The Clinical Assessment of Energy Expenditure in Pathological Gait
The studies presented in this thesis were carried out at the department of Rehabilitation Medicine of the VU University Medical Center Amsterdam, The Netherlands, and the department of Orthopaedics at Gillette Children’s Speciality Healthcare St Paul, USA.

The work was part of the research programme Musculoskeletal Disorders of the EMGO institute, and it was supported by grants from the Anna Fonds (02/07), ZonMw (014-32-031), and the Ter Meulen fonds, The Netherlands.

QBriks BV, Noppe Orthopedie BV, Kamer Orthopedie, Livit Orthopedie, ISPO Nederland, Basko Healthcare, Ipsen Farmaceutica BV, Biometrics Almere, and the Anna Fonds supported the printing of this thesis. Their financial support is gratefully acknowledged.

ISBN: 978-90-6464-139-8

Cover design: Arne Brans, QBriks BV, Amsterdam, www.qbriks.nl
Printed by: Ponsen & Looijen BV, Wageningen

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The Clinical Assessment of Energy Expenditure in Pathological Gait

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad Doctor aan
de Vrije Universiteit Amsterdam,
op gezag van de rector magnificus
prof.dr. L.M. Bouter,
in het openbaar te verdedigen
ten overstaan van de promotiecommissie
van de faculteit der Geneeskunde
op donderdag 21 juni 2007 om 10.45 uur
in de aula van de universiteit,
De Boelelaan 1105

door

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Chapter 1

General introduction

Merel-Anne Brehm
General introduction
Chapter 1

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.

Limitations in walking are, among other things, associated with an increased energy expenditure (EE) of walking, resulting from various gait abnormalities. Therefore, in rehabilitation medicine, interventions that aim to improve physical mobility by reducing the EE of walking are important treatment modalities to maintain or improve independent functioning.

This introduction outlines the focus of this thesis: The energy expenditure in pathological gait. It also introduces the terms ‘functioning’ and ‘disability’. The concepts of disability and functioning are essential to the understanding of rehabilitation medicine. Therefore, before elaborating on the main subject addressed in this thesis, rehabilitation medicine in general and the bio-psycho-social framework of functioning and disability, as used within rehabilitation, are explained.

Rehabilitation medicine

“Rehabilitation medicine can be defined as the multidisciplinary management of a person’s functioning and health”. (1) Within the current framework of disability — the WHO International Classification of Functioning, Disability and Health (ICF) (2)— functioning is categorized into three components: “body functions and structures”, “activities”, and “participation”. These components are seen in relation to a “health condition” (e.g. disorder or disease) as well as to contextual factors (i.e. “environmental factors” and “personal factors”).

(Figure 1)
Abnormalities of body functions and structures are referred to as *impairments*, defined as a significant deviation or loss of structures (e.g. joint malformation) and/or functions (e.g. muscle weakness). Difficulties in performing activities, which reflect a person’s individual functioning, are referred to as *activity limitations* (e.g. limitations in walking). Finally, *participation restrictions* refer to the problems a person may experience in societal functioning, i.e. in involvements in daily-life situations (e.g. restrictions in community ambulation). (3)

**Figure 1.** The current framework of functioning and disability — the WHO International Classification of Functioning, Disability and Health (ICF)

Following ICF terminology, functioning is an umbrella term for the components body functions/structures, activities and participation. It denotes the positive aspects of the interaction between the individual and the contextual factors of this individual. Disability denotes the negative aspects of the interaction between the individual and the contextual factors of this individual. It is used as an umbrella term for impairments, activity limitations, and participation restrictions. (3)
Rehabilitation management

Within its clinical context, rehabilitation medicine focuses on health condition consequences, i.e. on impairments, activity limitations, and participation restrictions. (1,4-5) Furthermore, rehabilitation management is patient-orientated. This means that the care that is provided is guided by patient-relevant problems. (1,4-5) These problems usually concern limitations in daily-life activities and restrictions in participation in society. Although the ultimate goal of rehabilitation is to improve participation, rehabilitation management essentially aims at maximising the individual’s ability to perform activities. (6) Therefore, the impairments that hinder the ability to perform activities first need to be identified. This problem-solving process is comprehensive, and therefore it is useful to analyse health condition consequences systematically. (4)

Structuring rehabilitation management

The systematic analysis of health condition consequences requires a structured approach to rehabilitation management with a logical sequence of steps. Stucki and Sangha (1) developed a practical and feasible model for this purpose, “the Rehab-cycle”, in which the ICF framework is used as a system to analyse problems from a patient-orientated viewpoint. (1,4) Harlaar and Lankhorst (7), who used terminology related to the ICIDH (i.e. the predecessor of the ICF), presented a similar approach for clinical decision-making. They introduced the assessment of impairments to be explicitly nested within the context of the assessment of activity limitations. (7) Based on the Rehab-cycle (1,4) and the nested model (7), the process of rehabilitation management can be divided into the following steps (1,4-5,7,8):

1. The identification of patient-relevant problems.
2. A comprehensive pre-assessment of the patient. This should include a) the assessment of impairments (i.e. clinical status) to determine the causes of the
General introduction

problems, b) the assessment of activity limitations (i.e. functional status) to determine the severity of the problems at the patient-relevant level, and c) the assessment of contextual factors to identify modifiable and limiting factors.

3. After the pre-assessment, and after interpretation of the outcomes, the next step is the selection of an intervention (including the possibility of no intervention), and the planning of the intervention treatment.

4. The post-assessment of impairments and activity limitations, to track goal attainment at both levels, is also a necessary step in the rehabilitation process. (5) This comprises the monitoring of a patient’s progress in the presence or absence of an intervention, as well as the final evaluation of the intervention outcomes (i.e. to determine the effectiveness of the intervention).

With this last step, the process of rehabilitation management is completed. Yet, depending on the results of the evaluation, i.e. depending on the patient’s progress and/or satisfaction, it might be necessary to adjust the intervention treatment, apply a different or additional intervention, or perform new assessments. (5)

Clinical testing

Clinical testing can assist the rehabilitation team in the different steps of rehabilitation management. (9) In this, the selection of an appropriate clinical test is of utmost importance, which ideally, should (i) measure at the level of outcome, (ii) be practical and feasible, and (iii) be of good methodological quality. (10)

(i) Level of outcome

Patient-relevant problem: increased physical effort of walking
The starting point of rehabilitation management, as described above, is the identification of patient-relevant problems. Because independent functioning around the home and in the community is of major importance to most people, and
independence in walking is one of the main prerequisites, relevant problems often include limitations in walking. (11) One of these limitations is associated with an increased physical effort of walking, which may result from various gait abnormalities, such as those found in patients with poliomyelitis, cerebral palsy, stroke, and multiple sclerosis. Addressing gait abnormalities to reduce walking limitations and to make walking energy-efficient is therefore an important treatment goal in rehabilitation medicine.

**Outcome tool: EE of walking capacity**

When an intervention addresses gait abnormalities to decrease limitations in walking and to reduce the physical effort of walking, the outcome of the clinical test that is used should be at the level of activities. This is the level of evaluation that is most relevant to the patient, and the measurement of EE during walking provides a useful and objective tool for this purpose. It is objective, because it does not rely on self-report, such as perceived exertion or perceived fatigue. (12) Furthermore, the tool can be considered to be of functional importance, because the outcomes give an indication of endurance, fatigue, and the ability to accomplish the routine daily activity of walking.

Although measuring EE of walking provides a means to quantify the physiological strain resulting from pathological gait (13), its interpretation only reflects what a person can do in a standardized situation, thus providing insight into a person’s walking capacity. Information about what a person truly does in daily-life, i.e. walking performance, requires additional measurements in the individual’s own environment. (6) Also, EE outcomes do not explain the mechanisms behind a certain walking limitation. (12) Therefore, EE assessment should preferably be used in combination with measurements of impairments in body functions/structures and their implications on gait abnormalities as obtained from clinical motion analysis.
General introduction

Method of assessment: indirect calorimetry
EE can be measured most accurately by determining the body’s heat production, referred to as direct calorimetry. (14) However, in most clinical exercise laboratory situations this method of assessment is not feasible, for practical reasons. For example, it requires expensive specialized equipment, and it is time-consuming. (13-15) Therefore, more practical methods of assessment have been developed to obtain an indirect estimate of EE. These methods are referred to as indirect calorimetry, and are based on the measurement of oxygen uptake ($VO_2$). (15,16) As far back as 1959 (17), the assessment of EE via indirect calorimetry has been found to be a useful tool with which to evaluate pathological gait. (13,17-21)

(ii) Practical feasibility
When introducing EE assessment in the evaluation of pathological gait, it is important that the equipment that is used is convenient for both the clinician and the patient. (22,23) For many decades the Douglas Bag (DB) has been used for the indirect measurement of $VO_2$, but although this method enables highly accurate gas-analysis, the equipment is bulky and stationary. This restricts the mode of testing to treadmill walking only, and thereby walking speeds are imposed. However, in patients with gait abnormalities this is not ideal, because many of these patients cannot walk on a treadmill, or have difficulties in adjusting to imposed speeds. (13,24) For these reasons, testing on level ground is preferred, and with the introduction of computerized portable gas-analysis systems this has become possible. (25) (Figure 2)
The advantage of using portable equipment is that EE can be assessed, without encumbrance to the patient, while walking around an indoor route. This makes it possible for the patients 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. (26,27) Therefore, measuring EE during walking at CWS generally produces the optimal value that makes valid comparison of EE data between and within subjects possible.
(iii) Methodological quality

**Measurement instrument: portable gas-analysis system**

The first generation of computerized portable systems, capable of measuring only VO$_2$, quickly evolved. (16) The advantage of the currently available technology (e.g. the Cosmed K4b2 or VmaxST) is that EE can now be estimated from recordings of both VO$_2$ and carbon dioxide production ($VCO_2$). From these recordings the caloric uptake can be determined by taking into account the relative contributions of nutrients in the metabolism (i.e. the ratio of $VCO_2$ to VO$_2$, defined as the respiratory exchange ratio [$RER$]). This should be included to calculate the actual amount of energy consumed by the body. (28)

When using these portable gas-analysis systems for clinical testing, the measurement results must be accurate. However, information about the accuracy of these systems is limited. Chapter 2 validates the accuracy of the portable VmaxST system against the DB method, the gold standard, for use in clinical gait studies.
Test procedures
Even with an accurate testing device, the correct test procedure is also very important to achieve valid test results. Therefore, the methodology is another important aspect. In the past, a diversity of procedures has been applied to measure VO$_2$. (17,29) VO$_2$ is usually assessed during 5-6 minutes of sub-maximal walking. (20,25,30-33). Other than that, however, there is considerable variation in the (i) mode of testing (treadmill versus level walking), (ii) walking speed (imposed versus self-selected), (iii) outcome measures (consumption versus cost), and (iv) evaluation protocols (gross versus net) that are used. Methodological issues are very important in the assessment of sub-maximal EE, because they must assure the attainment of a cardio-respiratory steady state. “Failure to achieve steady state makes the interpretation of the data problematic.” (34) Furthermore, for the purpose of clinical testing, it is essential that any testing method is appropriately validated. In addition to the evaluation of system accuracy, this must also include a reproducibility evaluation of the outcome measures and evaluation protocols that are used. (9,22)

Outcome measures: consumption versus cost
The EE of walking is generally expressed in two outcome measures, energy consumption ($ECS$) and energy cost ($EC$).

1. ECS is defined as the amount of energy used per unit of time. It indicates the intensity of physical effort during exercise, and it is time-dependent. (13) According to Garby and Astrup (35), the following equation can be used to calculate ECS:

$$ECS \ (J/kg/min) = (4.960 \times RER + 16.040) \times VO_2 \ (ml/kg/min)$$  \[1\]

2. EC is defined as the energy used per unit of distance. It indicates the amount of energy used to perform the task of walking, and it is not time-dependent. (13)

$$EC \ (J/kg/m) = ECS / \text{walking speed} \ (m/min)$$  \[2\]
A primary requirement of any outcome obtained from clinical testing, and thus also of ECS and EC, is that it should characterize the patient. This implies that the measurement method must be reproducible and that the quantity being measured is stable. (9,22) However, information about the reproducibility of ECS and EC outcomes is limited, especially in clinical populations. Yet, such information is required in order to consider the clinical application of these measurements in the monitoring and evaluation of patients and/or the effectiveness of interventions. Chapter 3 reports on the reproducibility of ECS versus EC of walking in persons with polio residuals and in healthy persons.

