Maximizing the efficacy of ankle foot orthoses in children with cerebral palsy
Cerebral palsy (CP) is the most common cause of children’s disability in Western Europe. Children with the spastic type of CP, which is the most common type of motor disorders, show impairments such as spasticity, muscle weakness, and a decreased selective motor control. These impairments lead to decreased motor function, and accordingly, these children experience gait-related problems.

The gait pattern of children with spastic CP is frequently characterized by specific gait deviations, which can be categorized into different gait types according to the classification of Becher. This thesis focuses on the children presenting with gait types 4 and 5, i.e. a gait pattern that is characterized by excessive knee flexion in (mid) stance. The excessive knee flexion during walking is usually accompanied by abnormal hip and ankle kinematics and kinetics, implying impaired biomechanical function. The gait deviations in CP are associated with an increase of energy consumption during walking. This especially applies to children with CP who walk with excessive knee flexion in stance, as these gait patterns are particularly energy consuming. To minimize the increased energy consumption, patients often decrease their walking speed. This leads to an increased walking energy cost (i.e. energy consumption per distance), reflecting poor gait efficiency. Although the nature of the association between underlying biomechanical gait deviations and the increased energy consumption in children with CP is not yet unraveled, abnormal knee and ankle kinematics and kinetics are considered key features.

To counteract the gait deviations, an ankle foot orthosis (AFO) is a commonly applied rehabilitation intervention in children with CP. AFOs apply a mechanical constraint to the ankle and foot, either to compensate for a loss of function, or to counteract an excess of function. As such, an AFO can directly control the ankle and knee joint motion, and dependent on its design, it may also affect the hip joint. Although the effects of AFOs on gait in CP have been frequently investigated, the results are inconclusive. Some studies report improvements of gait in terms of gait biomechanics, and/or efficiency, while other studies show that AFOs can have no effect or even detrimental effects in some children. Several factors may underlie the ambiguous results with regard to AFO efficacy, of which some are discussed in this thesis. The general aim of this thesis was to evaluate factors that enable an individual optimization of AFO prescription in order to maximize AFO efficacy in children with CP who walk with excessive knee flexion in stance.

Chapter II describes the protocol of the AFO-CP trial. This study aimed to optimize Ankle-Foot Orthoses for children with CP who walk with excessive knee flexion to improve their mobility and participation. One of the problems underlying the ambiguous
results within AFO research concerns the outcome at which the AFOs efficacy is being assessed. In order to prescribe a well-matched AFO, its effects should be evaluated on outcome measures at multiple domains of the International Classification of Functioning, disability and health (ICF) framework. Assessing the AFOs efficacy on multiple domains of the ICF framework could reveal mutual relations, which may give insight in the underlying working mechanisms of AFOs in CP. The protocol of the AFO-CP trial existed of an extensive evaluation of the effects of different degrees of AFO stiffness on gait-related outcome, covering all ICF domains, in children with CP who walk with excessive knee flexion in stance.

Another factor that might affect the AFOs efficacy, is the alignment of the ground reaction force with respect to the joint rotation center while walking with AFOs. This alignment is dependent on the properties of the AFO-footwear combination (AFO-FC), such as heel height. The shank-to-vertical angle (SVA) has been proposed as a relatively simple outcome parameter to quantify the alignment of an AFO-FC. In chapter III, we used an instrumented treadmill to investigate the effects of manipulations of heel height and footplate stiffness of an AFO-FC on both the SVA, and lower limb joint flexion-extension angles and net moments at midstance. To this purpose, ten healthy individuals walked with bilateral rigid AFO-FCs. We manipulated heel height in three conditions, which were controlled by an imposed SVA of 5°, 11° and 20°. These heel height conditions were combined with either a flexible, or a stiff footplate, resulting in six different walking conditions. We found that the SVA is responsive to changes in heel height, and less to changes in footplate stiffness. The increase in SVA resulted in concomitant changes in lower limb flexion-extension angles and internal net moments, especially at the level of the knee joint. As such, the results supported the potential of the SVA to serve as a control parameters for heel height manipulations of an AFO-FC in healthy adults.

The efficacy of AFOs in children with CP may also be related to an inadequate match between the AFO’s mechanical properties (e.g. stiffness) and the patient’s specific underlying impairments and personal characteristics. Rigid AFOs aim to shift the ground reaction force anterior to the knee joint and are therefore generally prescribed to reduce the knee flexion in children with CP who walk with excessive knee flexion in stance. The rigid AFOs however also obstruct ankle range of motion, therewith impeding ankle push-off power, which may negatively impact gait efficiency. Spring-like AFOs may enhance push-off power, and could therefore be more beneficial in terms of the gait efficiency.

