Summary

Human movement is essential for many daily-life activities, and has an important impact on functioning. Objective assessment of motor disorders and movement performance by means of physical examination and gait analysis is becoming increasingly relevant in the clinical practice of rehabilitation medicine, since clinical decision-making is based on the outcomes of these diagnostic tests and measurements. However, there is still a lack of focus on accurate, objective and quantitative measurement during physical examination. Furthermore, instrumented gait analysis is often limited by its complexity and the lack of equipment and gait laboratories.

The aim of this thesis is to evaluate the feasibility and quality of new ambulatory movement analysis systems, motivated by application in clinical motor function assessment. These systems have been developed to overcome the restrictions and limitations of laboratory-based movement analysis systems. Given their ability to measure motion in diverse settings, these systems may play an important role in objectifying and quantifying clinical motor function assessment. In this thesis, various different applications of ambulatory movement analysis systems are addressed in two different patients groups. First, the application of an Inertial and Magnetic Measurement System (IMMS) is evaluated in spasticity tests for children with cerebral palsy (CP) (Chapters 2 and 3). Secondly, the IMMS is applied in gait analysis of children with CP (Chapter 4). Thirdly, an instrumented force shoe (IFS) is used to measure the external knee adduction moment (KAdM) in adults with osteoarthritis (OA) of the knee (Chapters 5-7). Finally, the effects of gait modifications that have been suggested to reduce the KAdM are studied in a group of healthy young volunteers (Chapter 8).

In **Chapter 2**, IMMS are applied to measure objectively the angle of catch (AOC) in spasticity tests (SPAT) of the medial hamstrings, soleus and medial gastrocnemius muscles in 20 children with CP. IMMS sensor units contain 3D accelerometers, gyroscopes and magnetometers .The SPAT comprises a slow passive muscle stretch to define the range of motion, and subsequently a fast passive stretch to detect a catch (abrupt stop or sudden increased resistance in the movement), indicating a spastic muscle. The IMMS is found to be technically accurate (i.e. for the measurement of 3D orientation) within one degree, compared to an optoelectronic motion capture system. A sensor-to-segment calibration procedure is described, that is used to determine anatomical joint angles when applying IMMS, based on a functional axis and a reference posture. The conclusion of the chapter is that goniometry, which is currently used to measure the AOC, is a reasonably accurate

method for the measurement of a joint angle in a static situation. However, application of IMMS could improve the objectivity, accuracy and standardization of AOC measurement during spasticity assessments, since the currently used method suffers from the subjective experience of the examiners, joint repositioning, and erroneous readout of the goniometry.

The aim of the study described in **Chapter 3** is to evaluate whether, in the assessment of spasticity in children with CP, the catch observed by the examiner during the fast passive muscle stretch is caused by a sudden velocity-dependent increase in muscle activity. The IMMS is used to measure the joint angular velocity of the slow and fast passive stretch tests of the SPAT. Electromyography (EMG) is used to quantify muscle activity. It is found that in most fast stretch tests in children with CP, the catch is preceded by a burst in muscle activity, which is not present in the slow stretch tests, indicating that muscle activity is primarily responsible for the catch. Consequently, the conclusion is that the AOC can be used to quantify spasticity, when spasticity is defined as *"velocity-dependent hyper excitability of the stretch reflex"* (Lance, 1980). Furthermore, in clinical practice, the combination of IMMS with EMG may add to the reliability and meaningfulness of clinical spasticity tests, and may provide insight into the expression of spasticity at joint level. In the clinical assessment of spasticity, it is recommended to use the appropriate scales that really measure spasticity (such as Tardieu-based scales). Examiners should be aware of the influence of stretch velocity, and should further standardize the performance of spasticity tests.

Chapter 4 describes the application of IMMS, based on a protocol called Outwalk, in 6 children with CP and one typically developing child. Joint kinematics of the lower extremities are measured with the IMMS and the Outwalk protocol, and compared to concurrent measurements with a conventional laboratory-based system and protocol. The quality of joint angle measurement by means of the IMMS mainly depends on the anatomical calibration (i.e. sensor-to-segment), that can be achieved by the use of functional movements, reference postures and alignment of sensors with anatomical structures. Differences between Outwalk/IMMS and the laboratory-based system and protocol with regard to joint kinematics are mainly present in offsets in the knee frontal and transverse plane angles, and in the hip flexion, due to anatomical calibration. It is concluded that the IMMS is suitable for clinical gait analysis, since it is a good alternative for optoelectronic systems. Moreover, IMMS can be used for measurements outside a gait

laboratory, which enables measurement of a large number of consecutive gait cycles in a spontaneous, natural way. However, the anatomical calibration of the IMMS should be further optimized, in order to improve the accuracy of joint kinematic measurements, mainly in the transverse plane. This may include adjustment of the hip biomechanical model, anatomical calibration in a different posture (e.g. supine) to allow flexion in the joints, paying careful attention to the performance of the knee flexion/extension anatomical calibration, or the introduction of an IMMS calibration method based on bony landmarks. Additionally, since transverse plane angles might be subject to inaccuracies, due to anatomical calibration in both the IMMS and optoelectronic systems, careful interpretation of these angles is recommended.