**Evaluation protocol: gross versus net**

ECS and EC of walking are commonly reported in terms of gross utilization (i.e. total utilization). This means that a gross protocol is used for the evaluation. However, an important feature of EE is that the measurements are known to vary depending on the size of a subject (e.g. age, height, body mass). (12,24,29,34,36,37) Therefore, it is necessary to apply appropriate methods for normalizing EE data to account for these factors. This enables comparison between patients, and it also allows a more accurate comparison of follow-up measurements within patients.

The simplest way in which to normalize EE data is to divide the outcome measure by body mass. (29,36,27) However, in recent years it has been realized that body mass normalization alone seems to be inadequate, because the normalized quantity retains a marked dependence on clinically relevant factors. (37) One of these relevant factors is basal metabolic rate, the primary component of resting ECS, which is known to decrease with age in children. (21,38-40) This is an important issue, especially when interpreting follow-up measurements of EE in persons who have not yet reached their full stature. (37) Reporting EE data in terms of net utilization (i.e. gross – resting) has been shown to be a suitable way to account for this. (37) Although Ralston advised against using net EE outcomes, and many investigators have followed his recommendation (16), the use of a net evaluation protocol to determine ECS and EC of walking is currently recommended. (29,37)
With the growing application of the net evaluation protocol, it has become essential that information is available about the reproducibility of net measures for the correct interpretation of the outcomes. Surprisingly, nothing is yet known about the comparative reproducibility of net protocols and the commonly used gross protocols. Chapters 4 and 5 address this subject by evaluating the reproducibility of gross and net EC in children with cerebral palsy and in healthy children, as well as in adults with polio residuals and in healthy adults.

**Clinical outcome studies**

The above discussion leads to the first research question addressed in this thesis:

“Is the methodological quality of EE assessment appropriately sufficient, in patients with gait pathology, 1) to apply this tool in rehabilitation management, and 2) to evaluate clinical interventions or monitor changes over time?”

In this context (i.e. clinical testing), EE measurements are performed on individual patients and their interpretation is thus valid for individual patient care. Accordingly, the rehabilitation specialist can evaluate the individual effect of treatment in, in the case of EE testing, the domain of a capacity assessment for a functional activity. For evidence-based rehabilitation practice, however, information on the group effect of a recommended treatment is needed to obtain evidence of the effectiveness of the treatment. This results in the need for clinical outcome studies. (41,42)

In the past, several clinical outcome studies have published reports on sources of EE in pathological gait (21,43-51), and on the outcomes of treatment aimed to decrease EE. (52-56) Most of these studies relied on the use of single ICF domain outcomes, i.e. either measures of body functions/structures or activity capacities were used. However, a shortcoming of such a limited approach is that relationships between outcomes in the different ICF domains cannot be established. With an approach that addresses the different domains of the ICF simultaneously, as indicated in Figure 3,
such relationships may be revealed. For example, it may reveal explanatory mechanisms or underlying principles, thus providing information that can contribute to the process of rehabilitation management, as well as to the enhancement of the quality of current methods of treatment. Very few previous studies of pathological gait have used such an approach in terms of i) relating outcomes in the activity domain with outcomes in the domain of body functions/structures to expose underlying principles of activity limitations (12,42,57), or ii) relating changes in outcomes in the two domains to provide insight into possible explanatory mechanisms underlying treatment effects so that reasons for improvement/decline can be more clearly understood. Chapters 6 and 7 present two outcome studies, in which EC is used as the primary measure to evaluate the effects of treatment. EC is also used simultaneously in combination with outcomes in the ICF domain of body functions/structures (i.e. biomechanics of gait) to look for explanatory mechanisms and underlying principles. (Figure 3)

![Figure 3](image)

**Figure 3.** The ICF model, indicating an approach that addresses the different domains of the ICF simultaneously

This brings forward the second research question addressed in this thesis:

“*Can the measurement of EE of walking capacity, as an activity assessment tool, contribute to the rehabilitation management of patients with gait pathology?”*
Aim 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 clinical practice of rehabilitation medicine. Also investigated is the application of EE assessment in clinical gait studies to evaluate the effects of rehabilitation treatment in persons with lower extremity disorders, and to look for relationships with body functions/structures.

Outline of the thesis

The first part of this thesis describes the quality evaluation of EE assessment in normal and pathological gait. Chapter 2 assesses the accuracy of the portable VmaxST system against the DB method for gas-analysis measurements at rest, during exercise (i.e. at expenditure levels that are reached during walking in patients with gait pathology), and for derived net measurements. Chapter 3 reports on the reproducibility of walking EE measurements (ECS versus EC of walking) in persons with polio residuals and in healthy persons. Furthermore, it describes the energy demands of walking in both groups. Chapter 4 compares the reproducibility of gross and net EC measurements in children with cerebral palsy (CP) and in healthy children. Chapter 5 investigates on how the quality of net EC measurements can be improved for use in clinical practice by carefully examining the potential for optimising the protocol for data-analysis and study design adjustments. These results will be presented in a decision scheme.

The second part of this thesis describes the group evaluation of a rehabilitation intervention (i.e. orthotic treatment) in patients with gait pathology. Chapter 6 retrospectively evaluates the effects of ankle-foot orthoses (AFOs) on net EC of walking in children with CP. It also investigates the biomechanical changes in the gait pattern (at the level of body functions/structures) that are associated with
changes in EC. **Chapter 7** prospectively investigates the effects of carbon-composite knee-ankle-foot orthoses (**KAFOs**) on net EC of walking in persons with polio residuals, compared to conventional KAFOs. Relationships with intended biomechanical improvements (at the level of body functions/structures) are also investigated.

The general discussion, in **Chapter 8**, reflects on the implications of the various studies, defines the position of EE assessment in relation to other clinical assessment tools, and discusses the clinical usefulness of EE assessment for rehabilitation decision-making.

**References**


Chapter 2

Validation of the portable VmaxST system for oxygen-uptake measurement

Merel-Anne Brehm, Herman Groepenhof, Jaap Harlaar

Based on: Gait and Posture 2004; 20: 67–73
Validation of the portable VmaxST system

Abstract

Purpose: The aim of this study was to validate the accuracy of a new type of portable gas-analysis system (the Sensormedics VmaxST system) for the measurement of oxygen-uptake ($VO_2$) at expenditure levels that are reached during walking in patients with gait pathology. The criterion method was the Douglas Bag ($DB$), which is considered to be the gold standard.

Methods: Accuracy evaluations were made in two trials, randomly using the VmaxST and the DB method. Ten healthy adult subjects participated in the trials (age: 28.8 (4.3) yrs; body mass: 75 (13.3) kg; height: 179.3 (8.9) cm). Each trial consisted of two time periods: 5 minutes of resting in a comfortable chair and 5 minutes of cycling at an 80-Watt workload. During the fifth minute of each block, mean minute ventilation ($VE$), $VO_2$, and carbon dioxide production ($VCO_2$) were measured or calculated for both systems. Furthermore, energy expenditure ($EE$) values were calculated, and net values were computed by subtracting resting values from exercise values.

Results: No significant differences were found between the VmaxST and the DB method for the primary outcome parameters: $EE_{NET}$ and $VO_{2NET}$. Significantly higher values were found for resting and exercise values. However, these differences were very small.

Conclusion: The validity of the VmaxST is sufficient for use in clinical gait studies to determine the energy cost (EC) of walking, especially when net values are used.
Introduction

Efficiency of walking can be expressed as energy cost \((EC)\), defined as the energy used per unit of the distance covered during walking, and calculated by dividing energy consumption \((ECS)\) during walking by walking speed. Pathological gait is often associated with inefficiency, due to an increased EC of walking. \((1–7)\)

Information on EC is important in clinical gait studies, because it can help to determine the efficacy of specific treatments and interventions. EC of walking can be estimated, without encumbrance to the patient, with computerized portable gas-analysis systems that measure both the oxygen-uptake \((VO_2)\) and carbon dioxide production \((VCO_2)\). From these measurements the energy utilization can be calculated by taking into account the relative contributions of carbohydrates and lipids, denoted by the respiratory exchange ratio \((RER)\). \((8)\)

To use this computerized portable equipment in clinical gait studies, it is important that two basic properties are established: system accuracy, as well as the reproducibility of the gas-exchange measurements. However, as Macfarlane pointed out in an extended review article \((9)\) the accuracy and reproducibility of current computerized portable gas-analysis systems are not widely established, and very few independent validation studies have been published. A thorough literature search produced several publications on the accuracy of gas-exchange measurements. However, the majority of these articles focused on early generation laboratory-based and portable automated systems. Information about currently available portable automated systems is limited, and concerns the Aerosport KB1-C \((10)\) and the Cosmed K4 and K4b2. \((11–14)\) The accuracy of other automated portable gas-analysis systems that are currently available for exercise studies, such as the Cortex MetaMax3B and the Sensormedics VmaxST system, has not yet been evaluated in an independent study.
Detecting changes in efficiency of walking is not only dependent on the accuracy and reproducibility of the measurements, but also on the evaluation (i.e. normalisation) protocol that is applied. As pointed out by Baker et al. (15), most previous clinical gait studies applied gross evaluation protocols, i.e. measurement of total utilization while walking. Consequently, calculated parameters include both resting and exercise values, which makes it difficult to determine whether changes are related to alterations in resting or walking levels. Applying a net evaluation protocol, i.e. subtracting resting utilization from gross utilization, might give a more direct indication of the efficiency of walking.

The purpose of the present study, before the execution of a reproducibility study in patients with gait pathology, was to assess the accuracy of a new type of portable gas-analysis system, the Sensormedics VmaxST system, against the Douglas Bag criterion method. A further aim was to assess whether the variability of metabolic measurements can be reduced when a net evaluation protocol is applied instead of a gross evaluation protocol.

2. Methods

2.1. Subjects
Ten able-bodied, healthy adult subjects (five men and five women) volunteered to participate in the study. Their ages ranged from 24 to 37 years (mean 28.8 years), their body mass ranged from 63 to 98 kg (mean 75 kg) and their height ranged from 168 to 196 cm (mean 179.3 cm). The subjects were recruited from the university and hospital community. All subjects were informed about the experimental procedures in the study, and they were given specific instructions not to talk or to become distracted during testing. The Ethics Committee of the VU University Medical Center granted ethical approval for this study.
2.2. Equipment

VmaxST system (ST)

The VmaxST system (Sensormedics, Bilthoven, The Netherlands), which is identical to the MetaMax3B system (Cortex, Leipzig, Germany), was used. Both systems have some features that are similar to those of their predecessor, the MetaMax X1 (Cortex, Leipzig, Germany) that has been described elsewhere. (16) However, since the VmaxST uses breath-by-breath technology instead of mixing-chamber technology, a brief outline of this new equipment and of the companion calibration procedures is given.

The VmaxST system (Version 1.0) is a fully portable cardiopulmonary gas-exchange measurement system, based on breath-by-breath technology. It is composed of a close fitting facemask over the mouth and nose, a volume turbine measuring respiratory flow, a gas sample line measuring both oxygen ($O_2$) and carbon dioxide ($CO_2$) concentrations in the expired air, and a battery-operated unit which is worn on the shoulders. The measured data is transmitted directly to a PC by telemetry. Metabolic stress test software (Metasoft, Version 1.3) was used to measure and evaluate the recorded data. Periodic calibration of the analysers was necessary to maintain the highest possible accuracy. This was performed under conditions similar to the environmental condition in which the system operated. The calibration procedures were as follows:

1. Gas calibration of the $O_2$ and $CO_2$ analysers: a two-point reference gas calibration (certified reference gas with 15% $O_2$ and 5% $CO_2$ balance N2) was performed at least every 30 days, and a one-point calibration against ambient air was performed just before each test.

