Analysis of inter-individual anatomical shape variations of joint structures

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Introduction: Knowledge about inter-individual shape variations is useful for a variety of applications in orthopaedic surgery. On the one hand, it can be exploited to design surgical devices (guides or implants) that either fit a broader range of patients or are adapted to specific groups of patients (e.g. male or female). On the other hand, in a personalized therapeutic setting it helps reconstructing the patient's anatomy in a robust and automated way from medical image data, or is used for generating patient-specific yet objective surgical reconstruction plans.

Statistical shape models (SSM) are capable of capturing the variablity of anatomical shapes contained in a given population. Usually, the statistical analysis is performed on a given set of single-object training shapes (e.g. one bone/organ or a fixed compound of such structures), which are in correspondence with each other. Training instances of joint structures, such as the knee or hip, however, may exhibit different joint postures. Although one may model joint flexibility implicitly by capturing joint motion statistically (Klinder et al, MICCAI 2008; Heap et al., Image Vision Comput. 1996), this approach is beneficial only if relative transformations between individual objects are a statistical property of anatomy, which is, e.g., not the case for knee bending. Therefore, joint posture should be modeled independently by joint-specific degrees of freedoms.

We are presenting so-called articulated statistical shape models (ASSM), which model statistical shape variations independently of joint postures. This allows to measure and analyse characteristic shape changes under different joint postures. We see a potential benefit both in biomechanics-based simulation studies for the optimization of surgical devices, as well as a more robust reconstruction of joint structures in medical image data, especially in the presence of low signal-to-noise ratio, pathologies or artifacts.

Methods: In this work we are going to extend conventional SSM to ASSM of the human lower limb consisting of pelvic and femoral bones connected by hip joint, and femoral and tibial bones connected by knee joint.

We approximate the hip joint as an ideal ball and socket joint, as shown in (Kainmueller et al. EMBC 2009). It features three degrees of freedom, enabling an object (e.g. femur) to be rotated relative to the other object (e.g. pelvis) around arbitrary axes with a common hip joint center.

Our model of the knee joint exhibits a transformation of the tibia relative to the femur. The transformation consists of a rotation around the epicondylar axis of the femur and a translation of the tibia in a fixed direction of the tibial plateau. This joint model with two degrees of freedom is a reasonable approximation as shown in (Bindernagel et al., BVM 2011).

The joint models provide relative transformations of one object involved in the joint relative to the opposing object. To transform the whole object compound we introduce another global transformation consisting of seven degrees of freedom: a translation, an unrestricted rotation and a uniform scaling.

An SSM is built by performing a statistical analysis (e.g. principal component analysis (Cootes et al., Comp Vis Imag Underst 1995)) on a set of aligned, corresponding training shapes. We align that training data according to the aforementioned degrees of freedom. After performing statistical analysis the model is deformable in terms of shape variation. This yields a model with incorporated shape variation and joint flexion.

Results & Conclusion: With an evaluation on 50 CT datasets of the hip and 40 MRI datasets of the knee, we show that our ASSMs outperform reconstruction based on separate SSMs. ASSM are a promising tool for an accurate reconstruction of anatomical structures from poorly contrasted, incomplete or pathological medical image data.

Furthermore, our ASSM can easily be used to measure shape distances, areas or volumes of joint structures with varying joint postures over large number of individuals. This has great potential for the design of improved surgical devices using biomechanical simulations.