Computational methods in orthopaedics

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INTRODUCTION

The title of the session which incorporates this paper, 'Clinical Requirements for Computational Methods', is certainly an appealing one for a scientist who has applied these methods in a clinical environment for a number of years. It does leave room for a personalized report of previous experience and a discussion of research philosophy. Let us first establish that this title is probably not ment to imply that clinicians have requirements for computational methods, at least not the engineering kinds of methods we are discussing here. The majority of clinicians, surgeons in particular, is active mostly in handling patients. Diagnosis, treatment, and result assessment, using methods which are effective, efficient and safe; those are the prime goals. Bioengineers can contribute to these goals by supplying innovative information, techniques or instruments. These contributions may vary from advanced knowledge about the constitutive behavior of tissues, to improved practical tools to be used in surgery. They are almost invariably realized as a result of three sequential activities. The first of these is the identification of a clinical problem and its translation into a scientific question or hypothesis. The second is the actual performance of experimentation and analysis, and the third is the translation of results into practical solutions or useful additions to the scientific 'body of knowledge'. Although many young bioengineers tend to focus their attention on the second step, where computational methods are actually used, the first and third ones are certainly not less important, and bear heavily on, in fact determine predominantly, the requirements for the computational methods to be used.

A clinical (or biological) problem will almost invariably reach bioengineers in 'raw' form, that is to say, stated in terms which are not directly addressable by their scientific expertise and methodology. Before any analysis can be done at all, the problem must be translated into a well-defined scientific question or working hypothesis. Following this step, an experimental or mathematical model is developed for the actual investigation. The criteria for the model, hence also those for the computational methods used for the analysis, are directly derived from the question. They merely have to be efficient and effective in providing the answer. This is not always easily realized and may take much work and testing. However, it is our experience that the serious problems usually occur in the modelling process, where the characteristics of the biological reality must be described in mathematical terms. We will therefor concentrate, in this chapter, on the problems, rather than on their solutions. On why computational methods are used, rather than how they are used. First, we will briefly discuss the application of computational methods in Orthopaedic research and practice in general, thereby emphasizing the needs for development of computer simulation models. Then we will discuss the application of finite element methods for bone and prosthetic research in some more detail.

PROBLEM AREAS IN ORTHOPAEDICS

Orthopaedic surgery is a clinical specialism aimed at diagnosis and treatment of diseases and lesions of the musculoskeletal system. A considerable part of the surgical activities are related to reconstructions of bones and joints, causing pain and dysfunction due to traumatic causes, congenital deformities or diseases. Notorious examples are fixation of broken bones, replacement or repair of ligaments, re-alignment of bones and joints, and replacement of the articulating surfaces in the joints. Some of the most frequent and successful procedures are total joint replacements, predominantly for the hip, the knee and the finger joints, in cases of severe arthrosis (an abrasive process of the joint cartilage), rheumatoid arthritis or traumatic deformaties. The application of total joint replacements proliferated since the early sixties, when a few inventions were introduced by Sir John Charnley to successfully replace the hip joint for a prolonged period of time. Today about half a million of these procedures are conducted yearly in the western world, implying a normal (working) lifestyle for people who would otherwise have spent their days in pain and in wheelchairs.

The predominant task of the musculoskeletal system is to provide for the required motions in a variety of human functions, and carry the loads associated with it. Orthopaedic research is often aimed at the provision of a better understanding of the biological processes and mechanical relations which govern this task, the improvement and testing of reconstructive methods and implants, and the assessment of the causes of failures. Evidently, Biomechanical Engineering, in particular Biomechanics, plays an important role in this research.

Computers and computer software are increasingly important in orthopaedic clinical work, research and teaching, as they are in other professions. One notorious area of application is the documentation of patient data and statistical analysis for post-operative patient evaluations. Other, emerging ones are, for example, numerical storage and retrieval procedures for X-rays, and expert systems for diagnostic purposes.