2. Volume calibration of the Triple® volume transducer: the volume transducer was calibrated every 30 days with a 3 l syringe.

3. Pressure calibration of the pressure analyser: the analyser was calibrated once a year.
**Douglas Bag (DB) method**

The DB method, which was developed by Claude Gordon Douglas in 1911, involves collection of the expired air in a large impermeable rubber bag, and subsequent volume and chemical analysis. (17–19) For many decades, this manual method served as the ‘gold standard’. (20–22) To collect the expired air in the rubber bag (60 l), a plastic tube (122 cm, 3mm i.d.) was attached to the bag through a three-way tap. The other site of the tube was connected to a 2700 series two-way valve (Hans Rudolf Inc., Kansas City, USA) fitted with a rubber mouthpiece through which the subject breathed. To ensure that all the expired air was collected in the bag, subjects wore a nose clip. In addition, the bag and tube were inspected for leakage before the start of the study.

2.3. Study design

The accuracy of the VmaxST system for gas-analysis measurements was validated on a Rehcor cycle ergometer (Lode, Groningen, The Netherlands). The DB method served as the criterion method. Since future research will be focused on assessment of walking efficiency in people with disorders affecting the lower extremities, an external ergometer load was applied, which, to a certain extent, was comparable to the load of walking with gait pathology. The amount of the external load was set at 80 Watt, and was based on the results of preliminary gait studies in children with cerebral palsy and persons with polio residuals walking at their own comfortable speed. In doing so, the ECS of cycling at an 80-Watt workload was more or less equal to the ECS required for patients performing the walking exercise. Accuracy evaluations were made by means of two separate trials, randomly using the VmaxST in one trial and the DB method in the other trial.

2.4. Protocol

Each subject performed the two trials on the same day, with a resting interval of 20 minutes in between the trials. By randomisation, five subjects started with the VmaxST trial followed by the DB trial, and the other five started with the DB trial followed by the ST trial. Each trial consisted of two time-blocks: 5 minutes of
resting in a comfortable chair and 5 minutes of cycling at an 80-Watt workload. All measurement trials were performed in a quiet laboratory at the department of Pulmonology.

2.5. Environmental conditions
The barometric pressure \((\text{Pb})\), vapour pressure \((\text{PH}_2\text{O})\), temperature \((t')\) and fractions of inspired \(\text{O}_2\) and \(\text{CO}_2\) \((\text{FIO}_2\text{ and } \text{FCO}_2)\) were determined before each trial.

2.6. Gas volume and gas fraction analysis
The gas volume in the DB, which is the volume measured at ambient temperature and pressure, saturated \((\text{V}_{\text{ATPS}})\), was analysed with a dry gasometer (Meterfabriek Dordrecht, The Netherlands). The volumes were converted from \(\text{V}_{\text{ATPS}}\) to volume at body temperature and pressure, saturated \((\text{V}_{\text{BTPS}})\), for comparison with VmaxST minute ventilation \((\text{VE})\) (Table 1, equation 1), and to volume at standard temperature and pressure, dry \((\text{V}_{\text{STPD}})\), for additional calculation of \(\text{VO}_2\) (Table 1, equation 2). The fractions of expired \(\text{O}_2\) and \(\text{CO}_2\) \((\text{FEO}_2\text{ and } \text{FECO}_2)\) were determined with the analysers of a stationary gas-analysis system, the Vmax229 (Sensormedics, Bilthoven, The Netherlands), by sampling the air in the DB for 20s. Subsequently, \(\text{VO}_2\) and \(\text{VCO}_2\) were calculated using equations 3 and 4, respectively (Table 1). (23)

2.7. Data-analysis
During the fifth minute of the resting and exercise periods, mean \(\text{VE}, \text{VO}_2\), and \(\text{VCO}_2\) were determined. Letting in expired gas during that minute, and subsequently calculating the parameters by means of the above-mentioned formulas, produced the values for the DB. The parameter values for the VmaxST were determined by averaging all breath-by-breath values during the fifth minute. EE was calculated according to Garby and Astrup (Table 1, equation 5). (8) Furthermore, not only gross but also net parameter values were calculated by subtracting resting values from exercise values.
### Table 1. List of equations to calculate gas volume and gas fraction parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minute ventilation</strong></td>
<td></td>
</tr>
<tr>
<td>$V_{BTPS}$ (l/min)</td>
<td>$((V_{ATPS} \cdot (P_b-P_{H_2O}, t^o))/273 + t^o)/(273 + 37^o)/(P_b-P_{H_2O}, 37^o)$ [1]</td>
</tr>
<tr>
<td>$V_{STPD}$ (l/min)</td>
<td>$((V_{ATPS} \cdot (P_b-P_{H_2O}, t^o))/273 + t^o)/(273/760)$ [2]</td>
</tr>
<tr>
<td><strong>Oxygen-uptake</strong></td>
<td></td>
</tr>
<tr>
<td>$VO_2$ (l/min)</td>
<td>$V_{STPD} \times ((FIO_2 \times (1-FEO_2-FECO_2))/(1-FIO_2-FICO_2)-FEO_2)$ [3]</td>
</tr>
<tr>
<td><strong>Carbon dioxide production</strong></td>
<td>$V_{STPD} \times (FECO_2)$                                                  [4]</td>
</tr>
<tr>
<td><strong>Energy expenditure</strong></td>
<td></td>
</tr>
<tr>
<td>$EE$ (kJ/min)</td>
<td>$(4.960 \times RER + 16.040) \times VO_2$ [5]</td>
</tr>
</tbody>
</table>

Abbreviations: FEO$_2$ and FECO$_2$, fractions of expired oxygen and carbon dioxide; FIO$_2$ and FICO$_2$, fractions of inspired oxygen and carbon dioxide; $P_b$, barometric pressure; $P_{H_2O}$, vapour pressure; $V_{ATPS}$, volume measured at Ambient Temperature and Pressure, Saturated; $V_{BTPS}$, volume at Body Temperature and Pressure, Saturated; $V_{STPD}$, volume at Standard Temperature and Pressure, Dry.

### 2.8. Statistical analysis

The dependent variables VE, VO$_2$, VCO$_2$ and EE were examined for the resting condition, 80-Watt condition, and net condition. SPSS (10.0) for Windows was used for the statistical analysis. Paired t-tests were used to test for differences between the VmaxST values and the DB values. The level of significance was set at $p < 0.05$. Furthermore, Bland–Altman plots (24) were used to show the individual difference scores between the DB method and the VmaxST system (DB–ST).

### 3. Results

Average ST and DB values for the parameters VE, VO$_2$, VCO$_2$ and EE in all three conditions are presented in Table 2. Table 3 presents the mean absolute and mean relative differences for the parameters VE, VO$_2$, VCO$_2$ and EE in the three conditions.
The results of the paired t-tests (Table 3) revealed a significant difference for VE<sub>REST</sub>, while no significant differences were found for VE<sub>EXERCISE</sub> and VE<sub>NET</sub>. With regard to the VO<sub>2</sub>, the VmaxST showed significantly higher values for VO<sub>2REST</sub> and VO<sub>2EXERCISE</sub>. No significant difference was found for VO<sub>2NET</sub>. Similar results were seen for EE values, with significantly higher values observed at EE<sub>REST</sub> and EE<sub>EXERCISE</sub>, and no significant difference for EE<sub>NET</sub>. VCO<sub>2</sub> values revealed no significant differences.

**Table 2.** Average values of VE, VO<sub>2</sub>, VCO<sub>2</sub>, and EE: comparison of the VmaxST system and the Douglas Bag method

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VmaxST (mean ± (SD))</th>
<th>Douglas Bag (mean ± (SD))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rest</td>
<td>80 Watt</td>
</tr>
<tr>
<td>VE (l/min)</td>
<td>8.08 (1.8)</td>
<td>30.4 (3.6)</td>
</tr>
<tr>
<td>VO2 (l/min)</td>
<td>0.30 (0.06)</td>
<td>1.45 (0.15)</td>
</tr>
<tr>
<td>VCO2 (l/min)</td>
<td>0.25 (0.05)</td>
<td>1.18 (0.12)</td>
</tr>
<tr>
<td>EE (kJ/min)</td>
<td>6.1 (1.1)</td>
<td>29.2 (2.8)</td>
</tr>
</tbody>
</table>

**Table 3.** Mean absolute and relative differences

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Absolute difference (SD) †</th>
<th>Relative difference (%) ‡</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rest</td>
<td>80 Watt</td>
</tr>
<tr>
<td>VE (l/min)</td>
<td>1.00* (1.39)</td>
<td>0.40 (1.51)</td>
</tr>
<tr>
<td>VO2 (l/min)</td>
<td>-0.02* (0.02)</td>
<td>-0.04* (0.05)</td>
</tr>
<tr>
<td>VCO2 (l/min)</td>
<td>-0.01 (0.03)</td>
<td>-0.01 (0.09)</td>
</tr>
<tr>
<td>EE (kJ/min)</td>
<td>-0.39* (0.61)</td>
<td>-0.70* (1.17)</td>
</tr>
</tbody>
</table>

Abbreviations: DB, Douglas Bag; EE, energy expenditure; ST, VmaxST system; VCO2, carbon dioxide production; VE, minute ventilation; VO2, oxygen-uptake.

†Absolute difference: mean DB–mean ST
‡Relative difference: (absolute difference/(0.5*(mean DB+ mean ST)))*100%
* = Significantly different at p < 0.05
In the resting condition all parameters, except for the VCO₂, were significantly different. In the exercise condition both VO₂ and EE were significantly different from the DB, and in the net condition none of the parameters were significantly different. The magnitude of the differences was greatest in the rest condition for all parameters and smallest in the net condition.

**Figure 1.** Bland and Altman plot showing absolute differences in rest and exercise values between DB and ST. A: VO₂_{REST} (l/min), B: VO₂_{EXERCISE} (l/min), C: EE_{REST} (kJ/min), and D: EE_{EXERCISE} (kJ/min)
Figure 1 shows the Bland–Altman plots for the VO$_2$ and EE parameters, depicting the individual absolute difference scores between DB and ST and the calculated 95% limits of agreement (mean difference +/- 2SD). Figure 1A shows that for the VO$_2$$_{REST}$ condition one point is out of agreement. For the exercise condition none of the points are out of agreement (Figure 1B). The figures for EE parameters (Figure 1C and 1D) show that all individual data-points fall within the limits of agreement.

4. Discussion

The purpose of this study was to assess the accuracy of the VmaxST system for measurement of oxygen-uptake at expenditure levels that are reached during walking in people with disorders affecting the lower extremities. The criterion method was the DB method, which is regarded as the ‘gold standard’.

One of the limitations of this study was the inability to perform simultaneous gas-exchange measurements, connecting the VmaxST and the DB in series. Such a serial set up would be the perfect experimental design to test for differences in parameters measured with two dissimilar systems, because it rules out trial-to-trial bio-variability, and, thereby, only yields instrumental variability. However, pilot trials involving nine healthy adult subjects showed a systematic increase of 25–30% for VE$_{REST}$, VO$_2$$_{REST}$, VCO$_2$$_{REST}$ and EE$_{REST}$ values measured with the VmaxST system. One possible explanation for the large differences in resting values is that they may be a consequence of the difference in configuration, compared to the standard application. This causes an alignment problem in matching the gas concentration signals to flow signals, mainly due to the lag-before-start effect of the turbine. (25) This becomes increasingly critical as the sampling dead space increases, which happens in a simultaneous design when connecting two devices in series. Consequently, the accuracy of the VmaxST system was validated by means of non-
simultaneous measurements, randomly using the VmaxST system in the one trial and the DB method in the other trial. By applying this parallel set-up, a within-subject trial-to-trial variation of approximately 4.5% was expected. (26–28)

A second limitation of this study is due to the fact that only derived output variables are reported and discussed. Information about the raw data would bring more insight into how differences in the validation process arise and whether they arise from either gas-concentration measurements, ventilation measurements, from temperature and pressure recordings, or from combinations of these. Information about the raw data could, for example, enlighten the large discrepancy between systems resulting from simultaneous measurements, such as that found in the above-mentioned pilot trails. Furthermore, it could clarify some notable findings in resting values showed in the present study. Unfortunately, the VmaxST system does not give insight into all the raw measurement data. Fractions of expired O$_2$ and CO$_2$ are not enclosed as output variables. In particular, these variables are needed to explain differences in VO$_2$, VCO$_2$ and EE. Despite specific inquiries with the manufacturer, the FEO$_2$ and FECO$_2$ variables could not be ascertained from the measurements. It seems that the functioning of the VmaxST system is dependent on certain assumptions and calculations. These remain a ‘black box’ to the users, thereby making it very difficult to explain the differences that were found.

