Abstract: Motion and morphology (shape) are two fundamental aspects to evaluate the functionality of human joints. The motion of the joint can be recorded by (optical) motion tracking systems, the morphology, i.e. the – sometimes pathological – shape of the joints, can be recorded by medical imaging methods (in vivo) or more precisely by laser scanning of the joint surfaces (in vitro). In order to supply clinically relevant data to the physician, motion and shape information must be integrated. A measurement system which combines shape and motion measurement has been established, computational methods for registrations and for creating 3D computer models have been developed. Moving the computer model according to real motion data facilitates the understanding of the intraarticular relations.

Keywords: Biomechanical measurements, motion tracking, laser scanning

1. INTRODUCTION

Joints are important components of the human motion system. To understand functionality of the joints (e.g. hip or knee) accurate measurements of both kinematics and geometry are needed. In vivo measurements are complicated to realize, but also cadaveric studies (in vitro) can answer important questions, like the normal movement of the joint (Freeman and Pinskerova, 2005) or the role of ligaments and muscles (Bach and Hull, 1995). They can support surgery design and also can influence prosthesis implantation techniques (Kessler et al., 2009).

Most in vitro studies (Churchill et al., 1998, Kessler et al., 2009, Takeuchi et al., 1999) are using knee simulators to model in vivo motion. Cadaver knee simulators are varied on producing motion or modelling muscle forces, but in the majority only the resected joint is mounted, the proximal femur (upper leg) and distal tibia (lower leg) is missing.

The kinematics of the joint can be recorded continuously during dynamic motion, or through a series of static positions (Lerner et al., 2003). In the latter case real dynamic activities cannot be studied, because the continuous motion must be interrupted. On the other hand with static 3D medical imaging devices (Computer Tomography – CT, Magnetic Resonance Imaging – MRI) we can “look inside” the joint; however the narrow examining chamber and the sensitivity to metals can also be problematic. Motion tracking systems are appropriate to record dynamic movements, because of their accuracy, high frequency of sampling, large measurement volume and insensitivity to metals. They are widely used during kinematic studies, also in vivo for navigated total knee arthroplasty.

Shape of the contacting surfaces (i.e. morphology of the joint) is decisive for the joint functionality. 3D imaging devices can be used to reconstruct the 3D surfaces of the joint structures, and build up a computer geometrical model. CT delineates only the bony surfaces (Eckhoff et al., 2005) therefore it does not accurately represent the articular surfaces. MRI also delineates cartilage surfaces, but manual segmentation is needed, which is time consuming, and ambiguous (Lerner et al., 2003, DeFrare et al., 2004). 3D coordinate measuring devices, such as 3D laser scanners can provide accurate data sets (Trinh et al., 2006), however this method needs direct overlook of the surface.

Besides the existing cadaveric measurement methods, there is need for a method which allows dynamic measurements on resected bones and allows “looking inside the joint” during motion. The evaluation of the size and the shape of contacting areas requires precise geometrical model of the bones with the cartilage. By registering it to kinematical data a computerized morpho-kinematical model can be built up. In this paper, we present a method for creating high quality bone surface model, and its matching with precise kinematical data. This provides solid basis for detailed evaluation of joint motion and intraarticular relations of the joint.

2. DATA ACQUISITION

Kinematic data characterizing the joint motion were acquired by the optical measurement system Polaris, (Northern Digital Inc., Waterloo, Canada). Polaris system uses a position sensor (stereo infrared camera) to detect infrared-emitting markers affixed to a tool (trackers and pointer). The system continuously records positions of the trackers and the pointer in 3D with 0.35 mm accuracy and 60 Hz sampling rate. Trackers were rigidly attached to the femur and to the tibia, and their spatial relationship to the important reference points was recorded by the pointer; the position of all points and axes on the femur relative to the tibia could be computed. Four different measurements were performed on each specimen, and the connection between them was achieved by corresponding fiducial marker points. Intracortical screws were used for this purpose, because their location could be
accurately defined both with motion tracking, and on the computer model. In order to align the anatomical coordinate system accurately landmarks far from the joint (centre of the femoral head and ankle joint) was determined on the whole body.

