Summary

The clinical assessment of energy expenditure in pathological gait
**General introduction**

The ability to walk is an important prerequisite for the performance of many daily-life activities. Most people with disorders affecting the lower extremities experience limitations in walking, which may restrict their physical mobility and, subsequently, cause significant disability.

The goal of rehabilitation management is to minimize the disability of the patient. Although this may often require treatment at impairment level, the evaluation of treatment should also be performed at the patient-relevant level of activity limitations. When such activity limitations are related to an increased physical effort of walking, the assessment of energy expenditure (EE) of walking capacity is considered to be the appropriate criterion evaluation tool.

Currently, EE can be assessed, without encumbrance to the patient, with computerized portable gas-analysis systems, which enable the measurement of oxygen-uptake ($VO_2$) and carbon dioxide production ($VCO_2$) during walking over level ground. This makes it possible for subjects to walk at their own, self-preferred speed. It has been found that, when walking at a self-preferred speed, people adopt a comfortable walking speed (CWS) that is close to their most efficient speed. Therefore, measuring EE during walking at CWS generally produces the optimal value that makes valid comparison of EE data between and within subjects possible.

To use these portable gas-analysis systems for the purpose of clinical testing, it is essential that the methodology is appropriately validated. In addition to the evaluation of system accuracy, this must also include an evaluation of the reproducibility of the outcome measures that are used.

EE of walking is generally expressed in two outcome measures, energy consumption ($ECS$) and energy cost ($EC$). The ECS indicates the intensity of physical effort during walking, and the EC indicates the amount of energy used to perform the task of walking. Additionally, ECS and EC can be reported in terms of gross utilization (i.e. total utilization) or net utilization (i.e. subtracting resting utilization from gross utilization). Information from the literature on the reproducibility of all these...
different outcomes is limited, especially in clinical populations. Furthermore, information on system accuracy is limited. Therefore, both of these aspects are investigated in Chapters 2-5.

EE assessment is not only used for the purpose of clinical testing, but also in the context of clinical research to obtain evidence of the effectiveness of rehabilitation treatments. Chapters 6 and 7 describe two clinical gait studies, in which EC is used as the primary measure to evaluate the effects of orthotic treatment, and to look for relationships with the biomechanics of gait.

**Purpose of the thesis**

The aim of this thesis is to evaluate the clinical application of EE assessment in patients with pathological gait. Initially, this evaluation is made for the purpose of clinical testing, to determine the methodological quality of the measurement instruments and protocols that are currently used in the clinical practice of rehabilitation medicine. Also investigated is the application of EE assessment in clinical outcome studies to evaluate the effects of rehabilitation treatment, e.g. orthotic treatment, in persons with lower extremity disorders, and to look for relationships with the biomechanics of gait.
Chapter 2: Validation of the portable VmaxST system for oxygen-uptake measurement

EE during walking can be assessed, without encumbrance to the patient, with computerized portable gas-analysis systems that measure both the VO$_2$ and VCO$_2$ while walking. In order to use these portable gas-analysis systems in the clinical practice of rehabilitation medicine, it is important that they are sufficiently accurate. Therefore, the accuracy of the portable VmaxST system, a dual gas-analysis device, was validated against the Douglas Bag method, the gold standard, for its use in clinical gait studies. Accuracy evaluations were made in ten healthy adults during five minutes of resting and five minutes of cycling at an 80-Watt workload (i.e. an expenditure level that is, on average, reached during pathological walking) The results show that even though significant differences were found in the resting condition and the 80-Watt condition for the parameters VO$_2$ and EE, the magnitude of the differences was within 7.5% of the Douglas Bag values. This is considered to be physiologically and clinically insignificant for most purposes. Therefore, it is concluded that the VmaxST system is an accurate instrument when used to determine the EE of walking in patients with lower extremity disorders.

Chapter 3: Energy demands of walking in persons with postpoliomyelitis syndrome: relationship with muscle strength and reproducibility

Although it has been shown for many patient groups with lower extremities disorders that the EE of walking is elevated, the energy demands in adults with polio residuals have not yet been fully described. As mentioned in Chapter 2, EE of walking can be accurately measured with computerized portable gas-analysis systems. However, in order to consider the applicability of the EE outcomes (ECS and EC) for routine clinical testing, i.e. to evaluate clinical interventions or monitor changes over time in individual patients, information about day-to-day
reproducibility is required. Therefore, the reproducibility of ECS and EC was evaluated in 14 former polio patients and in 14 healthy adults during 10 minutes of resting and five minutes of walking at a self-preferred comfortable speed. The measurements were repeated four times on four different days, with a 1-week interval between tests.

