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Original Article

Experimental strain analysis on the entire bony leg compared with FE analysis

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ABSTRACT

The present study addresses the question of evaluating, by combining both experimental and numerical approaches, the stress/strain distribution within a complete model of the entire lower bony chain. With this purpose an experimental model and a complete 3D finite element one were realised. A load of 700 N has been applied at the top of pelvis and the feet were rigidly fixed. Obtained results reveal interesting consequences deriving by taking into account the complete bony chain; it is possible to get information on load sharing between bones, location of high strain concentrations, and bone relative motion.
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1. Introduction

In general, bone is a good composite material, having an overall strength higher than either of its components, apatite or collagen. The softer collagen (low-modulus) prevents the stiff apatite (high-modulus) from undergoing brittle fracture, while apatite acts as a rigid scaffold to prevent collagen from yielding. Not surprisingly, the mechanical properties of bone are as complex and varied as the anatomy and composition. Seemingly simple properties such as bone strength, stiffness, and energy absorption to failure depend not only on material properties of bone (e.g., inherent composition, microscopic morphology of bone components, bonds between fibres and matrix and bonds at points of contact of fibres) but also on structural properties (e.g., geometry of whole bone, bone length, and bone curvature). Furthermore, it is well known that the material strength of bone varies with the age, sex, and species of animal under investigation and with the location of bone, such as femur versus humerus. In attempting to assess structural and material properties of bone using mechanical testing techniques, additional variation in bone strength may result from factors such as the orientation of load applied to the bone (since bone is anisotropic), strain rate (rate of deformation), and testing conditions, including tension versus compression, bending versus torsion, wet bone versus dry bone. Mechanical testing may yield even wider dispersion in results when specifically applied to the material and structural properties of healing bone. Amount of callus, type of callus, and degree of callus reorganisation all affect the mechanical assessment of bone healing.

Bone, in performing its function, must withstand a complex pattern of imposed forces. In a static situation, bone acts largely to resist the forces of gravity, supporting the weight of the body and the attendant muscular activity necessary to maintain a given static posture. In a dynamic mode, however, such as during locomotion or athletic activity, these forces may be magnified many fold and may be omnidirectional.

Bone, in function, experiences two types of imposed forces. In general, intrinsic forces may be considered physiologic and are imparted to bone through articular surfaces by means of ligaments surrounding joints and at tendinous sites of muscle insertion. Under normal circumstances such forces sustain ground reaction forces during posture and gait and only under unusual circumstances do they approach the inherent breaking strength of bone. Extrinsic forces, on the other hand, originate from the environment and, unlike the intrinsic system, have no limitation on magnitude or direction of application, for example, automobile impact. Clearly it is these nonphysiologic forces that have the greatest potential to result in catastrophic bone failure (fracture) and that must be understood to evaluate the biomechanics of fracture aetiology.

Intrinsic and extrinsic forces act to cause microscopic deformations of bone. The degree of deformation is dependent on the magnitude of the imposed force, the geometry of the bone

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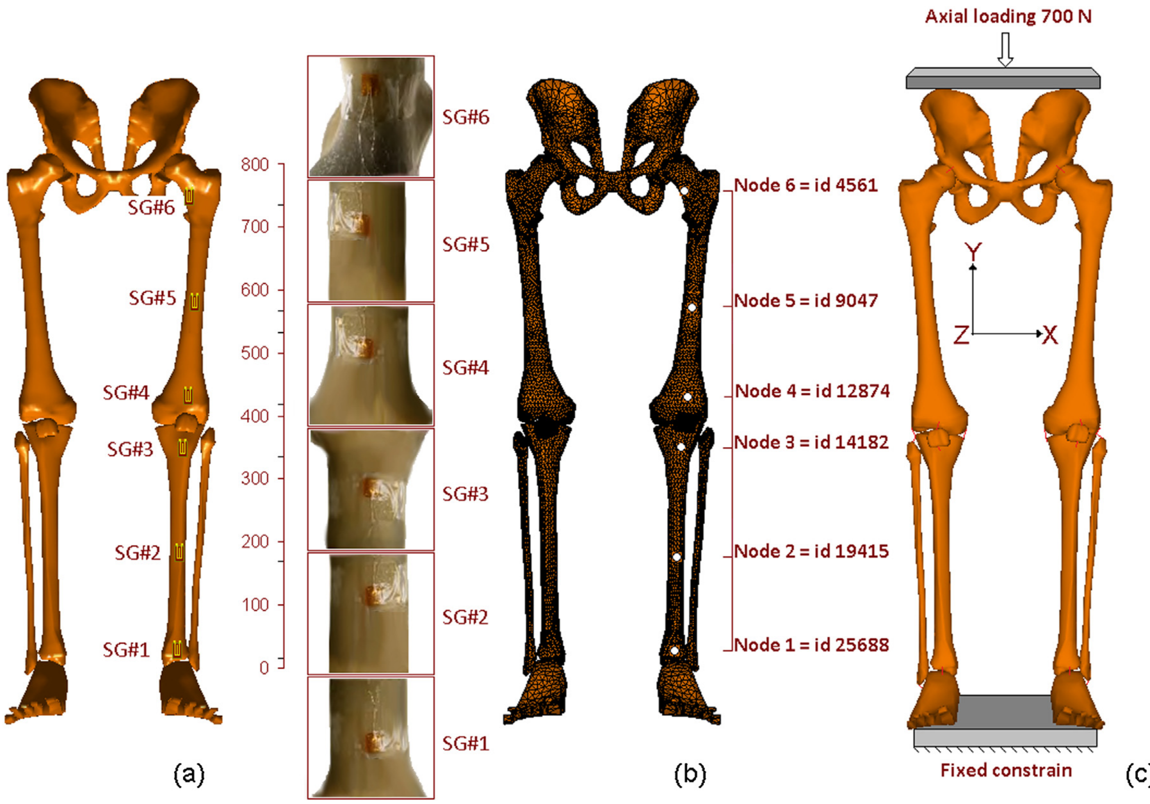