The main finding of the present study is that the VmaxST system is an accurate device for measuring VO$_2$ when applying a net evaluation protocol. Measurements of VO$_2$ at rest and during moderate exercise showed significantly higher values than DB. However, the difference in size between DB and ST values was small (20 and 40 ml/min, respectively for VO$_{2REST}$ and VO$_{2EXERCISE}$). These results are comparable with the results of other validation studies, assessing the accuracy of similar computerized portable gas-analysis systems [10,13]. King et al. (10) applied a simultaneous design to test for differences between the Aerosport KB1-C system and the DB method. Their results showed significantly higher values for the KB1-C, both at rest and at a 50-Watt workload. Difference magnitudes were 30 ml/min for VO$_{2REST}$ and 90 ml/min for VO$_{2EXERCISE}$. McLaughlin et al (13) validated the
accuracy of the Cosmed K4b2 system against the DB method by means of non-simultaneous measurements. They found no significant difference for VO$_{2\text{REST}}$ values, and significantly higher values for VO$_2$ at a 50-Watt workload (about 90 ml/min higher than DB).

VCO$_2$ values were not significantly different. This is similar to the results found in the study carried out by McLaughlin et al. (13) King et al. (10) found significantly higher values for VCO$_{2\text{REST}}$ and VCO$_{2\text{EXERCISE}}$.

VE$_{\text{REST}}$ values were significantly lower for the ST than for the DB, while no significant differences in VE were found for the 80-Watt condition and the net condition. King et al. (10) found a comparable difference in VE$_{\text{REST}}$, but their values were significantly higher than the criterion method. They suggested that the flow setting of the pneumotachometer (10–120 l/min) could be a partial explanation for the differences found in VE$_{\text{REST}}$. The mean flow rate at rest (9.9 l/min measured with the DB) was below the flow setting of their pneumotachometer. Consequently, the KB1-C was not expected to track the ventilation rate accurately at this level of flow. However, the flow setting of the VmaxST volume turbine (3–1200 l/min) was large enough to track the low ventilation rate during rest measurements, and, therefore, could not be an explanation for the VE$_{\text{REST}}$ differences found in the present study. A more likely explanation may be partly linked to linearity problems caused by inertia of the turbine-vane. This problem occurs at low flow rates, and is referred to as the ‘lag-before-start’ effect. (25) An alternative interpretation for the lower values in VE$_{\text{REST}}$ for ST (11.7%) might be related to the method of data capturing. For both systems, data capturing and additional calculations involved only the last minute of the resting block. At an approximate frequency of 12 breaths per minute during rest, the inclusion of one extra breath in the DB bag or the exclusion of one breath in the VmaxST parameter calculation, would lead to an 8% lower resting ventilation value for the ST. This is commensurate with the differences observed.

With regard to EE values, a significant difference was found for both the resting and the exercise condition. These differences in EE could either be related to differences in VO$_2$ or RER (i.e. VCO$_2$/VO$_2$). Since the VCO$_2$ values did not differ significantly, the differences in EE measurements were, consequently, caused by the significantly
higher VO₂ values. A comparison of these energy consumption (ECS) results with the results of other studies is not possible, because most studies report on oxygen consumption, thereby referring to ECS. However, oxygen consumption is only related to ECS under the assumption of a certain RER. Such an RER value is needed because it gives information about substrate use, which should be included to calculate ECS correctly. Since the VmaxST also provides the VCO₂ output, the ECS can be calculated with a true RER, so an assumption of RER is not needed. Yet, in most studies a RER value of 1 is used. Theoretically, the use of an RER = 1, instead of a true RER, will yield differences ranging from 0% (RER = 1) to 7.6% (RER = 0.7). Considering a true RER value at rest (RER = 0.83), and during cycling at an 80-Watt workload (RER = 0.81), such as produced in the present study, will, subsequently, yield differences of 4.5% and 4.7%, respectively. The magnitude of these differences might be considered an additional source of variance.

Another finding of this study is that subtracting resting values from gross values (i.e. using net values) reduced the variability of VO₂ and EE measurements. This was also demonstrated by the results of recent work carried out by Baker et al. (15) They suggested two sources causing substantial variability, one being variability arising from inter-individual differences in the resting rate. They showed that applying a net evaluation protocol on healthy adult subjects reduced the variability of VO₂ measurements, thereby increasing its sensitivity to detect changes in a subject’s condition. This procedure will also rule out systematic instrument-errors. The result of our study, which is in accordance with the above-mentioned findings of Baker et al. (15), is a good starting point from which to evaluate the effect of applying a net rather than a gross evaluation protocol on the reproducibility of EE measurements in clinical populations.

Even though significant differences were found in the resting condition and the 80-Watt condition for the two primary parameters, VO₂ and EE, the magnitude of the differences was within 7.5% of the DB values. King et al. and McLaughlin et al. (10,13) pointed out that differences up to 10%, which approximates 100 ml or 2000
Joules during exercise, are physiologically insignificant for most purposes. Differences that go beyond 10% might thus be regarded as clinically relevant when considering the effects of therapy and interventions in clinical practice. A future reproducibility study in patients with disorders affecting the lower extremities should provide more insight into the amount of physiological variability of such clinical populations, thereby giving a more complete reference to what might be considered a clinically relevant change (CRC). Further research should focus on reproducibility evaluations of gross and net VO$_2$ measurements in clinical populations, and on EE calculation based on true RER values.

5. Conclusion

It was shown that the VmaxST system is an accurate instrument to determine the energy demands at expenditure levels that are reached during walking in people with lower extremities disorders, especially when net values are used.

References

Validation of the portable VmaxST system


Chapter 3

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

Merel-Anne Brehm, Jaap Harlaar, Frans Nollet

Based on: Archives of Physical and Medical Rehabilitation 2006; 87: 136-140.
Abstract

Purpose: The aim of this study was to describe the energy demands of walking in persons with postpoliomyelitis syndrome (PPS) in comparison with the demands in healthy persons, and to assess the reproducibility of walking energy expenditure measurements.

Design: Four repeated measurements with a 1-week interval between each measurement occasion.

Setting: Outpatient clinic of a university hospital.

Participants: Fourteen patients with PPS and 14 age- and gender-matched healthy persons.

Outcomes: Primary parameters: walking speed and energy cost (EC) of walking. Correlation parameter: lower-extremity muscle strength sum (MSS). Reproducibility parameters: standard error of measurement (SEM) and smallest detectable difference (SDD).

Results: Walking speed in persons with PPS (61.8 m/min) was significantly lower (-28%) and EC (4.8 J/kg/m) was significantly higher (40%) than in healthy persons. MSS correlated strongly with EC of walking ($r = -0.84; p < 0.001$), explaining 71% of the variance. The SEM of the EC outcome ranged between 1.7% and 3.4% for PPS patients and between 1.2% and 2.4% for healthy persons. The SDD ranged between 4.6% and 9.4% for PPS patients and between 3.3% and 6.6% for healthy persons, depending on the number of repeated measurement occasions that were considered.

Conclusions: EC of walking in persons with PPS is strongly related to the extent of muscle weakness in the lower extremities. Although variability was greater for PPS persons than for healthy persons, reproducibility of the EC outcome was high. Therefore, the metabolic assessment of EC of walking is a sensitive tool that can reveal clinically relevant changes even in an individual person with PPS.
Introduction

Although it has been shown that the energy demands of walking are elevated for many patient groups (1-6), those demands in persons with polio residuals have not yet been fully described. In our review of the few publications that have focused on this topic, we found that studies either concentrated on the cardio-respiratory responses of training programs (7,8) on walking energy expenditure in general, (9) or on the energy demands of walking in children with polio. (10) No studies have yet described the energy demands of walking in adults with polio residuals, and compared those with the demands of matched healthy persons. Such information may be relevant, because it has been proposed that late onset neuromuscular symptoms, which are referred to as the postpoliomyelitis syndrome (PPS), might partly be explained by severely reduced work capacity and the increased energy demands of performing sustained sub-maximal exercise (8,11), thereby predisposing people with PPS to premature fatigue in carrying out activities of daily-life. Nollet et al. (11) reported that oxygen consumption during sub-maximal cycling was significantly higher in former polio persons than in healthy persons, because of a reduced muscle capacity. However, as they proposed in their conclusion, results from cycling cannot simply be generalized to walking, due to task-specific muscle loads.

The energy demands of walking can be estimated with fully automated portable gas-analysis systems that measure both the oxygen uptake ($VO_2$) and carbon dioxide production ($VCO_2$). From these measurements, energy expenditure ($EE$) can be calculated, by taking into account the relative contributions of carbohydrates and lipids. (12) Several systems that are currently available are accurate for determining the EE during walking. (13-17) However, information on the reproducibility of these portable systems is limited. (18) Most studies have focused on laboratory-based systems (19, 20) and portable systems of an early generation (21,22); little is known about the reproducibility of the currently available portable systems. (23,24) There have been no studies of the day-to-day reproducibility of sub-maximal walking EE,
as determined with an up-to-date portable gas-analysis system, in persons with polio residuals or other lower extremity disorders. Such information is required in order to consider the clinical application of the assessment of EE in evaluating patients with gait pathology and/or the effects of interventions.

The objective of this study was two-fold: 1) to describe the energy demands of walking in persons with PPS by comparing them with age- and sex-matched healthy persons, and 2) to assess the reproducibility of the walking EE outcome measures.

2. Methods

2.1. Participants

The study sample included 14 adults with PPS, defined according to the March of Dimes Foundation criteria (25), and 14 healthy adults. Participants with PPS (6 men, 8 women) were recruited from the outpatient clinic of the Department of Rehabilitation Medicine at the VU University Medical Center in Amsterdam. The inclusion criteria were: (1) a history of poliomyelitis with residual muscle weakness in at least 1 leg; (2) ability to walk for at least 4 minutes at a self-preferred, comfortable walking speed (with or without walking aids); (3) age between 18 and 70 years; and (4) no existent impaired pulmonary or cardiac disease, as confirmed by medical examination. They ranged in age from 36 to 67 years (mean, 55 y), their body mass ranged from 53 to 95 kg (mean, 72 kg), and their body mass index (BMI) ranged from 20 to 28 kg/m2 (mean, 24.5 kg/m2).

The 14 healthy adults (6 men, 8 women) were employees of the outpatient clinic. The activity levels of these persons were moderate, meaning that they engaged in some form of physical exercise once or twice per week. The healthy persons were matched to the PPS persons with regard to gender, age, body mass, and height. Their ages ranged from 31 to 64 years (mean, 51 yrs), their body mass ranged from 53 to
95kg (mean, 74 kg), and their BMI ranged from 19 to 29 kg/m² (mean, 24.1 kg/m²). Subject characteristics did not differ between the groups.

The clinical condition of the PPS patients with respect to muscle strength in the lower extremities, self-reported maximal walking distance, and walking devices is described in Table 1. Muscle strength for hip flexors, hip extensors, hip abductors, hip adductors, knee flexors, knee extensors, dorsiflexors, and plantarflexors was assessed by manual testing, according to the Medical Research Council scale. (26) From these strength measurements, two parameters were determined: a muscle strength sum (MSS), and a muscle strength asymmetry (MSA). Both parameters were calculated according to the method described by Nollet et al. (27) The VU University Medical Ethics Committee approved the study, and written informed consent was obtained from all participants.