The results show that the reproducibility of the EC outcome is superior to the reproducibility of the ECS outcome. Furthermore, EC is more reproducible for healthy persons than for persons with polio residuals. Nevertheless, the assessment of EC of walking provides a sensitive tool that can reveal clinically relevant changes in an individual polio patient, i.e. the smallest detectable difference ($SDD$) for EC was less than 10%, whereas changes are considered to be clinically relevant if they exceed 10%. It is furthermore shown that persons with polio residuals use considerably more energy for walking, i.e. 40% per unit of the distance covered, than age and gender-matched healthy persons. This reduced walking efficiency in former polio patients is strongly associated with the degree of lower-extremity muscle weakness.

Chapter 4: Reproducibility evaluation of gross and net walking efficiency in children with cerebral palsy

In evaluating the EC of walking, referred to as walking efficiency, gross measurement protocols (i.e. measuring total utilization) are commonly used for the assessment. However, in recent years the use of net measurement protocols (gross – resting utilization) has been recommended. With the growing application of net protocols, it has become essential to determine the reproducibility of such measures for the proper interpretation of the outcomes. Surprisingly, nothing is known about the comparative reproducibility of net protocols and the commonly used gross protocols. Therefore, the reproducibility of gross and net EC was evaluated in 13 children with cerebral palsy ($CP$) and in 10 children with typical development during 10 minutes of resting and five minutes of walking at a self-preferred
comfortable speed. The measurements were repeated four times on four different days, with a 1-week interval between tests. The results of this chapter show that gross EC is more reproducible for children with typical development than for children with CP. Furthermore, the reproducibility of gross EC is superior to that of net EC, because there is more intra-subject variability in net EC, as a result of variations in the resting ECS between days. Therefore, on the basis of the methodology used, it is concluded that the use of gross EC, rather than net EC, seems to produce a more sensitive measure of walking efficiency to detect clinically relevant changes in an individual child with CP. Furthermore, it is concluded that children with CP use considerably more energy for walking, i.e. 43% per unit of the distance covered, than age and gender-matched children with typical development.

Chapter 5: Methodological considerations for improving the reproducibility of walking efficiency measures in clinical gait studies

In recent clinical gait studies, and especially in those evaluating the gait of children, the use of net EC outcomes, rather than gross EC outcomes, has been recommended. However, as demonstrated in Chapter 4, the reproducibility of net EC is inferior to that of gross EC. Consequently, net EC seems to be a less sensitive measure in gait studies to detect clinically relevant changes. However, the recent literature has shown that net EC, compared to gross EC, does have several important advantages, because it is independent of resting ECS levels. This makes net EC clinically a more meaningful measure. Therefore, in this study the potentials of two methods that can be applied to improve the reproducibility of net EC were evaluated, in order to be able to use net values as the preferred outcome for clinical practice. Evaluations of the reproducibility of gross and net EC were made in 14 former polio patients, 14 healthy persons, 13 children with CP, and in 10 children with typical development, during 10 minutes of resting and five minutes of walking at a self-preferred
comfortable speed. The measurements were repeated four times on four different days, with a 1-week interval between tests.

The first method that was used to improve the reproducibility included optimizing the protocol for data-analysis. Because we had applied a 10-minute resting period it was possible to select multiple time-intervals for resting ECS to calculate net EC, and to determine the interval with the smallest measurement error value in each group. For both of the patient groups and for the healthy subjects this method was found to be effective in reducing measurement error. Apart from the optimization of data-analysis procedures, a further decrease in measurement error was achieved by adjusting the study design, i.e. by increasing the number of measurement occasions. The outcomes of this evaluation also demonstrated that an increase in the precision of net EC can be obtained, and that this clearly increases the clinical usefulness of this measure in terms of its sensitivity to detect clinically relevant changes.

In conclusion, the reproducibility of net EC in adults and children with locomotion disorders can be substantially improved by careful standardization and using a multiple repetition study design. As a result, this outcome measure becomes more suitable for detecting clinically relevant changes at the individual level.

