced with real-time intraoperation simulations. BrainLAB (Heimstetten, Germany), which specializes in intraoperative navigation, has, for example, already implemented 3D visualization of a generic vertebra model in its VectorVision Spine module. For intraoperative navigation, the 3D data set is registered to the corresponding patient by surface matching. Subsequently, surgeons can track the movement of their instruments on the corresponding 3D representation of the generic bone displayed by the navigation system. Acquisition of additional CT scans of the patient is thus not necessary and exposure to ionizing radiation is reduced.

Preclinical and clinical medical education can also benefit from access to bone volume data. Anatomy should not only depict isolated formaline specimens, but should also embrace a wider spectrum of the biological interindividual variability. Technology for true 3D visualization capable of handling large data is now becoming increasingly available. Although dissection studies will remain an essential part of medical training, high-tech methods will progressively replace traditional teaching and learning approaches. Consequently, there will be a continuously rising demand for pertinent digital data sets depicting human morphology. Rematerialization studies and rapid prototyping replica produced by 3D printers can be used for surgical training. Surgical skills can be practiced on genuine or generic bone morphologies as reported, for example, in Otolaryngology, and maxillofacial and cranial reconstructive surgery.[4] Fracture simulations with 3D models[5] can already replace plastic bones for training of osteosynthesis as illustrated in Figure 3. Exercising preoperative planning on a generic 3D environment will permit the trainee to gain a more a comprehensive understanding of the pertinent bone's morphology. This can subsequently result in more adequate selection and placement of surgical implants.

This introduces another innovative application of the bone database: taking generic 3D procedure simulation to real-case clinical preoperative planning by implementing 2D to 3D image matching.[6]

Fig 4. Example of 2D to 3D registration. The fracture as seen on the 2D x-rays has been transposed onto the 3D bone model using a semiautomatic procedure.

Conventional orthogonal radiographies are still the best available diagnostic tool. To avoid additional CT scanning of the patient before treatment, it would be useful to have access to a database of generic bones. By matching biometrics of the patient's 2D radiographs to the data in the database, a generic CT volume can be accessed that closely resembles the patient's actual morphology. Fracture topology can thereafter be transferred from the patient's 2D pictures to the generic 3D bone model as shown in Figure 4. Thus a CT scan would become superfluous and radiation exposure for the patient drastically diminished. In a future study, we intend to verify our hypothesis that morphometrics from 2D x-rays are sufficient to precisely determine the 3D morphology of the bone and are suitable for selecting an equivalent generic bone from a database.

CONCLUSION

A database of bone scans in full length and corresponding 3D virtual models of entire bones provide morphological and biomechanical information useful for a number of preclinical and clinical applications. Many of these are ongoing or are yet to be realized so that we anticipate a large demand for structured databases of virtual bones. The AO Development Institute is therefore continuously expanding its database and working on defining and assessing new morphometric criteria.

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