Table 1. Clinical condition of persons with PPS

<table>
<thead>
<tr>
<th>MSS †</th>
<th>MSA †</th>
<th>Walking distance ‡</th>
<th>Walking devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.0</td>
<td>0.52</td>
<td>250-500m</td>
</tr>
<tr>
<td>2</td>
<td>22.5</td>
<td>0.16</td>
<td>&gt; 1000m</td>
</tr>
<tr>
<td>3</td>
<td>20.0</td>
<td>0.60</td>
<td>&lt; 250m</td>
</tr>
<tr>
<td>4</td>
<td>20.0</td>
<td>0.30</td>
<td>500-1000m</td>
</tr>
<tr>
<td>5</td>
<td>25.5</td>
<td>0.06</td>
<td>250-500</td>
</tr>
<tr>
<td>6</td>
<td>17.5</td>
<td>0.83</td>
<td>&gt; 1000m</td>
</tr>
<tr>
<td>7</td>
<td>23.5</td>
<td>0.36</td>
<td>250-500m</td>
</tr>
<tr>
<td>8</td>
<td>26.0</td>
<td>0.23</td>
<td>500-1000m</td>
</tr>
<tr>
<td>9</td>
<td>28.0</td>
<td>0.14</td>
<td>&gt; 1000m</td>
</tr>
<tr>
<td>10</td>
<td>24.0</td>
<td>0.25</td>
<td>&gt; 1000m</td>
</tr>
<tr>
<td>11</td>
<td>24.5</td>
<td>0.81</td>
<td>500-1000m</td>
</tr>
<tr>
<td>12</td>
<td>13.0</td>
<td>0.85</td>
<td>&lt; 250</td>
</tr>
<tr>
<td>13</td>
<td>18.0</td>
<td>0.78</td>
<td>&lt; 250</td>
</tr>
<tr>
<td>14</td>
<td>12.5</td>
<td>1.00</td>
<td>500-1000m</td>
</tr>
</tbody>
</table>

Abbreviations: AFO, ankle-foot orthosis; BL, bilateral; KAFO, knee-ankle-foot orthosis; L, left; MSA, muscle strength asymmetry; MSS, muscle strength sum; R, right.
† MSS range, 0-32; MSA range, 0-1.
‡ Self-reported maximal walking distance classified into 4 categories: < 250m; 250-500m; 500-1000m; > 1000m.
2.2. Equipment
A lightweight portable gas-analysis system (VmaxST), based on breath-by-breath technology, was used to determine EE of walking. The system is composed of a facemask, a Triple volume transducer, a gas-sample line, and a battery-operated unit (650g) that is worn on the shoulders. To maintain the highest possible accuracy, a periodic calibration of the analysers with certified calibration gases was performed in accordance with the manufacturer’s instructions. (17)

2.3. Procedures
Each measurement consisted of a resting test followed by a walking test. Subjects were first seated in a comfortable chair, and the equipment and the facemask were put on. The fitting of the facemask was carefully inspected for leakage. The resting test, which consisted of sitting quietly for 10 minutes, was then started. Subjects were given specific instructions to not be distracted, or to talk or laugh, and to fidget as little as possible. This test was followed by the walking test, which consisted of walking for 5 minutes on an indoor oval track with a length of 50 meters. Subjects were asked to walk at their usual, self-preferred, comfortable speed. During the resting test and the walking test, there were breath-by-breath registrations of VO$_2$ and VCO$_2$. The measurements were completed 4 times on 4 different days (occasions), with a 1-week interval between the measurement occasions.

2.4. Data-analysis
Walking speed was expressed in meters per minute and was calculated as the distance walked over the last 2 minutes of the test, divided by 2. For each walking test, the mean VO$_2$ and VCO$_2$ were determined by averaging all breath-by-breath values for the last 2 steady-state minutes of the test. Respiratory exchange ratios (RERs) were calculated as the quotient of VCO$_2$ and VO$_2$. RER and VO$_2$ values of each breath were then used to calculate the following body mass normalized EE outcome measures:
• Gross energy consumption \((ECS)\), defined as the total energy used per unit of time, was calculated in J/kg/min, according to Garby and Astrup. ([12], also Table 1, equation 5 on page 34)

• Gross energy cost \((EC)\), defined as the total energy used per unit of distance, was calculated in J/kg/m by dividing ECS during walking by walking speed.

2.5. Statistical analysis
Based on a normal distribution of the data, parametric statistics were used. Systematic differences between groups were analysed with Student t-tests. For persons with PPS, Pearson product-moment correlations were calculated for walking speed and EC with MSS and MSA. Stepwise multiple regressions were applied to determine their combined effect on walking speed and EC. A factor with a \(p\)-value below 0.05 was entered in the regression model, whereas it was removed with a \(p\)-value above 0.10.

Reproducibility was analysed using the Generalizability Theory. (28,29) As a measure of reproducibility, the intraclass correlation coefficient \((ICC)\) was calculated. Furthermore, the standard error of measurement \((SEM)\), reflecting the variability of measurements due to the repeated occasions and random error, was calculated, as well as the smallest detectable difference \((SDD)\), reflecting the smallest change that can be detected in a subject. Based on the method described by Roebroeck et al. (28), reproducibility parameters were calculated for different study designs (i.e. for different numbers of measurement occasions).

SPSS for Windows was used for the statistical analysis. The \(\alpha\)-level of significance for all tests was set at \(p < 0.05\).
3. Results

3.1. Walking demands

A significant difference was found between the two groups for all walking parameters. Walking speed was 28% lower, and ECS and EC were, respectively, 9% and 40% higher for persons with PPS than for healthy persons (Table 2).

Table 2. Mean walking parameter values over four occasions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PPS Subjects† (n=14)</th>
<th>Healthy Subjects† (n=14)</th>
<th>Difference ‡</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (m/min)</td>
<td>61.8 (10.2)</td>
<td>82.0 (8.0)</td>
<td>-20.2 (-28%)</td>
<td>0.000*</td>
</tr>
<tr>
<td>ECS (J/kg/min)</td>
<td>291 (29.3)</td>
<td>266 (41.1)</td>
<td>+25 (+9.0%)</td>
<td>0.002*</td>
</tr>
<tr>
<td>EC (J/kg/m)</td>
<td>4.8 (0.78)</td>
<td>3.2 (0.28)</td>
<td>+1.6 (+40%)</td>
<td>0.000*</td>
</tr>
</tbody>
</table>

† Values are presented as mean over 4 occasions ± standard deviation.
‡ Difference is presented as absolute and as a percentage (%); percentages are calculated as ([PPS-healthy]/[PPS + healthy]/2)*100%.
* Significantly different.

For the PPS patients, both MSS and MSA correlated significantly with walking speed ($r = 0.77$, $p = 0.001$; $r = -0.56$, $p = 0.036$, respectively) and EC ($r = -0.84$, $p<0.001$; $r = -0.56$, $p = 0.036$, respectively) (Figure 1). Lower-extremity MSS explained 59% of the variance in walking speed and 71% of the variance in EC measurements. MSA accounted for 32% of the variance in both walking speed and EC measurements. Multiple regression analysis showed that MSA was not an independent contributor to either walking speed or EC ($p = 0.363$).
3.2. Reproducibility

The measurements of walking parameters were more variable for the PPS persons than for the healthy persons, that is, smaller ICC values and greater SEM and SDD values were found for the PPS persons. The healthy persons did not show much difference in reproducibility for the different parameters of walking speed, ECS, and EC, whereas in PPS persons the reproducibility of EC was better than the reproducibility of ECS or walking speed (Tables 3 and 4 for healthy persons and PPS persons, respectively).
The Tables 3 and 4 also show the effect of increasing the number (n) of measurement occasions on reproducibility. In healthy persons SEM and SDD values were below 2.4% and 6.6%, respectively, for a design with 1 occasion, and reduced to approximately half their size when the number of repeated occasions was increased to 4 (Table 3). For the PPS persons, the SEM and SDD values were below 5.7% and 16.0%, respectively, for a design with 1 occasion, and also reduced to half their size in case of 4 occasions (Table 4).

### Table 3. Reproducibility for healthy persons, depending on the n of measurement occasions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ICC</th>
<th>SEM †</th>
<th>SDD †</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Speed (m/min)</td>
<td>0.97</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECS (J/kg/min)</td>
<td>0.98</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC (J/kg/m)</td>
<td>0.93</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

### Table 4. Reproducibility for PPS persons, depending on the n of measurement occasions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ICC</th>
<th>SEM †</th>
<th>SDD †</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Speed (m/min)</td>
<td>0.93</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ECS (J/kg/min)</td>
<td>0.73</td>
<td>0.89</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
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<tr>
<td>EC (J/kg/m)</td>
<td>0.96</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
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</tr>
</tbody>
</table>

Abbreviations: EC energy cost; ECS, energy consumption; ICC, intra class correlation coefficient; n, number of repeated occasions; SDD, smallest detectable difference; SEM, standard error of measurement.

† SEM and SDD values are presented as absolute and as a percentage (%). Percentages are calculated as (absolute/mean of measurement occasions taken)*100%.
4. Discussion

In this study, persons with PPS used considerably more energy for walking, 40% per distance covered, than age- and gender-matched healthy persons. Similar results were found in the only study on the energy demands of walking in children with polio. (10) In a group of 8 children with polio residuals, comfortable walking speed appeared to be 32% lower, and ECS and EC were, respectively, 7% lower and 50% higher, in comparison with healthy children. (10) Studies that assessed the energy demands of walking in persons with other lower extremity disorders, such as cerebrovascular lesions, multiple sclerosis, osteoarthritis, or amputations, (1-6) found similar increments in walking demands: a slight elevation in ECS, a much lower walking speed and, consequently, a moderate to severe increase in EC.

The differences in walking demands are greatest when expressed as the energy used per unit of distance, which is in line with the review by Fisher and Gullickson. (1) In this review in the biomechanics and determinants of normal gait are described, and the energy demands of walking in normal and pathological gait are summarized. The 6 major determinants of gait are pelvic rotation, pelvic tilt, lateral displacement of the pelvis, knee flexion, and foot and knee mechanisms. (30) Fisher (1) argued that in people with gait pathology, these determinants are changed or lost. This increases the vertical excursion of the center of body mass. (31) In response, patients decrease their walking speed to avoid an increase in ECS. As a result, there is an increase in the energy demands for walking a set distance, which makes walking less efficient in terms of EC.

The reduced walking efficiency in PPS persons was strongly associated with the degree of lower-extremity muscle weakness. MSS, a lower-extremity muscle strength index, correlated with comfortable walking speed, and accounted for 59% of the variance. This is consistent with the results of the study by Siegel et al., (32) who found a comparable association in children with idiopathic inflammatory myopathies. MSS correlated even better with EC, accounting for 71% of its variance. Although MSS is an indicator of the severity of polio, this percentage is
Energy demands of walking in polio: reproducibility of consumption versus cost measures

surprisingly high, considering that most patients used orthoses and/or crutches to compensate for paresis. These devices influence the EC of walking because of their weight and properties. It is, however, difficult to separate these effects from the severity of paresis, as many patients cannot walk without them. Orthotic and walking devices may also account in part for the unexplained variance in EC. Yet, from a clinical perspective, it is important to realize that the severity of paresis is apparently a strong indicator of the increased EC of walking in PPS persons. The observation that PSS persons with more severe paresis are less able to perform activities of daily living and perceive more limitations in physical functioning (33) may, to a certain extent, be due to such increases in EC of walking.