To mount the joint into the knee simulator the femur and tibia were resected 16 cm above and below the joint line, while soft tissues around the joint were preserved. The knee simulator produced flexion-extension, but did not limit the rotation and abduction. The femur was fixed, and the quadriceps muscle was replaced by a loaded string. The bending was produced by a 10 N load on the tibia similar to Takeuchi (Takeuchi et al., 1999). Kinematic data were collected along three consecutive cycles, each ranging from full extension to minimum 110° flexion. After the measurements the bones were isolated and cleaned of soft tissues.

Anatomical coordinate system was created for the femur using the femoral head and the cylindrical axis (Eckhoff et al., 2007), for the tibia using the ankle joint centre and the anatomical axis (Cobb et al., 2008).

3. RECONSTRUCTION OF BONE SURFACES

To obtain precise shape information of the joint surfaces coordinate measurements by a hand-held line laser scanner was performed for the bone and cartilage surfaces. We used ModelMaker H40, (3D Scanners LTD, UK) laser scanner. It works with two cameras mounted on the end of an articulated arm (Sterling FaroArm, Faro International, USA) with seven degree of freedom. The spatial position of a surface point can be acquired with 0.2 mm accuracy. Scanning of the surface from different viewpoints and directions provides an unstructured set of points, a point cloud that describes the shape of the tibia and femur surfaces. Typical parameters for scanning knee surfaces are: average distance of neighbouring points is 0.1 mm, number of points is 500.000 – 1.000.000. Accuracy of the geometrical model can be verified by measuring dedicated points using coordinate measuring machine.

Raw data points are prone to noise, they must be noise filtered, and outliers must be eliminated. Decimation (i.e. reducing the number of points still preserving shape features) serves to diminish storage requirements and alleviate subsequent computations. After filtering, decimating and smoothing a triangulated mesh is constructed, which acts as the geometrical model of the joint. Triangulation introduces topology (i.e. neighbourhood relations) into the point set, by connecting appropriate data points by lines. This is necessary for computer handling of the spatial object: for displaying and moving and also for the geometrical calculations. A good triangulation must be topologically correct (no intersecting or flying triangles) and geometrically feasible (size of triangles is adapted to the local curvature of the surface). Rapidform XOR2 (INUS Technology Inc., Seoul, Korea) was used for filtering, decimating and triangulating point clouds obtained by scanning knee surfaces. By setting appropriate parameters (number of point, average distance between points, etc.) a triangular mesh of 100-200.000 points in good quality can be obtained. Fiducial points and anatomical landmarks were identified on the surface model with Rapidform. (Fig. 1.)

4. REGISTRATION

Data are acquired from different measurements (whole body, resected body, fresh bone, dry bone) using two different devices (motion tracking and laser scanner). In order to move 3D surfaces according to motion data, transformations and registrations are needed between coordinate systems. The connection between the coordinate systems is provided by the fiducial points, which were identified on each measurement. Transformations between coordinate systems of different measurements are performed by registration i.e. matching two objects with unknown mutual position and orientation in different coordinate systems. The registration results in transformation matrices \( M_{\text{ref}} \). Robust and stable registration and transformation algorithms were developed which work well for noisy data as well.

![Fig. 1. Measured data points and femur surface](image1)

![Fig. 2. Registration and the morpho-kinematic model](image2)
Registration starts with identifying at least 3, (in our case 6) corresponding fiducial points on both objects. Let the fiducial points \( X_1, X_2, ..., X_k \) and \( Y_1, Y_2, ..., Y_k \) respectively, \( k \) is the number of fiducial points and the correspondence between them is known. The linear transformation \( AX+b \) describes registration, where matrix \( A \) represents rotation, \( b \) translation by minimizing the sum of squared distance of \( X \) and \( Y \):

\[
\sum_{i=1}^{k} (A \cdot X_i + b - Y_i)^2
\]

(1)

\( A \) and \( b \) can be obtained by computing partial derivatives In this way a system of linear equations is obtained, which can be solved in closed form as (2) and (3).

\[
A = \left( \sum_{i=1}^{k} (X_iY_i^T) \sum_{i=1}^{k} (X_iY_i^T) \right)^{-1}
\]

(2)

\[
b = \frac{1}{n} \sum_{i=1}^{n} Y_i
\]

(3)

Computation of the linear transformation with matrix \( A \) does not give a rigid body motion, it allows scaling and stretching.