Engineering computer techniques used in Orthopaedics can be divided in three categories of applications:

- Data acquisition, processing and analysis.
- Computer graphics.
- Simulation models.

The first category includes methods for the measurements of motion, deformation, shape or structure. A notorious example is the measurement of human motion for functional patient evaluations. Although still in an experimental stage, some specialized clinics already use facilities for gait analyses routinely for diagnostic and documentative purposes. Computational methods play an important role both in the on-line registration of data, as in subsequent analyses, for instance to estimate joint and muscle forces. Other examples are the application of (knee) joint laxity testers, used to quantify the effects of ligament lesions, and stereographic methods to analyse back shapes to document spine problems. All these methods have in common that the quantities to be evaluated are often ill-defined, variable and not easily accessible for direct measurements. Human-joint motion, for example, usually takes place in different planes, which cannot always be accurately defined in an unambigious anatomical reference system, while the moving parts themselves are covered with thick layers of soft tissues. This implies that mathematical models must often be used for data processing and analysis, requiring sophisticated computational facilities.

The same is true for computer graphics methods, which will become increasingly important in Orthopaedics in particular. The reason for this is, that bone and joint reconstructions, as they are carried out in Orthopaedic surgery require considerable insight into three-dimensional geometric and kinematic proportions. Both in teaching and in clinical practice, this insight can be improved by using 3-D computer graphics visualization. Presently, sophisticated software is being developed, associated with CT and MRI scanning equipment, enabling surgeons to visualize a complex bone fracture three-dimensionally before an operation, and even simulate and visualize alternative reconstructive methods.

Computer simulation models, which are emphasized in this chapter, are used mostly in research. Examples are models for musculoskeletal dynamics (multi-body system analysis), muscle dynamics, human-joint motion, stress analyses of soft and hard tissues, and of bone/prosthesis structures. Although presently applied almost exclusively for research purposes, they have a great potential for applications in combination with clinical tools, as for instance in combination with measurement systems and computer graphics visualization methods, as can be derived from the above discussion. Let us, for example, consider the schematic representation of the knee joint as a mechanical system in Fig. 1. The joint

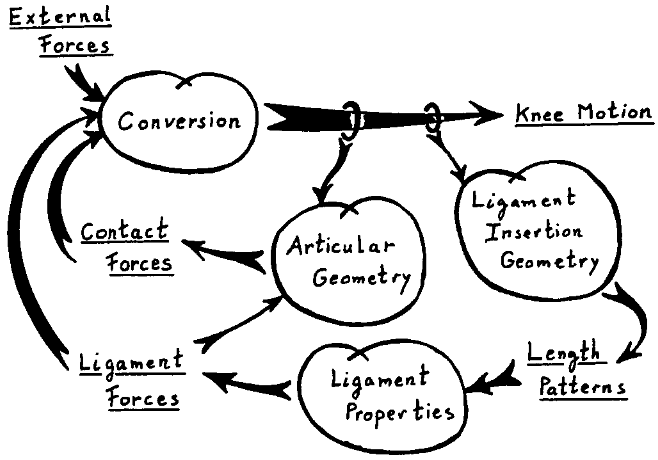

Fig. 1: A schematic representation of the knee-joint as a mechanical system, illustrating the complex feed-back loops in the force/motion relationship. To untwine this mechanism and analyse its structural relationships requires the use of computer simulation models.

motions depend on the loads exerted on the bones, composed of external (e.g. muscle) forces and internal forces, generated by articular contact and inter-connecting ligaments. Through several feed-back loops, the internal forces are coupled to the motions. This coupling, and the complex material and geometrical characteristics of the anatomical structures, create an extremely complex relationship between forces and motions. The only way to untwine such a mechanism and develop an understanding for the relations between anatomy and function is by using mathematical computer simulation models, in which both aspects can be quantitatively described. The Orthopaedic surgeon has to deal with these aspects on two levels. First, when the extent of damage to the joint structures has to be diagnosed from a manual or instrumented test, whereby the abnormality of the force/motion relationship must be evaluated. And second, when criteria for a reconstruction of the damaged parts must be applied. On both accounts, simulation models could be usefull. In fact, it is quite feasible that surgeons would practice alternative knee ligament reconstruction methods on a computer model and evaluate their mechanical consequences, before an actual operation is carried out; if not for particular cases, then certainly to investigate and practice surgical techniques in general.