Previously, it has been reported that oxygen consumption was elevated in persons with polio residuals who performed a cycling exercise, (11) mainly in association with a reduced muscle capacity of the lower extremities. Oxygen consumption during cycling increased significantly with increasing strength asymmetry. (11) Our study showed that EC of walking was associated with strength asymmetry (MSA). However, it was not a significant contributor. This dissimilarity may be due to differences between walking and cycling, i.e. differences between muscle loads for the two activities. Additionally, it is conceivable that the walking devices used, such as braces and canes, partly compensated for strength asymmetry during walking. Nevertheless, both our study and that of Nollet et al. (11) provide important information about the physical strain of performing sub-maximal activities in relation to the severity of polio paresis, especially in that the extent of the paresis appeared to be a determinant of change in physical functioning over time. (33)

Limitations of this study are its small sample size and our inclusion criteria. Subjects were selected for their ability to walk for at least 4 minutes with or without walking devices. Therefore, selection bias toward less severely affected patients may be assumed. However, given the severity of polio residuals and the use of assistive devices in our sample, we believe that this bias is limited, and that our sample was a good representation of people with PPS who are capable of walking. Nevertheless, we do not advocate that our results should be generalized to all people with polio residuals.
The reproducibility of the walking EE outcomes obtained from respiratory gas-analysis with the portable VmaxST system was high, especially the reproducibility of the EC outcome. When comparing reproducibility between the two groups, the variability of measurements was greater for persons with PPS than for healthy persons. This implies less sensitivity to detect changes in the PPS persons. Applying more repeated occasions in the study design diminishes variability, thereby making measurements more sensitive to change. We showed that by increasing the number of occasions, the SDD for the walking parameters (i.e. the smallest change that can be identified) could be reduced to levels well below what is considered to be clinically relevant. McLaughlin et al. (15) reported that a difference up to 10% during exercise is physiologically insignificant for most purposes. It appears that a study design with 2 repeated occasions guarantees sufficient sensitivity to determine clinically relevant changes in the EC of walking in persons with PPS.

5. Conclusions

Walking efficiency in persons with PPS was significantly lower than in healthy persons. Walking efficiency decreased with the severity of paresis of the legs. Future research into maintaining functional abilities in persons with PPS should focus on stabilizing or decreasing the energy demands of physical activities by means of exercise programs and/or improvements in walking devices (e.g. lower extremity orthoses). The assessment of walking efficiency with portable gas-analysis systems provides a sensitive tool with which to detect clinically relevant changes in individual persons with PPS.
Energy demands of walking in polio: reproducibility of consumption versus cost measures

References

Chapter 4

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

Merel-Anne Brehm, Jules Becher, Jaap Harlaar

Based on: Developmental Medicine & Child Neurology 2007; 49: 45-48
Abstract

Purpose: In evaluating energy cost (EC) of walking, referred to as walking efficiency, the use of net evaluation protocols (i.e. net = gross − resting) has recently been recommended. The aim of this study was to evaluate the comparative reproducibility of net protocols and the commonly used gross protocols.

Methods: Ten minutes of resting and 5 minutes of walking at a self-preferred speed were used to determine gross and net EC in 13 children with spastic cerebral palsy ([CP]; seven males, six females; mean age 8yrs 7mo [SD 3yrs 4mo], range 4yrs 1mo-13yrs 0mo), and in 10 children (three males, seven females) with typical development. In the former, their Gross Motor Classification System levels ranged from level I to level III, seven had hemiplegia and six had diplegia. There were four repeated sessions on different days, with periods of 1 week between sessions. Reproducibility was assessed for speed, and gross and net EC, by using the standard error of measurement.

Results: The results of this preliminary study showed that EC measurements were more variable for children with CP than for children with typical development. Furthermore, in both groups there was considerably more variability in net outcome measures than in the gross outcome measures.

Conclusions: It is concluded that, on the basis of the methodology used, the use of gross EC, rather than net EC, seems to be a more sensitive measure of walking efficiency to detect clinically relevant changes in an individual child with CP.
Introduction

It has been documented for several decades that energy cost (EC) of walking in children with cerebral palsy (CP) can be up to three times that in children with typical development. (1-4) Accordingly, children with CP are expected to be less able to perform mobility-related activities of daily-life.

EC, defined as the energy used per unit of the distance covered during walking, is widely accepted as an accurate indicator of walking efficiency. (5) Walking efficiency can be assessed by the measurement of oxygen-uptake ($VO_2$) during walking at a self-preferred comfortable speed. However, efficiency of walking can be assessed more accurately when it is based not only on $VO_2$ measurements but also on the measurement of carbon dioxide production ($VCO_2$). The reason for this is that the ratio of $VCO_2$ to $VO_2$ (respiratory exchange ratio; $[RER]$) gives information about the percent participation of nutrients in energy metabolism, which is needed for calculating the actual amount of energy used by the body. (6)

Walking efficiency based on the combined measurement of $VO_2$ and $VCO_2$ can be assessed with modern portable gas-analysis systems. The accuracy of these gas-analysis systems has already been established. (7-11) However, information about the reproducibility, which includes both the quality of the outcome measures and evaluation protocols that are applied, is limited. (12) A few studies on this topic were found, focusing mainly on the reproducibility assessment of conventional systems (i.e. systems that measure only $VO_2$) (13-15), and only one study included reproducibility measures of a modern portable system, assessed in five healthy children. (16) No study has yet investigated the reproducibility of walking efficiency measured with a modern portable gas-analysis system in children with CP, walking at a self-preferred speed. Moreover, the reproducibility with regard to the evaluation protocols that are applied has not yet been studied, namely gross versus net. For many decades gross evaluation protocols (i.e. measurement of total utilization while walking) were commonly used to assess EC. However, in recent years net protocols (= gross utilization – resting utilization) have been recommended. (17,18) 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. The purpose of this study was to assess the reproducibility of gross and net walking efficiency measures in children with CP, and to compare this with the reproducibility in children with typical development.

2. Methods
This study was conducted at the VU University Medical Center in Amsterdam, the Netherlands. Ethical approval was obtained (VU University Medical Ethics Committee), and a written informed consent statement was obtained from all participants and their parents.

2.1. Study population
Thirteen children with spastic CP (seven males, six females) were recruited from the outpatient clinic of the Department of Rehabilitation Medicine at the VU University Medical Center. Children were included in the study on the basis of the criterion of being able to walk for at least 4 minutes at a self-preferred comfortable speed. The ages of these children ranged from 4 years 1 month to 13 years 0 months, with a mean of 8 years 7 months (SD 3yrs 4mo). A group of 10 children with typical development of similar ages and sizes (three males, seven females) was used for reference. A description of the both groups is given in Table 1.

2.2. Measurement instrument
A lightweight, portable gas-analysis system (VmaxST, Sensormedics, Bilthoven, the Netherlands), based on breath-by-breath technology, was used to determine walking efficiency. The system is composed of a facemask, a Triple volume transducer, a gas-sample line, and a battery-operated unit (650g) that is worn on the shoulders. All the measurements and calibration procedures were conducted in accordance with the manufacturer’s instructions. (11)
Table 1. Characteristics of the children with typical development and children with CP

<table>
<thead>
<tr>
<th>Children with typical development</th>
<th>Children with CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex (y:mo)</td>
<td>Age (y:mo)</td>
</tr>
<tr>
<td>M</td>
<td>4:7</td>
</tr>
<tr>
<td>F</td>
<td>4:7</td>
</tr>
<tr>
<td>F</td>
<td>5:0</td>
</tr>
<tr>
<td>F</td>
<td>5:1</td>
</tr>
<tr>
<td>M</td>
<td>7:10</td>
</tr>
<tr>
<td>F</td>
<td>7:0</td>
</tr>
<tr>
<td>F</td>
<td>11:3</td>
</tr>
<tr>
<td>M</td>
<td>10:7</td>
</tr>
<tr>
<td>F</td>
<td>10:0</td>
</tr>
<tr>
<td>F</td>
<td>10:0</td>
</tr>
<tr>
<td>M</td>
<td>13:0</td>
</tr>
<tr>
<td>M</td>
<td>13:3</td>
</tr>
<tr>
<td>M</td>
<td>10:0</td>
</tr>
</tbody>
</table>

Abbreviations: AFO, ankle-foot orthosis; BL, bilateral; CP, cerebral palsy; F, female; GMFCS, Gross Motor Function Classification System (19); L, left; M, male; R, right.

2.3. Procedures

Each measurement consisted of a resting test and a walking test. The children were first seated in a chair, and the equipment and the facemask were put on. The fitting of the facemask was carefully inspected for leakage. The children were given specific instructions not to eat or drink 1.5 hours prior to testing, not to talk or laugh, and to fidget as little as possible. During the resting test the children sat quietly for 10 minutes watching a video movie. This test was followed by the walking test, which consisted of walking for 5 minutes on an indoor oval track (50m). Subjects were asked to walk at their usual, self-preferred speed. Throughout both tests breath-by-
breath VO\textsubscript{2} and VCO\textsubscript{2} values were registered. The distance covered during the walking test was also registered in order to calculate the speed. The measurements were repeated four times on four different days, with a 1-week interval between tests.

2.4. Data Analysis
Walking speed was calculated as the mean speed during the last 2 minutes of the walking test. For the resting and the walking test, RERs were calculated for each breath as VCO\textsubscript{2} divided by VO\textsubscript{2}. Breath-by-breath RER and VO\textsubscript{2} values in the last two minutes of both tests were then used to calculate the average steady state energy demands as defined by (4.960*RER+16.040)*VO\textsubscript{2} [20]) A standard procedure of mass normalization was applied (namely dividing the energy demands by body-mass), and the following parameters were derived: resting energy consumption (ECS), gross ECS, and net ECS (net = gross − resting), expressed in J/kg/min. Gross EC was calculated by dividing gross ECS by speed, and net EC was calculated by dividing net ECS by speed, both expressed in J/kg/m.

2.5. Statistical analysis
Student’s t-tests were used to calculate the differences between children with CP and children with typical development. The level of significance was set at \( p < 0.05 \). Reproducibility was assessed according to the Generalizability Theory, which is based on analysis of variance (ANOVA). (21,22) The three components of variance that were estimated with this analysis included the inter-Subject variance, the variance related to the repeated sessions (i.e. Occasion variance), and the Error variance. These last two were used to calculate the standard error of measurement (\( SEM = \sqrt{(Occasion+Error)} \)). The smallest detectable difference (SDD), representing the smallest change that can be detected within an individual, was calculated as (1.96*SEM*\( \sqrt{2} \)). The intraclass correlation coefficient (ICC) was also calculated. SPSS (version 10.0) for Windows was used for the statistical analysis.
3. Results

All the children were able to complete the walking tests. However, in the resting tests the VmaxST system was not capable of measuring volume flow and VO$_2$ for the very small children. Therefore, resting and net values were only analysed for eight children with CP and for six children with typical development. Statistically significant differences between the two groups were found for all parameters. Walking speed was 14% lower, resting ECS was 16% higher, and gross ECS and gross EC were respectively 19% and 36% higher for the children with CP than for the children with typical development. Net ECS and net EC were respectively 20% and 43% higher for the children with CP (Table 2).

Table 2. Group means (SD) for walking speed, energy consumption and energy cost

<table>
<thead>
<tr>
<th></th>
<th>CP (N=13, n=8)</th>
<th>Healthy (N=10, n=6)</th>
<th>Difference † [95%CI] ‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS (m/min)</td>
<td>65.5 (14.6)</td>
<td>75.3 (6.5)*</td>
<td>-9.8 (-14%) [-4.8 to -5.2]</td>
</tr>
<tr>
<td>Resting ECS (J/kg/min)</td>
<td>119 (32)</td>
<td>101.4 (15)**</td>
<td>+18 (+16%) [4 to 32]</td>
</tr>
<tr>
<td>Gross ECS (J/kg/min)</td>
<td>433 (101)</td>
<td>359 (55)*</td>
<td>+74 (+19%) [39 to 110]</td>
</tr>
<tr>
<td>Gross EC (J/kg/m)</td>
<td>6.84 (2.0)</td>
<td>4.80 (0.8)*</td>
<td>+2.0 (+36%) [1.37 to 2.7]</td>
</tr>
<tr>
<td>Net ECS (J/kg/min)</td>
<td>275 (67)</td>
<td>224 (35)*</td>
<td>+51 (+20%) [20 to 78]</td>
</tr>
<tr>
<td>Net EC (J/kg/m)</td>
<td>4.42 (1.5)</td>
<td>2.87 (0.3)*</td>
<td>+1.6 (+43%) [0.90 to 2.1]</td>
</tr>
</tbody>
</table>

Abbreviations: ECS, energy consumption; EC, energy cost; CP, cerebral palsy; N, number of subjects for walking speed, gross ECS, and gross EC; n, number of subjects for resting ECS, net ECS, and net EC; WS, walking speed.