Fig. 1. Experimental model, finite element model with identification of reference nodes, loading and constrain conditions.

(size, shape, diameter, curvature), and the material properties of bone (cortical versus cancellous). It is intuitive that should the magnitude of imposed forces on bone exceed the ultimate strength of that bone, catastrophic failure will result. The introduction of finite element analysis (FEA) into orthopaedic biomechanics allowed continuum structural analysis of bone and bone-implant composites of complicated shapes. However, besides having complicated shapes, musculoskeletal tissues are hierarchical composites with multiple structural levels that adapt to their mechanical environment. Mechanical adaptation influences the success of many orthopaedic treatments, especially total joint replacements. Recent advances in FEA applications have begun to address questions concerning the optimality of bone structure, the processes of bone remodelling, the mechanics of soft hydrated tissues, and the mechanics of tissues down to the micro structural and cell levels, but still have deeply difficulties to analysed complied skeletal chains involving different bony parts, because of the model size, and above all the boundary conditions to impose. Many different works in literature have investigated the single bony part such as femur, knee, tibia, or feet, fixing the base and loading with more or less detailed systems of forces. In this paper this question is faced by adopting a simplified experimental and numerical models of the human leg, intended to assess how the stress shielding can influence the integrity and resistance of bones, if loaded with a vertical force of 700 N, and by comparing the obtained results with the ones presents in literature. The comparison of experimental strains measured on the model with those predicted by the finite element model revealed good agreement.

2. Materials and methods

2.1. Experimental model

Two couple of fourth-generation femur and tibia (*model 3403 and 3401*), a couple of fourth generation patella (*model 3419*), a fourth generation pelvis (*model 3415-1*), feet and a couple of fibula in a solid foam, produced by Pacific Research Labs., Vashon Island, WA, USA, were used to perform the experimental tests. These bone analogues model natural bone using a mixture of short e-glass fibres and epoxy resin for the corticalis (density 1.7 g/cm^3, tensile modulus 12.4 GPa, compressive modulus 7.6 GPa, Poisson ratio 0.3, tensile strength 90 MPa, compressive strength 120 MPa) and a polyurethane foam core for the cancellous bone (density 0.27 g/cm^3, compressive modulus 0.1 GPa, compressive strength 4.8 MPa). Left leg was instrumented with six resistive foil strain gauges (Hottinger Baldwin Messtechnik, Darmstadt, Germany), connected in quarter bridge to a digital data acquisition system (System 6100, Vishay Measurement Group, Raleigh, NC, USA). Unidirectional strain gauges (SGs) were positioned as shown in Fig. 1(a). Before bonding the SGsensors, the area for strain measurement was preliminary treated with sandpaper (#100), carefully cleaned and degreased first with ethanol, then with acetone and 2-propanol, and smoothed with fine sandpaper (#400). A bi-component epoxy adhesive was employed to glue the SGs onto the femur surface. Bones have been connected by elastic rods to simulate tendons by screws, while feet were rigidly constrained to a base; in order to avoid sliding between pelvis and femur, femur and tibia, and tibia and foot extremity of bones were rasped. Hence, a series of tests have been carried out on the entire model, having cared to fix the structure. Simulation of the loading conditions occurring in the stance of gait was obtained by applying a single axial load of 700 N on the top of the pelvis. Although this may appear as a rough approximation of the physiological loading condition, in which there are also several thigh muscles acting on the bones at different locations, the experimental set-up was greatly simplified, improving measurement repeatability and reproducibility. A material testing machine (Lloyd Instruments Inc., Fareham, UK); equipped with a 1000 N load cell (±0.5% full scale accuracy) was used to impose the vertical load. The model was pre-loaded with 100 N, to asses equilibrium conditions, and then a

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