FINITE ELEMENT METHODS

One computational technique frequently applied for mathematical models in orthopaedic research is the Finite Element Method (FEM). Many problems in orthopaedic surgery can be translated into questions related to strength and stiffness of structures, requiring analysis of the relations between stresses, forces and structural parameters. The FEM is pre-eminently suited for this purpose.

In a review of early FEM applications in orthopaedic research (Huiskes and Chao, 1983) we have found that initially this method was often considered as a miracle tool to solve all solid biomechanics problems in this area. Many FEM analyses of a variety of bones and bone/prosthesis structures were carried out merely for the sake of the analysis itself, in the expectation that once the results were available, appropriate problems for the solutions provided would be found. The lack of well-defined scientific questions or hypotheses, in combination with the severe limitations in the capabilities of the models used, have often frustrated this early enthusiasm. It was concluded at that time that progress in this area would depend on the feasibility to generate more dependable experimental data to put into the computer models, on the interests of clinicians for an ongoing dialogue on realistic problem definitions, and on our potential to attract skilled young mechanical engineers. In the meantime the FEM has established itself as a routine research tool for biomechanics analysis and testing, used in combination with laboratory and animal experiments, and patient-evaluation studies, even sometimes by orthopaedic surgeons. The number of new applications of an advanced nature, however, has declined, and relatively few research groups have remained to further develop the FEM for this area, and enlarge its applicability.

Generally speaking, the problems of FEM applications in Orthopaedic research can be categorized as follows:

(i) Loads in bones and joints as caused by gravity, accelerations, muscle contractions and constraints are variable, often of an essential dynamic nature (impact), and known to a limited extent, for a few musculoskeletal functions only.

(ii) The geometry of bones and other structures is irregular, often essentially three-dimensional, and inter-individually variable.

(iii) The material of bone and soft tissues is often discontinuous (e.g. cancellous bone), usually nonhomogeneous and anisotropic, often essentially nonlinear elastic or visco-elastic (e.g. ligaments and other collageneous tissues).

(iv) Boundary conditions, in particular where it concerns bone/bone or implant/bone contacts, can be quite variable and uncertain. Sliding with friction may occur, imposing nonlinear conditions on the model, and often the boundaries are rather irregular.

(v) The biological nature of the materials makes them liable to gradual structural changes. This introduces a time-dependency in the geometry, the material properties and the boundary conditions.

(vi) The structure is often a composite of substructures with vastly different dimensions and very small aspect ratios. The thinnest layer may impose a FE-density which is unacceptable for an efficient analysis.

(vii) The criteria for stresses and strains are uncertain. Failure models for biological materials are not well established as yet; implant/bone-connection failure modes are particularly uncertain. Tissues may react to stresses and strains in a variety of ways, not yet firmly established.

This inventory may be rather discouraging for any young bioengineer considering to enter this field armed with expertise in FE-analysis. Particularly disturbing may be the fact that most of these problems are due to biological variabilities and a lack of dependable experimental data, which usually FE-analysts do not feel inclined to supply. The point is, however, that although it may seem that FEM simulation models can not be usefull before these problems are solved, in fact these problems can not be solved without the use of FEM models. In order to illustrate that, let us consider the problems (v) and (vii) where it concerns the biological reactions of bone to stresses and strains.