† Differences are presented in absolute units and as a percentage (%); percentages are calculated as \([\text{CP} - \text{control}]/[(\text{CP} + \text{control})/2]*100\%\)

‡ 95% confidence interval of the difference

* = Significantly different \((p < 0.001)\) from children with CP

** = Significantly different \((p < 0.013)\) from children with CP
The ICC, SEM, and SDD values in the both groups are presented in Table 3. All measurements except walking speed were more variable for children with CP than for children with typical development, which was apparent from the higher SEM values for the CP children. Comparing the reproducibility of gross with net measures, there was much more variability for the net protocol than for the gross protocol.

**Table 3**: Reproducibility for children with CP and children with typical development

<table>
<thead>
<tr>
<th></th>
<th>ICC CP</th>
<th>ICC Healthy</th>
<th>ICC CP</th>
<th>ICC Healthy</th>
<th>SEM† CP</th>
<th>SEM† Healthy</th>
<th>SDD† CP</th>
<th>SDD† Healthy</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS</td>
<td>0.93</td>
<td>0.49</td>
<td>3.91</td>
<td>4.73</td>
<td>10.83</td>
<td>13.09</td>
<td></td>
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</tr>
<tr>
<td>Resting ECS</td>
<td>0.89</td>
<td>0.87</td>
<td>11.4</td>
<td>5.9</td>
<td>31.7</td>
<td>16.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross ECS</td>
<td>0.88</td>
<td>0.80</td>
<td>35.9</td>
<td>25.5</td>
<td>100.0</td>
<td>70.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross EC</td>
<td>0.99</td>
<td>0.97</td>
<td>0.168</td>
<td>0.158</td>
<td>0.464</td>
<td>0.437</td>
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</tr>
<tr>
<td>Net ECS</td>
<td>0.82</td>
<td>0.59</td>
<td>28.6</td>
<td>23.0</td>
<td>79.3</td>
<td>63.6</td>
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<tr>
<td>Net EC</td>
<td>0.95</td>
<td>0.89</td>
<td>0.362</td>
<td>0.118</td>
<td>1.00</td>
<td>0.327</td>
<td></td>
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</tr>
</tbody>
</table>

Abbreviations: ICC, intraclass correlation coefficient; SEM, standard error of measurement; SDD, smallest detectable difference; WS, walking speed (m/min); ECS, energy consumption (J/kg/min); EC, energy cost (J/kg/m).

† SEM values are presented in absolute units; SDD values are presented in absolute units and as a percentage (%), percentages are expressed as (SDD/group mean over 4 occasions)*100%

**4. Discussion**

The results of this preliminary study showed a satisfactory reproducibility of gross walking efficiency measured with the VmaxST system in children with CP and in children with typical development. Sufficient sensitivity was guaranteed to detect clinically relevant changes; the SDD for gross EC in both groups was less than 10%, whereas changes are considered to be clinically relevant if they exceed 10%. (23)
When comparing reproducibility between the two groups, measurement variability was greater for children with CP than for children with typical development, except for walking speed. Bowen et al., who assessed the reproducibility of VO\textsubscript{2} measurements using five repeated measurements within a period of 10 weeks, found a similar result. (14) However, their measure of reproducibility contained the percent variability (PV), which was not included in the measures we used. Therefore, in order to compare our findings with those of Bowen et al., PVs were calculated for the data from the present study according to their method. (14) This additional analysis produced a PV of 8.9% for gross ECS and 2.0% for gross EC in children with CP, whereas Bowen had reported PVs of 17.5% and 13.2%, respectively. The greater variability in their measurements may have been related to the longer period between the sessions. Measurements obtained within a period of 10 weeks could be expected to be more variable than measurements obtained within a period of four weeks. Another explanation may be a difference in the degree of disability. The children in the Bowen study had a more serious disability (four out of five children were at Gross Motor Classification System (GMFCS) levels II or III), compared to the children included in the present study (eight out of 13 children were at GMFCS level I, five out of 13 were GMFCS levels II or III). Hence, it could be hypothesised that the higher degree of variability in the Bowen study might be related to a higher degree of disability. This hypothesis was confirmed by a subgroup analysis that we performed for GMFCS-level. We, therefore, do not advocate the generalization of the present results to all children with CP.

For many decades gross measurement protocols were commonly used to assess walking efficiency, but in recent years the use of net protocols has been recommended. (17,18) It has been shown that net measurements give a more direct indication of gait efficiency, because they are independent of resting ECS. (18) It has also been shown that net walking efficiency measurements reduce the inter-subject variability, and it was, therefore, proposed that net measures could also be used to reduce the intra-subject variability. (17) We subsequently incorporated this hypothesis in our study protocol, and evaluated whether calculating net values
would indeed reduce intra-subject variability. However, a comparison of gross with net measures showed that there was considerably more variability in the net protocol than in the gross protocol. The increased intra-subject variability of net measures was primarily due to variations in resting ECS between days (error), even though the resting measurements were quite well controlled by carefully checking the fitting of the facemask for leakage, and by giving the children specific procedural instructions. However, we did not apply the standard conditions for the measurement of resting energy consumption such as that described in the literature; namely abstinence from food and exercise for 8 to 12 hours. (24) This could be an explanation for the large variation in the resting measurements. Nevertheless, it does not seem feasible to apply such strict conditions in clinical practice. Further research is needed to develop a more reproducible method for the measurement of resting ECS, in order to use net walking efficiency measures as the preferred outcome assessment tool for clinical purposes (18), e.g., for the evaluation of medical interventions.

5. Conclusion

In this study a multiple repetition design and a modern portable system for gas-exchange, the VmaxST system, were used to evaluate the reproducibility of gross and net walking efficiency at a self-selected speed in children with CP. The results showed that gross EC is more reproducible for children with typical development than for children with CP. Furthermore, the reproducibility of gross EC was 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, the use of gross EC, rather than net EC, seems to be a more sensitive measure of walking efficiency to detect clinically relevant changes in an individual child with CP. However, further work, assessing the reproducibility in larger groups of children with CP is needed to extend our preliminary results.
Chapter 4

References


Chapter 5

Methodological considerations for improving the reproducibility of walking efficiency outcomes in clinical gait studies

Merel-Anne Brehm, Dirk Knol, Jaap Harlaar

Gait and Posture (accepted for publication, currently in press)
Abstract

Purpose: The aim of this study was to assess the reproducibility of gross and net energy cost (EC) of walking in adults and children with lower extremity disorders, using a portable system for gas-exchange. Furthermore, methodological considerations were proposed to improve the reproducibility of these outcomes.

Methods: Assessment of reproducibility was made in adults with polio residuals (n=14) versus healthy adults (n=14), and in children with cerebral palsy (n=13) versus healthy children (n=10). There were four repeated measurement sessions on different days, with inter-session periods of one week. All the measurements had been conducted at the outpatient clinic between 2002-2004.

Results: Based on the Generalizability Theory for data-analysis, it was shown that there was much less intra-subject variability in gross EC of walking compared to net EC of walking among adults and children with locomotion disorders, which was apparent from the lower standard error of measurement values. Data-analysis optimization and study design adjustments were considered and presented in a decision scheme, to demonstrate that the reproducibility of net EC can be substantially be improved.

Conclusions: The use of gross EC, rather than net EC, in patients with lower extremity disorders seems to be a more reproducible measure of walking efficiency. However, reproducibility of net EC can be substantially improved by careful standardization and using a multiple repetition study design, as a result of which this outcome measure becomes suitable for detecting clinically relevant changes at the individual level.
Introduction

In recent clinical gait studies there has been increasing interest in the use of walking energy expenditure (EE) measurements as an outcome tool. (1-4) Sequential measurements of walking EE can provide a quantitative evaluation of the decline or improvement in a person’s condition over time. In order to interpret such changes as either measurement error or a true change, knowledge on the reproducibility of the outcome measures and measurement protocols that are used is required.

EE of walking is generally expressed in two outcome measures: energy consumption (ECS) and energy cost (EC). There is increasing evidence in the literature that EC is a more reproducible measure than ECS, and moreover, EC is sufficiently sensitive to detect changes in a patient’s condition. (5-8) This makes it very useful as a support for clinical decision-making, and also as an evaluative measure in gait studies.

In the field of clinical gait analysis, EC is well accepted as an accurate indicator of walking efficiency (9), defined as the energy used per unit of the distance covered. EC is commonly reported in terms of gross utilization (total utilization), which means that a gross protocol is used for the evaluation. However, in recent years the use of net EC (gross utilization – resting utilization) has been recommended. Because net EC is independent of resting utilization, it has several important advantages, compared to gross EC. (7,10,11) For example, net EC gives a more direct indication of walking efficiency and it is largely independent of speed. (7,10) Another advantage becomes clear from the work of Schwartz et al. (11) Namely, basal metabolic rate, as the primary part of resting utilisation, is known to vary with age. (11-15) Inherently, this means that gross EC is only valid for short-term evaluations. Long-term evaluations over a period of maturation require appropriate normalization. Reporting EC in terms of net utilization has shown to be a suitable way for this (11), and benefits the clinical utility. However, one aspect that disadvantages the clinical utility of net EC is concerned with its limited reproducibility. (16)
A statistic that expresses reproducibility is the standard error of measurement (SEM). It is related to the smallest detectable difference (SDD). (17) Both are expressed in the actual units of measurement, which is useful when evaluating changes at the individual level. The SDD is used to discriminate measurement error from true change, therewith enabling a valid interpretation of a decline or improvement. However, a meaningful interpretation of a true change also requires an assumption about what is considered to be a clinically relevant change (CRC). An outcome measure is only clinically useful when it has been proved to contain sufficient sensitivity to determine a relevant change, i.e. the SDD is smaller than a desired CRC as an external criterion. The SDD is dependent on the different variance components that constitute measurement error, and they result from the measurement protocol and study design that are applied. The Generalizability Theory (18) can be used to recognize and estimate such variance components in a G-study, providing the raw data on measurement error and SDDs. In order to reduce the SDD, 1) careful standardization of the measurement protocol is known to reduce the magnitude of the variance component(s), and 2) the contribution of the variance components can be reduced, by adjusting the study design (i.e. using repeated measurements). (17,19) This can be evaluated in a so-called decision study (D-study). A D-study uses the variance components that are estimated in a G-study, and relates to the practical use of a measurement. By analysing different D-studies, the SDD can be tuned to match a desired CRC, and with this, information is provided about the type of design that is needed for the specific purpose of the study. As a result, the quality of actual measurements can be optimised, both for research purposes and for patient assessment.

This study investigates on how the reproducibility of net EC can be improved by examining the potentials for careful standardization of the data-analysis protocol and study design adjustment. A further aim was to construct a decision scheme that can be used as a tool for selecting a suitable study design to evaluate net EC of walking in individual patients.
2. Methods

2.1. Study population

Four groups, including patients and healthy subjects, participated in the study. The patients were recruited from the outpatient clinic of the department of Rehabilitation Medicine (at the VU University Medical Center in Amsterdam). Healthy subjects were employees working in the outpatient clinic, and their children.

