Chapter 2

Knee joint kinematics
2.1 Normal knee joint kinematics

The knee joint can be seen as a pivotal hinge joint. It consists of four bones: femur, tibia, fibula and patella bone and two articulations: between the femur and tibia, and between the femur and patella. The lack of congruency between the bony surfaces allows six degrees of freedom of motion about the knee including 3 translations (anterior-posterior, medial-lateral, proximal-distal) and 3 rotations (flexion-extension, internal-external, varus-valgus). The total range of motion is dependent on several parameters such as muscle activation and soft tissue restraints.

The healthy knee employs a passive system of ligaments and menisci to provide stability and intrinsic control of knee motions over the functional range of motion. The four primary ligaments of the knee are the anterior and posterior cruciate ligaments located in the centre of the knee joint and the medial and lateral collateral ligaments. The anterior cruciate ligament (ACL) resists anterior displacement and the posterior cruciate ligament (PCL) resists posterior displacement of the tibia on the femur during flexion. The ACL also controls the screw-home mechanism of the tibia in terminal extension of the knee. The PCL controls external rotation of the tibia with increasing knee flexion and guides femoral rollback in flexion. The main function of the medial and lateral collateral ligaments is to restrain respectively valgus and varus rotation of the knee and external and internal rotation of the tibia.

Kinematics of the knee during frequently occurring activities, like walking and ascending and descending stairs, has been thoroughly studied. However, the exact in vivo kinematics of the knee is still not entirely resolved. Flexion-extension, the predominant motion of the knee, involves a combination of rolling and sliding. During flexion the femoral condyles move posterior with respect to the tibia, called ‘femoral rollback’. At the beginning of flexion, the knee ‘unlocks’ with internal rotation of the tibia with respect to the femur. Axial rotations of more than 10° occur at the knee during daily activities. Axial rotation is feasible because of asymmetry between the lateral and medial femoral condyles. The lateral condyle being smaller allows the condyle to roll a greater distance than the medial condyle during the first
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20° of knee flexion (Dennis et al., 2005; Lafortune et al., 1992).

The hamstrings and quadriceps are the main muscle groups that control the motions of the knee. The quadriceps muscle group is located in the front of the thigh and controls extension of the knee. The hamstrings muscle group, in the back of the thigh, controls flexion of the knee. Normal muscle activation patterns are characterized by a pattern of activation and relaxation related to the function of the muscle group during a specific activity. Co-activation of agonist and antagonist muscle groups is a common strategy adopted to reduce strain and shear forces at the joint. However, it also increases joint torque and axial load (O’Connor, 1993). The forces across the normal knee joint are complex and involve loads in axial compression, torsion and shear.

2.2 Knee prosthesis kinematics

Normal function of the knee joint requires a high degree of mobility and stability while sustaining high loads during daily activities. Therefore, the knee joint is vulnerable to changes in alignment or loss of passive and active soft tissue stability. After total knee replacement surgery, joint resistance to external force and torque must be guaranteed primarily by the articulating surfaces and by the ligaments throughout the functional range of motion. Also, one wants to achieve ‘normal’ mobility and stability at the replaced joint (Andriacchi, 1994; Bellemans et al., 2002; Catani et al., 2006).

In vivo functional testing seems extremely useful in optimizing knee implant designs for better function, better fixation and improved long-term results (Andriacchi et al., 1982; Banks and Hodge, 2004b). Three-dimensional (3D) fluoroscopic analyses are the most accurate measurement technique to examine the in vivo kinematics of total knee prostheses under weight-bearing activities (Banks et al., 1997b; Dennis et al., 1996, 1998; Garling et al., 2005a; Stiehl et al., 1999). The position and orientation of 3D computer models of total knee components are manipulated so that their projections on the images match those captured during the in vivo knee motions (Garling et al., 2005a; Kaptein et al., 2006). Because of the high accuracy of
fluoroscopy, small patient cohorts are in general sufficient to study the parameters of interest.

Fluoroscopic studies of total knee prostheses have shown a broad range of kinematic patterns of the femur with respect to the tibia during dynamic activities and a significant proportion of implanted knees has abnormal kinematics (Banks et al., 2003a; Callaghan et al., 2000; Callaghan, 2001; Dennis et al., 1998, 2003; Morra et al., 2008; Pandit et al., 2005; Saari et al., 2005; Stiehl et al., 1997, 1999; Walker et al., 2002). Abnormal kinematics found in fixed-bearing designs, such as paradoxical anterior-posterior translations and reversed axial rotations, are common and also found in mobile-bearing designs. Paradoxical anterior-posterior translations may lead to accelerated wear of the polyethylene insert and may restrict flexion (Krichen et al., 2006; McEwen et al., 2005; Sansone and da Gama, 2004). Abnormal kinematics, which the knee prosthesis is not designed for, may even result in a feeling of instability and excessive stresses at the bone-implant interface leading to aseptic loosening (Taylor and Barrett, 2003; Hilding et al., 1996).