In chapter IV, we investigated the mechanical properties of a spring-hinged AFO to assess its potential use in children with CP who walk with excessive knee flexion in.
stance. This AFO was manufactured with an integrated hinge of which stiffness could be varied by applying different springs, each holding specific mechanical properties. The mechanical properties of the five available springs were assessed using the Bi-articular Reciprocal Universal Compliance Estimator (BRUCE) device. The mechanical behavior of the springs was not linear, but could be described in terms of a threshold, a stiffness, range of motion, and an energy release. The stiffest spring showed the highest threshold and stiffness, which was combined with a small range of motion. We hypothesized that this spring would counteract the knee flexion most effectively. The higher energy return of the second stiffest spring was expected to enhance ankle push-off power more compared to the stiffest spring, although at the expense of higher knee flexion angles.

In chapter V, we evaluated the effects of different hinge settings (i.e. degrees of stiffness) of the spring-hinged AFO on gait biomechanics and gait efficiency in 15 children with CP walking with excessive knee flexion in stance. The AFO was configured in a rigid (i.e. aiming to eliminate spring-like properties and ankle range of motion), stiff (i.e. stiffest available spring) and flexible (i.e. second stiffest available spring) hinge setting. The effects of the three AFO stiffness levels were compared to walking shoes-only. The results showed that all AFOs equally reduced the knee flexion angle and internal knee flexion moment. Ankle push-off power was reduced by the rigid AFO, while remaining push-off power was preserved by the stiff and flexible AFO compared to walking shoes-only. Accordingly, ankle work was reduced by the rigid AFO, while being preserved by the two-spring like AFOs. The AFOs contribution to ankle work was smallest for the rigid AFO and comparable between the stiff and flexible AFO. Overall, the net energy cost was significantly reduced by all AFOs compared to walking with shoes-only, while no significant differences were found between AFOs. The potential benefit of spring-like AFOs on ankle kinematics and kinetics was therefore not reflected in larger energy cost reductions. These findings may suggest that, in children with CP walking with excessive knee flexion in stance, the optimal AFO stiffness that maximizes gait efficiency is primarily defined by its effects on knee kinematics and kinetics during stance, and less by its effect on ankle push-off power.

The results of chapter V were used to individually select the optimal AFO stiffness for each participant of the AFO-CP trial. In chapter VI, the effects of the stiffness-optimized AFO on the walking energy cost, knee angle and daily walking activity were investigated. The optimal AFO stiffness selection was based on the peak knee extension during single limb support (primary aim) and the walking energy cost (secondary aim) while walking with AFO. In total, 29 legs of 15 children with spastic CP were evaluated.
In eight participants, the selection lead to bilateral stiff AFO prescription. Four children were prescribed with bilateral flexible AFOs. Two participants were prescribed with one stiff, and one flexible AFO, and one participant with one rigid and one flexible AFO. After three months of wearing the optimized AFO, the net energy cost was reduced in 11 of 14 patients, with an overall energy cost reduction of 9% compared to walking shoes-only. Some children showed a reduction of more than 10%, indicating the clinical relevance of individually optimizing AFO stiffness in a subgroup of children with CP. The optimized AFO significantly reduced the knee angle, while daily walking activity was not affected at follow-up. The variety in the assignment of the optimal AFO stiffness emphasized an individual approach to AFO prescription to maximize its effects on the gait pattern and gait efficiency in children with CP who walk with excessive knee flexion in stance.

A third factor that might affect the efficacy of AFOs could be the acclimatization to an AFO. In research on the effects of AFOs on gait, an acclimatization time is generally applied. However, the applied duration of this acclimatization period in current literature varies between less than a day, and more than six weeks. The need of an acclimatization period remains therefore unclear. In chapter VII, we investigated the need of an acclimatization time for the gait pattern to adapt to a newly prescribed AFO. To this purpose, a specific set of biomechanical parameters was assessed immediately after applying a new AFO, and after four weeks of acclimatization time. Although we found some variation in our data, the results showed no significant changes in the assessed parameters after acclimatization. As such, our results suggested that, in independently walking children with spastic CP, inclusion of an acclimatization period to reliably evaluate biomechanical effects of an AFO on gait may not be needed.

In chapter VIII, the main findings of the presented studies were critically discussed, leading to clinical implications and ideas for future research. First, the exact association between changes in gait biomechanics and changes in the walking energy cost need to be explored. When this association is more clear, the potential benefit of adjustable AFOs can be optimally used to tune the mechanical function of the AFO to the specific (gait) impairments of the patient. Future research should also unravel the patient characteristics that underlie the (in)efficacy of AFOs in order to predict and improve treatment efficacy in children with CP. With regard to the clinical implications, it is advised that clinicians consider to prescribe spring-like AFOs in children with CP who walk with excessive knee flexion. However, an individual approach to AFO prescription is emphasized, which should be guided by evaluations of the AFO’s effects on gait-related outcome that is significant in the context of the prescription’s indication.