**Chapter 6: The effect of ankle-foot orthoses on walking efficiency and gait in children with cerebral palsy**

Gait abnormalities in children with CP are known to cause a more than twofold increase in the EC of walking, compared to healthy children. Such increases in EC have a negative influence on their level of physical activity, thereby predisposing them to early fatigue in performing daily-life activities. Orthotic treatment, and specifically the use of ankle-foot orthoses (AFOs), plays an important role in the management of gait abnormalities in order to reduce the physical effort of walking. This study retrospectively evaluated the effect of two types of AFOs (solid AFOs and posterior leaf spring AFOs) on the net EC of walking in a heterogeneous group of 181 children with CP. Also investigated were the biomechanical changes in the gait pattern that are associated with changes in EC of walking.
The results show that the use of an AFO causes a statistically significant decrease in the net EC of walking. This intervention effect was more significant for more involved children (i.e. triplegics) than for less involved children (i.e. hemiplegics and diplegics). The decrease in EC is related to both a faster and a more efficient gait pattern. Yet, this improvement in walking efficiency is not profoundly reflected in changes in the biomechanics of gait, except for stance-phase knee motion, i.e. those children whose knee flexion angle improved toward the typical normal gait range demonstrated a decrease in EC, and vice versa. This finding supports the hypothesis that an improvement in knee flexion angles reflects a reduction in the required muscle forces during the stance-phase of walking, thus explaining to some extent the benefit in energy efficiency.

Although, knee motion outcomes differed significantly between the groups that showed a good EC response versus a bad EC response, the analyses revealed very little difference in the baseline characteristics of the children. This indicates that it is plausible that differences in AFO configuration (i.e. design, type of material, stiffness, combination with footwear, etc) might have had a significant effect on walking efficiency. Future research on the effects of AFOs in patients with CP should focus on large-scale prospective studies, in which specific hypotheses related to treatment goals and AFO prescriptions, in combination with footwear design, are analysed.

Chapter 7: The effect of carbon composite knee-ankle-foot orthoses on walking efficiency and gait in former polio patients

Persons with a history of poliomyelitis often exhibit gait abnormalities, due to residual lower extremity pareses and joint deformities. In Chapter 3 it was shown that gait abnormalities in former polio patients result in reduced walking efficiency. Both the reduction in walking efficiency and the gait abnormalities themselves can lead to a decline in their functional abilities, with a decrease in walking ability as the most prominent problem. Lower extremity orthoses, such as knee-ankle-foot
orthoses (KAFOs), are often prescribed for persons with polio residuals to maintain functional performance. Previously, these KAFOs were often made of leather and metal (LM), as a result of which they were rather heavy and provided insufficient correction. Orthoses made from plastic, such as polypropylene, usually with metal parts (PM), are frequently manufactured to reduce weight. A disadvantage of such devices, however, is the limited rigidity of plastic materials, which implies that these orthoses still provide insufficient correction. A recent innovation that may be more promising is the application of carbon-composites, which makes it possible to construct full carbon KAFOs that are lightweight, rigid and strong, and that enable total contact fitting. This study prospectively investigated the effects of carbon-composite KAFOs on walking efficiency and gait in persons with polio residuals using either conventional LM or PM KAFOs.

The results show that carbon-composite KAFOs reduce the physical effort of walking with clinical significance by decreasing the increment in net EC of walking above norm values with 18%. Improvements in the knee flexion angle, forward excursion of the centre of pressure, peak ankle moment, and timing of peak ankle power were significantly associated with the decrease in net EC. These improvements, which could be achieved due to the properties of carbon-composite, provide an important option to reduce overuse and to maintain functional abilities in persons with polio residuals.

General discussion

The general discussion, in this final chapter, critically evaluates the clinical application of the assessment of EE of walking in patients with pathological gait, by reflecting on requirements for usefulness of EE assessment, and its position in comparison to other clinical assessment tools, and also by discussing the clinical usefulness of EE assessment, i.e. describing its role for clinical decision-making in rehabilitation management. Furthermore, several recommendations are made for future research and clinical practice.
In order to determine whether EE assessment will be useful in the rehabilitation management of patients with pathological gait, six requirements for usefulness are evaluated. As a first requirement for usefulness, the accuracy and reproducibility of measurements of EE in pathological gait were evaluated in Chapters 2-5. These evaluations showed that:

1. The portable VmaxST system, which was used to assess EE of gait, is an accurate instrument that is adequate and sufficient for use in clinical gait studies.
2. Measurements of EC are more reproducible than measurements of ECS.
3. The use of gross EC, rather than net EC, seems to be a more reproducible measure of walking efficiency in patients with gait pathology.
4. The reproducibility of net EC can be substantially improved by the optimisation of data-analysis procedures and using a multiple repetition study design, which results in a higher sensitivity to detect clinically relevant changes in individual patients. These results are presented in the decision scheme on page 83.