Chapters 5-7 describes the application of the IFS for the measurement of the KAdM in 20 adults with OA of the knee. The IFS is an orthopaedic sandal that is equipped with two 6-degrees-of-freedom force/moment sensors under the heel and forefoot. The influence of wearing an IFS on the gait pattern of these patients is studied in **Chapter 5**. If wearing an IFS altered the gait significantly, it could not be considered as an alternative to the conventional force plate measurement. However, the changes in gait characteristics with IFS (compared to gait with normal shoes) are small, compared to normal variation and clinically relevant differences. Moreover, no effect is found on the KAdM, which is an important parameter for OA.

When applying an ambulatory movement analysis system, consisting of IFS and IMMS, for measurement of the KAdM, information on joint positions is lacking. However, the position of the knee joint with respect to the centre of pressure is required to calculate the KAdM. This position can be obtained by applying a linked-segment model based on segment orientations only. In **Chapter 6**, the KAdM of patients with knee OA is estimated with an IFS, in combination with a linked-segment model in which segment orientation is obtained from an optoelectronic motion capture system to simulate IMMS. It is found that the IFS is accurate in measuring the ground reaction force and centre of pressure. Furthermore, the combination with a linked-segment model for joint position estimation shows promising results towards the measurement of the KAdM with an ambulatory movement analysis system. The accuracy, compared with a laboratory-based reference system, is mainly limited by the linked-segment model.

In contrast to Chapter 6, in which segment orientations from an optoelectronic motion capture system are used as a substitute for IMMS, the study described in **Chapter 7** applies segment orientations from the actual IMMS (from gyroscope and accelerometers, but not from magnetometers) in the linked-segment model. In this way, the accuracy of the entire ambulatory movement analysis system is evaluated for estimation of the KAdM in the gait of patients with knee OA. This resulted in differences in the KAdM up to 23%, mainly in early stance and late stance (compared with the laboratory-based reference system), which is in the same order of magnitude as the differences between OA patients and healthy controls. This indicates that the ambulatory system is yet not accurate enough to discriminate between healthy subjects and patients. The accuracy of the KAdM should therefore be improved by using a more advanced calibrated linked-segment model to estimate joint positions from IMMS orientations.

Finally, **Chapter 8** describes how gait manipulations, such as walking speed, foot position and trunk sway, affect the KAdM during gait in a group of 14 healthy subjects. It has been suggested that such gait manipulations may decrease the rate of progression of knee OA by minimizing the load on the affected compartment of the knee. The KAdM is measured with a force plate and optoelectronic motion capture system. Toe-in and trunk sway substantially reduce the KAdM in early stance, whereas toe-out significantly reduces the KAdM in late stance. A faster walking velocity increases the KAdM in both early and late stance, whereas a slower walking velocity does not decrease the KAdM. All gait modifications also result in changes in sagittal and transverse knee moments and kinematics. This indicates that, when estimating knee-load, taking only the frontal plane kinetics into consideration may result in erroneous simplifications. The use of gait alterations in the retraining of patients with knee OA (either medial or lateral) remains questionable. For measurements of the KAdM in clinical practice, it is important to control walking speed and to be aware of the possible effects of foot position and trunk sway that might interact with a treatment effect.

In conclusion, the evaluation of the feasibility and quality of new ambulatory movement analysis systems in clinical motor function assessment in this thesis demonstrates that IMMS and IFS are techniques that can be applied for accurate 3D movement analysis in a laboratory-free setting. With IMMS, the physical examination of spasticity will be more accurate, objectified and standardized. This may support clinical-decision making and optimize the evaluation of spasticity treatment. Furthermore, IMMS and IFS make 3D gait

analysis (kinematics and kinetics) possible without a gait laboratory. This opens up the way for a more frequent use of 3D clinical gait analysis in children with CP, and knee-load measurements in patients with knee OA. Additionally, ambulatory movement analysis systems can measure a large number of consecutive gait cycles, which may result in a more accurate assessment of the average gait pattern and the step-to-step variability. Prior to the implementation of ambulatory movement analysis systems in clinical practice, future research should focus on optimization of the anatomical calibration of such systems, and optimization of user-friendly protocols.