Mathematically it is not a congruency which means that matrix \( A \) is not orthogonal in general. The solution to the problem of orthogonalization of a matrix is singular value decomposition (SVD). Matrix \( A \) is decomposed as \( A=UDV \) i.e. in the form of three matrices, where \( U \) and \( V \) are orthogonal, \( D \) are diagonal matrices. The modified matrix can be computed as \( A=UV \) which gives the best rigid body motion in least square sense. SVD decomposition is unique, fast and stable methods are available to compute the component matrices.

Fiducial points that are identical in every coordinate system are used for generating registration matrices \( M_{m-t} \). These matrices allow the transformation of anatomical landmarks to the same coordinate system, regardless of the source they were identified. These anatomical landmarks are used to generate the anatomical coordinates. System of coordinate transformations and registrations is shown in Fig. 3. where \( X \) stands for measured data, \( T, M \) for transformation matrices; first indices refer to coordinate systems: \( c, t, m \) for camera (motion tracking), tracker, and computer model, respectively; second indices refer to coordinate systems: \( t, f \) and \( l \) refer to fiducial and anatomical landmarks, respectively.

Fiducial point data \( X_{c,f} \) and anatomical points \( X_{c,l} \) are measured in the global coordinate system of the motion tracking device (this is fixed to the camera). Polaris system also provides series of time-dependent transformation matrices \( T_{c-t}(t) \) that define the relative motion of the trackers and pointer in the global coordinate system. To calculate the relative positions with respect to the trackers (that are fixed to the moving bones), fiducial points and anatomical landmarks are transformed with \( T_{c-t} \) into the tracker coordinate system (local coordinate system) attached to the corresponding tracker. Transforming data to this coordinate system has the advantage that recorded points remain accurate if the camera or the specimen is moved during fiducial point and landmark identification.

Data for the computer model are generated in the local coordinate system of the laser scanner. Fiducial points \( X_{m,f} \) and anatomical points \( X_{m,l} \) were identified on the computer model.

In order to create a morpho-kinematical computer model, kinematical and geometrical data were registered to each other. Registration is based on matching corresponding fiducial points \( X_{c,f} \) in the local coordinate systems of the motion tracking device and that of the computer model \( X_{m,f} \) to each other, which means minimizing the sum of squared distances between the corresponding fiducial marker points. Registration accuracy between corresponding fiducials was 1.42 (±0.52) mm in the examined cases. As a result of registration, matrices \( M_{m-t} \) (one for whole cadaver, resected cadaver, fresh bone, dry bone, each for tibia and femur) are computed that represent the relation between the coordinate systems.

Knee motion can be evaluated in a clinically relevant way only in the anatomical coordinate system, which is based on anatomical landmarks. Anatomic landmarks can be identified in every measurement, and also later on the computer model. The generation of the transformation matrix \( T_{t-a} \) is according to anatomical coordinate system definition.
4.1 Delineation of motion

3D knee surfaces can be moved according to the motion data by registering laser data to the motion tracking coordinate system. Process of the moving the knee on computer is shown in Figure 4. In addition to the previous indices, indices fem and tib are used to denote data and transformation matrices referring to femur and tibia, respectively. Three types of information is used: geometrical model (scanned bones) \( X_{m\text{ fem}} \) \( X_{m\text{ tib}} \), registration matrices as above and above time dependent tracker transformations between the moving tracker and the fix global (camera) coordinate systems of the motion tracking system.

Three types of motion visualizations are possible. Original motion in the global coordinate system of Polaris means that both femur and tibia moves, as it is seen by the camera. This kind of motion can be visualized by transforming scanned model \( (X_m) \) into the tracker coordinate system by registration matrix \( M_{m\text{ fem}} \) (that connects scanner and tracker systems) and then applying time dependent coordinate transformations \( T_{i\text{ tib}}(t) \) between local tracker and global camera coordinate systems for both femur and tibia. Transformation \( T_{i\text{ fem}}(t) \) is the inverse of \( T_{i\text{ tib}}(t) \) used during registration process.