Reflection on the five other requirements of usefulness shows that measurements of EE correlate well with the patient’s functional capacity, are not directly observable by the physician or therapist, are readily identifiable in a physical or physiological analogue, and clearly distinguish between normal and abnormal. Moreover, the measurement technique does not significantly alter the performance of the evaluated ability.

Further support for the usefulness of EE assessment in pathological gait is derived from discussing the potential value of this tool, in comparison to other clinical assessment tools in the different ICF domains. This discussion showed that, in relation to other capacity measurement tools, the assessment of EE during walking is considered to be the most appropriate way to estimate the physical effort of walking. The tool provides a means to objectively quantify the physiological strain resulting from pathological gait, and the outcomes are accurate, reproducible, and sensitive enough to detect clinically relevant changes in an individual patient. Yet, because the interpretation of capacity measurements only reflects what a person is capable of achieving in a standardized situation, measurements in the domain of walking performance are needed to determine what a person actually achieves in daily-life.
Measurements in the domain of impairments are also needed to reveal the underlying causes of increases in the physical effort of walking. Knowledge about the relationships between the outcomes in these different domains will make it possible to optimise treatment in such a way that it is most likely to result in functional improvement. With regard to biomechanical gait outcomes in the impairment domain and EE outcomes in the capacity domain, such relationships were established in Chapters 6 and 7, and provided information that can be used to optimise orthotic treatment. Further research is needed to investigate any possible relationships between EE outcomes in the capacity domain and outcomes in the performance domain.

Based on these considerations it is concluded that the methodological quality of EE assessment is appropriate and adequate in patients with gait pathology, 1) to use this tool in rehabilitation management, and 2) to evaluate clinical interventions or monitor changes over time.

The clinical usefulness of EE assessment, i.e. the potential usefulness of this tool in the process of clinical decision-making, is also evaluated. This concept is related to the question of whether the use of EE assessment will suggest a different treatment outcome than would be suggested without use of this tool. This question can be answered after consideration of the results of Chapters 6 and 7, showing that measurements of EE provide information on the effect-size of an applied intervention, i.e. they provide information on treatment outcome with regard to the physical effort of walking. As such, EE assessment, as part of a more comprehensive assessment, can be used in the process of clinical decision-making to determine the potential for functional gain. Accordingly, because EE assessment provides information on functional gain, the use of this tool can suggest a different treatment than would be recommended without use of the tool. This implies that when the disadvantages that medical treatment inherently brings about outweigh the functional gains, then a patient might choose to have no treatment, or the clinician might recommend no treatment and/or suggest a different treatment.
Based on the above considerations it is concluded that the assessment of EE of walking capacity, as an activity assessment tool, does contribute to the rehabilitation management of patients with gait pathology.

Finally, three important recommendations are made for future research:

1. Future clinical gait studies should investigate the relationship between EE capacity outcomes and performance outcomes, such as measured with activity monitoring. This might give indications to whether changes in walking EE will also result in changes in the performance of functional, purposeful activities of daily life.

2. Future clinical gait studies should focus on the mechanical properties of muscles and mechanical power estimates in order to obtain better understanding of the mechanisms underlying increases in sub-maximal EE levels in pathological gait.

3. Future clinical gait studies should determine maximal EE levels, preferably measured during functional walking test (e.g. the shuttle run test), in combination with sub-maximal walking EE levels, in order to determine the relative physical strain of walking. This could be integrated in the development of cardio-respiratory training programmes, which possibly provide an additional intervention option in the management of pathological gait.

As a recommendation for rehabilitation practice it is advocated that the assessment of EE of walking should become part of the routine pre/post-assessment in the rehabilitation management of pathological gait. As such, it can serve as a tool for patient selection, i.e. to determine the potential for functional gain and decide whether treatment will be beneficial. Secondly, it can serve as a tool for patient evaluation, to determine whether certain treatment was, indeed, effective.