Electromyographic (EMG) data can provide important information about total knee prosthesis functioning like co-activation and control of movements (Andriacchi, 1994; Benedetti et al., 2003; Garling et al., 2005c). Knowledge of the muscular control of knee prosthesis provides insight into the integration of the prosthesis within the musculo-skeletal system. This information is particular relevant when combined with information about the implant kinematics (Benedetti et al., 2003). Muscle activation is not only influenced by aspects of an implant design but also by long lasting adaptations to a destructed knee joint. The extra degree of freedom in mobile-bearing knees might require higher muscle activity levels of the quadriceps and hamstrings muscles to stabilize the knee. Also, early muscle activation or anticipatory stabilization of the knee joint is seen in patients with a mobile-bearing knee (Catani et al., 2003; Garling et al., 2005c, 2008). Anticipatory stabilization and co-activation are mechanisms to protect the soft tissue from external loads by increasing the stiffness of the knee (Andriacchi, 1994). However, moving with excessive muscle activations and co-activations is inefficient and large forces are transmitted to the
bone-implant interface which could lead to micromotion of the tibial component (Grewal et al., 1992).

Different total knee prosthesis designs result in different in vivo knee joint kinematics. Joint kinematics are highly dependent on the intrinsic prosthetic constraint (Andriacchi et al., 1982; Kessler et al., 2007). The argument as to whether posterior cruciate knee ligaments should be preserved or sacrificed continues to this day (Nelissen and Hogendoorn, 2001). Long-term follow-up studies do not show any significant differences, although gait appears to be less abnormal if ligaments are preserved, especially when walking up and down stairs. Posterior-stabilized knee prostheses have been introduced on the basis that the post-cam system might induce femoral rollback during flexion. The post-cam mechanism drives tibiofemoral contact towards the posterior edge of the insert, allowing for higher flexion prior to impingement (Banks et al., 2003a; Dennis et al., 2003; Morra et al., 2008). However, others report that the posterior-stabilized mechanism fails to prevent paradoxical anterior-posterior translations and does not contribute to initial or increasing rollback during flexion (van Duren et al., 2007; Pandit et al., 2005).

The rotational freedom and higher congruency between the femoral component and the insert in a mobile-bearing knee could provide better kinematic behaviour by minimizing the paradoxical anterior-posterior sliding of the femoral component in flexion (Sansone and da Gama, 2004). Rotational mobility of the insert could also allow a better reproduction of internal tibial rotation during flexion (Delport et al., 2006). However, rotation centres inconsistent with the insert’s pivot location are no exception in mobile-bearing knees, probably caused by insufficient congruency and will result in a less optimal congruency between the femoral and tibial component (Banks and Hodge, 2004a).

### 2.3 Motion of the mobile insert

Using fluoroscopy it is also possible to analyse the in vivo kinematics of marked polyethylene inserts in mobile-bearing knee prostheses (Garling et al., 2005a). Axial
rotation of the insert is not only affected by internal-external rotation of the femoral component but also by the anterior-posterior and medial-lateral translations of the femoral component (Hamai et al., 2008). The broad range of kinematics patterns seen in mobile-bearing knees could be explained by the absence of motion or occurrence of erratic motion of the polyethylene insert. This will enhance wear of the polyethylene surface and could increase the torsional forces at the bone-implant interface, induce more aseptic loosening (Garling et al., 2005a; Henricson et al., 2006). The mobile insert may also be encapsulated by soft tissue after a period of time. As a consequence, the mobility of the mobile-bearing which should prevent wear of the mobile-bearing is cancelled out, and might even induce more wear when it is fixed in an abnormal position. However, the discussion whether the mobile insert is moving during knee motion and if it copies the natural movement of the healthy knee is still ongoing. A number of studies show that the polyethylene insert keeps its mobility over time (Sansone and da Gama, 2004; Uvehammer et al., 2007) while other studies show limited or no motion of the insert at all (Fantozzi et al., 2004; Garling et al., 2007b).