Bone is known to react to mechanical stimuli by a so-called 'strain-adaptive' process. When bones are disused, they become osteoporotic, which happens for instance to astronauts and bedridden patients. When the bones are continuously overloaded, for instance in sports training, bone volume increases by that same adaptive mechanism. A similar process may occur after a joint prosthesis is fixed in a bone. Due to 'stress shielding', the strains in the bone are reduced relative to normal, hence bone resorption occurs, at least to some extent. This mechanism potentially threatens the longevity of the joint replacement, because it may result in a serious reduction in fixation strength. The amount of bone resorbed probably depends on the degree of stress shielding, hence also on the structural properties of the prosthesis. In theory, then, the FEM could be applied to predict the bone strains relative to normal, and from the difference to predict the extent of the adaptive process. A scheme for such a simulation model (Huiskes et al., 1987) is shown in Fig. 2. The problem is,

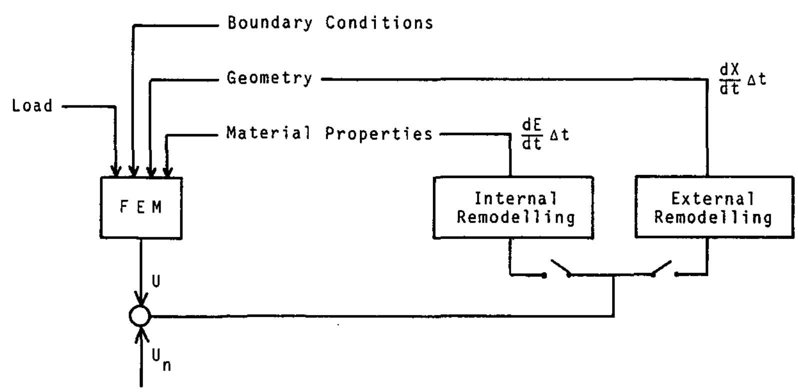

Fig. 2: Scheme of a computer simulation model for strain-adaptive bone remodeling. The actual distribution of the strain-energy-density U in bone is determined with the FEM, based on loads, geometry, material properties and boundary conditions. The difference between the actual and a natural SED U_n is used as a control signal to add or remove bone material internally or externally. The model iterates until the SED has again reached a natural distribution (from Huiskes et al., 1987).

however, that the relations between actual strain state, normal strain state and the extent of bone remodeling in terms of changes in mass are in fact unknown. Hence, the plan to predict bone resorption and thereby assess the chances for prosthetic longevity seems rather premature. The point is now, that these simulation models can be and are being used, not for the practical engineering purpose of design analysis, but for the scientific goal of uncovering the unknown relationships governing strain-adaptive remodeling. For that purpose, hypothetical remodeling rules are introduced and applied in the above iterative scheme to predict the eventual configuration of the bone in a particular loading environment, starting from a particular initial configuration. The final prediction is then compared to corresponding results from experimental findings in animals and humans. Hence, the model is used to simulate clinical or animal experiments, trying different remodeling hypotheses until a realistic one is established.

This is only an example, and many similar ones from biomechanics research in this area could be supplied. In this area, the FEM is not merely an engineering tool for design analysis of 'orthopaedic structures', but often a scientific method for uncovering basic mechanisms, relevant for Orthopaedics. Seen in this light, the above mentioned modeling problems are challenging, rather than frustrating.

CONCLUSION

Future improvements of diagnostic and surgical procedures in Orthopaedics require developments in measurement systems, 3-D computer-graphics visualization methods and basic information about musculoskeletal biomechanics. For these developments, the use of computational methods will become increasingly important. Required in particular are computer simulation models describing musculoskeletal dynamics, joint kinematics, hard and soft tissue mechanics, and strain-adaptive processes in tissues. Due to the geometrical and material complexities of the musculoskeletal parts, the lack of experimental data, and the biological variability, the development of dependable simulation models is a difficult task, in complexity probably unsurpassed by any field of present day mechanical engineering. It can be a frustrating endeavor, but is certainly a challenging one, requiring the most talented Bioengineers.

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