Relative motion of knee components can be better understood when the tibia or femur is fixed. In this case motion is described as follows. In case the femur is fixed, the femur model \( (X_m\text{ fem}) \) is first transformed into the femur tracker coordinate system (which is fixed to the moving femur) by \( M_{m\text{ fem}} \). The tibia is first transformed into the tibia tracker coordinate system (which is fixed to the moving tibia) by \( M_{m\text{ tib}} \). The motion of the tibia is described by the time dependent transformation matrices \( T_{t\text{ tib}}(t) \). However these transformations represent motion with respect to the camera (global) coordinate system. Consequently another transformation is needed that transforms motion to the local coordinate system of the femur tracker: \( T_{c\text{ fem}}(t) \). A result, motion of the tibia will appear with respect of the fixed femur. The same process with the corresponding transformations works when the tibia is fixed and the motion of the femur is referred to it. Applying these operations the computer delineates exactly the same motion as the real bones performed during the cadaver experiment.

5. RESULTS

The morpho-kinematic computer model opens the way to the profound investigation of knee joint, its functionality, morphology and internal relations. We show only results of three investigations; measurement of motion parameters, the alteration of the contacting area during motion and the evaluation of the cartilage thickness.

The computer model contains all important reference points for axis alignment, like the centre of the femoral head, despite the kinematic measurements were performed on a resected joint. Registering the computer model to the kinematic data allowed studying the intraarticular scenario of motion, despite we did not used any 3D imaging techniques (e.g. MRI) during the kinematic measurements. The anatomic landmarks can be identified both on the real bone, and on the computer model.

The validity of the morpho-kinematical model can be proved by analysing the distance of the two bone models through the motion cycles. The femur and tibia were assumed as two contacting rigid bodies, intersection and displacement between these surfaces were used as an error parameter; 1.30 \((\pm 0.55)\) mm displacement has been observed between the surfaces.

5.1 Measurement of motion parameters

The parameters of knee motion can be precisely determined and numerically characterized in the anatomical coordinate system by the method discussed above. The clinically relevant functions are rotation and abduction as a function of the flexion (bending) of the knee. These functions can be seen on Figure 5. The rotation of the examined knee started with 15 degrees of external rotation in extended position. In the first 30 degrees of flexion 10 degrees of internal rotation occurred, during further bending only slight rotation can be observed. The abduction remains approximately constant during the whole range of motion. These data are characteristic for the motion of the human knee, however, precise values are influenced by several sources of error, such as error of the measurement or registration error.
5.2 Size and shape of contacting areas

Investigating the contact area during dynamic motion is challenging, since cartilage can be imaged well only on static MRI images. We matched the geometric surface model to the kinematic data; therefore the model performed the same motion, as the real bones during the experiment, so we can “look into” the joint during dynamic measurements. Calculating the distance between the femur and tibia surface reveals the contacting area during motion. Since the two cartilage surfaces are very close to each other in a large area, the dimension of this area is very sensitive to the accuracy of the model. In order to reduce the effect of registration error on the results, the ‘0’ distance was set to the measured minimum distance between femur and tibia in every time instant for both condyles separately. Practically it means that we established contact between femur and tibia, although they were not exactly in touch, due to the error of the model and registration. The contacting area on the tibia is not moving substantially on the medial side, while on the lateral side 10–15 mm roll back can be seen as a result of the internal rotation of the tibia (see Figure 6).

5.3 Cartilage thickness

The most common method of measuring the cartilage thickness is manual segmentation of MR images, which is time consuming and inaccurate. In our method each bone was scanned in fresh (with cartilage) and dry (after maceration – without cartilage) condition. After registering the two models to each other, the cartilage thickness was computed by calculating the distance between the two models. This method is very fast and accurate, especially if volumetric registration is performed according to the shaft of the bones (Figure 7.). Black areas around the cartilage represent the bony surface, gray areas represent around 3 mm thick cartilage. The cartilage thickness is almost equal on the femur; it is slightly thicker on the distal part. On the tibia the side the plateaus has 3 mm thickness, but their central part is thicker, especially on the lateral side, where 6 mm can be measured. White areas on the eminences of the tibial plateau are due to the remained soft tissues during scanning the fresh bone.

6. CONCLUSION

Cadaveric (in vitro) investigations reveal important details of knee functionality which can not be analyzed in vivo conditions. A new measurement method was developed for in vitro knee investigations, which combined different measurements: dynamic recording of the motion in a knee motion simulator and laser scanning. The latter resulted in a realistic bone model with and without cartilage. Creating the morpho-kinematic model provides the opportunity to assess the kinematics of the knee and investigate internal relations such as contacting surfaces or shape and size of the cartilage.

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