The first group consisted of 14 adults with polio residuals (6 men, 8 women). Their mean age was 55 years (SD, 9.2 yrs), their mean body-mass was 72 kg (SD, 10.8 kg), and their mean height was 171 cm (SD, 10.5 cm). A group of 14 healthy adults of similar ages and sizes (6 men, 8 women) was used for reference. The third group consisted of 13 children with cerebral palsy (CP) (7 boys, 6 girls). Their mean age was 8.7 years (SD, 3.3 yrs), their mean body-mass was 32 kg (SD, 13.3 kg), and their mean height was 132 cm (SD, 21.1 cm). A group of 10 healthy children of similar ages and sizes (three boys, seven girls) was used for reference. A description of these four groups has been previously presented. (8,16)

2.2. Measurement system

A lightweight, portable gas-analysis system (VmaxST; Sensormedics, Bilthoven, the Netherlands), based on breath-by-breath technology, was used to measure EC of walking. The system is composed of a facemask, a Triple volume transducer, a gas-sample line, and a battery-operated unit (650g) that is worn on the shoulders. All the measurements and calibration procedures were conducted in accordance with the manufacturer’s instructions, described in detail elsewhere. (20)

2.3. Procedures

Each measurement consisted of a resting test and a walking test. The subjects were first seated in a chair, then the equipment was put on and the facemask was fitted. The fitting of the facemask was carefully inspected for leakage. The subjects were given specific instructions not to eat or drink 1.5 hours before testing, and not to fidget, talk or laugh during testing. During the resting test the subjects sat quietly for
10 minutes watching a video. This test was followed by the walking test, which consisted of walking for 5 minutes on an indoor oval track (50m). Subjects were asked to walk at their usual, self-preferred comfortable speed. Throughout both tests breath-by-breath oxygen uptake ($VO_2$) and carbon dioxide ($VCO_2$) values were registered. The distance covered during the walking test was also registered in order to calculate the speed. The measurements were repeated four times on four different days, with a 1-week interval between tests.

2.4. Data-analysis

Walking speed (m/min) was calculated as the mean speed during the last 2 minutes of the walking test. For the resting test and the walking test, respiratory exchange ratios (RER) were calculated for each breath as VCO$_2$ divided by VO$_2$. Breath-by-breath RER and VO$_2$ values in the last two minutes of both tests (i.e. minute [8-10] for resting, minute [3-5] for walking) were then used to calculate the average steady state energy demands ($((4.960*\text{RER}+16.040)*\text{VO}_2$ [21]). A procedure of mass normalization was applied, and the following parameters were derived: resting ECS, gross ECS, and net ECS, expressed in J/kg/min. Gross EC was calculated by dividing gross ECS by speed, and net EC was calculated by dividing net ECS by speed, expressed in J/kg/m.

Reproducibility was assessed according to the Generalizability Theory, which is based on analysis of variance (ANOVA). (18,19) The three components of variance that were estimated with this analysis included the inter-Subject variance, the variance related to the 4 repeated occasions, and the Error variance. These last two were used to calculate the SEM ($\sqrt{\text{Occasion + Error}}$), and the SDD was calculated as $(1.96*\text{SEM} \times \sqrt{2})$. Furthermore the intraclass correlation coefficient (ICC) was calculated: $(\text{Subject/ Subject + Occasion + Error})$. SPSS (11.5) for Windows was used for the statistical analysis.

In order to improve the reproducibility of the outcomes, the potentials of two options that can be used to reduce the SEM were evaluated (described in the introduction).
First, the potential of optimising the protocol for data-analysis was examined, by calculating resting ECS for five other time-intervals than minute [8-10] (i.e. [3-5], [4-6], [5-7], [6-8], and [7-9]). Subsequently, related net EC values were calculated for these intervals to determine the outcome with the smallest SEM. Second, the effect of study design adjustments was examined. This was in done in D-studies by increasing the number ($n$) of measurement occasions and then using the mean score over the $n$ occasions as the subject’s result. (18) Based on this method, SEM and SDD values were calculated for three hypothetical D-studies (for designs with 1, 2, and 4 occasions). The results of these D-studies and of data-analysis optimisation were used to construct a decision scheme, based on the following components:

- The **study population** that is being investigated
- The **evaluation period** that is being considered (short-term versus long-term)
- The **measurement protocol** containing the least amount of measurement error.
- The **clinical relevant change** to be detected (CRC ≥ 15%, 10%, and 7%)
- The resulting **$n$ of occasions** that should be chosen to detect a desired CRC.

### 3. Results

The mean scores, ICCs, and the SEMs and SDDs for speed, gross EC and net EC are presented in Table 1. Measurements of gross EC were equally variable in former polio adults, healthy children and CP children (i.e. SEM values were similar), whereas in healthy adults there was half as much variability. Comparing the reproducibility of gross EC with net EC, all groups showed an increased intra-subject variability for the net protocol, i.e. a 7% and 18% increase for, respectively, healthy adults and children, and a 30% and 140% increase for, respectively, polio adults and CP children.
Table 1. Reproducibility results for speed, gross EC and net EC, depending on the number (n) of measurement occasions

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>ICC $</th>
<th>SEM †</th>
<th>SDD ‡</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>n</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Healthy adults</td>
<td>82.0</td>
<td>0.97</td>
<td>1.50</td>
<td>1.09</td>
</tr>
<tr>
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<td>61.8</td>
<td>0.93</td>
<td>2.71</td>
<td>1.92</td>
</tr>
<tr>
<td>Healthy children</td>
<td>75.3</td>
<td>0.49</td>
<td>4.72</td>
<td>3.34</td>
</tr>
<tr>
<td>CP children</td>
<td>65.5</td>
<td>0.93</td>
<td>3.91</td>
<td>2.76</td>
</tr>
<tr>
<td>Gross EC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Healthy adults</td>
<td>3.24</td>
<td>0.93</td>
<td>0.078</td>
<td>0.055</td>
</tr>
<tr>
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<td>4.82</td>
<td>0.96</td>
<td>0.160</td>
<td>0.113</td>
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<tr>
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<td>4.80</td>
<td>0.97</td>
<td>0.158</td>
<td>0.111</td>
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<td>6.84</td>
<td>0.99</td>
<td>0.168</td>
<td>0.118</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>2.43</td>
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<td>0.063</td>
<td>0.044</td>
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<tr>
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<tr>
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<td>0.114</td>
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</tr>
<tr>
<td>CP children</td>
<td>4.44</td>
<td>0.97</td>
<td>0.267</td>
<td>0.189</td>
</tr>
</tbody>
</table>

Abbreviations: CP, cerebral palsy; EC, energy cost; ICC, intraclass correlation coefficient; n, number of repetitions; SDD, smallest detectable difference; SEM, standard error of measurement.

$ ICC: (Subject/Subject + Occasion + Error)
† SEM values are absolute values ((\(\sqrt{\text{Occasion + Error}}\)) /n);
‡ SDD values are absolute values ((1.96*SEM*\(\sqrt{2}\)) /n) and percentages (%). Percentages are calculated as (absolute/mean of measurements taken)*100%
The effects of data-analysis optimisation are shown in Figure 1. The SEMs that must be considered for the six net EC intervals in each group are presented in this figure. Firstly, it was shown that measurement error differed between the groups: measures of net EC varied more for patients than for healthy subjects. Secondly, measurement error differed between the time-intervals: measures of net EC became more variable as the resting period increased, especially for the patients. For healthy children the opposite trend was seen. Healthy adults and polio adults showed the smallest SEM value for net EC using resting ECS values of, respectively, interval [4-6] and [5-7], obtaining a variability reduction of 13% and 17%, respectively. For healthy children and CP children the smallest SEM was found for net EC using resting ECS values of, respectively, interval [7-9] and [3-5], obtaining a variability reduction of 3% and 30%, respectively.

**Figure 1.** Standard error of measurement values, expressed in J/kg/m, for net energy cost (EC) using resting energy consumption values of six different time-intervals in healthy adults, polio adults, healthy children, and cerebral palsy (CP) children. The circles represent the time-intervals with the smallest SEM value.
The results of increasing the $n$ of measurement occasions on the SEMs and SDDs are also presented in Table 1. SEM values for net EC were all below 0.267 J/kg/m for a design with 1 occasion, and reduced to half their size when the $n$ of occasions was increased to 4.

The decision scheme is presented in Figure 2. It can be seen that with regard to the gross protocol there is very little difference in study design between the different groups to detect a certain CRC, whereas for the net protocol these differences are clearly present. For polio adults and CP children more occasions are needed to detect a CRC, compared to the two groups of healthy subjects.

### 4. Discussion

The results of this study show a superior reproducibility for gross EC, compared to net EC in patients with locomotion disorders. However, optimising data-analysis procedures and adjusting the study design can substantially improve the reproducibility of net EC. This leads to a higher sensitivity to detect clinically relevant changes when using net EC in the evaluation of gait.

The inferior reproducibility of net EC, compared to gross EC, must be attributed to variability in the resting ECS. This finding could best be compared with two other clinical studies on this subject. (22, 23) First, Bell et al. (22) reported that variability in resting ECS in adult cystic fibrosis patients was nearly twice that in healthy adults, which was similar to the results found in the present study. Interestingly, Ashley et al. (23) found a lower variability in resting ECS for children with cystic fibrosis, compared to healthy children, in contrast to our results. This might be due to the fact that measurements in their study were repeated on the same day, whereas measurements in the present study were repeated on different days. Consequently, the day-to-day variability related to the disease, or to the influence of physical activity and food intake the day before testing will be missed by such a design.
However, such sources of variability are very likely to be present in multiple measurements of resting ECS that are obtained on different days (24,25), especially in clinical populations. Hence, they will also be inherent to related net EC measures, as was found in the present study. Another explanation for the contrast in results may be a difference in measurement protocols. The resting protocol in our study included 10 minutes of sitting, compared to the 20 minutes of lying supine used in the Ashley study (23). For patients with chronic infections this has shown to be a reproducible and feasible method. (22,23) However, for patients with locomotion disorders, including joint contractures and spasticity, these conditions do not seem feasible. Future research is needed to explore potentially more valid methods for the measurement of resting ECS in this population.

Although there was obviously a higher variability in net EC, the recent literature clearly shows that net outcomes have superior clinical meaning, compared to gross outcomes. (7,10,11) Therefore, two methodological options were proposed to reduce the variability in net EC, so that the clinical utility of this measure could be improved. A first reduction of variability in net EC was obtained by an optimisation of the data-analysis procedure. Because we had applied a 10-minute resting protocol it was possible to select multiple time-intervals for resting ECS to calculate net EC, and to determine the interval with the smallest SEM, i.e. variability, value in each group. For both patient groups and for healthy adults net EC became more variable as the resting period increased (Figure 1). This might have been related to the movement of body or limbs to correct an uncomfortable sitting position (26), indicating that a long resting period is not always favourable for patients with motor disorders. A further reduction of variability was obtained by adjusting the study design. This approach was used in D-studies, and has previously been shown to be effective in the clinical application of measurements. (8,27,28) We therefore also evaluated several D-studies for the clinical application of net EC, and calculated the SEM for designs with 1, 2, and 4 occasions.
Methodological considerations for improving measurement reproducibility

**Figure 2.** Decision scheme for planning clinically applicable protocols (short-term versus long-term) to measure gross and net EC of walking in healthy adults, polio adults, healthy children, and cerebral palsy (CP) children. The study design can be adjusted by increasing the number \(n\) of measurement occasions in order to detect a desired clinically relevant change (CRC).

Table 1 showed that the SEM value decreases with a factor of \(1/\sqrt{n}\) when the number of occasions is increased by \(n\), resulting in a variability reduction of almost 50% for a design with 4 occasions. These results, as well as the recent work of Schwartz (29), demonstrate that an increase in the precision of net EC can be obtained, and this clearly benefits the clinical utility of this measure in terms of its sensitivity to detect a CRC.
The second aim of this study was to construct a decision scheme that can be used as a tool for planning clinically applicable protocols on individual patients. When using the scheme, several decisions have to be made, starting with the selection of the study group that will be evaluated, and secondly, the protocol that is used for evaluation. As indicated above, a net protocol is preferred, most certainly for long-term evaluation. However, based on the current reproducibility results, one may choose a gross protocol for short-term evaluation. The next step then is to decide on the desired CRC. Although no general accepted value is available for this yet, some literature indicates that changes in EC are considered to be clinically relevant if they meet/exceed 10%. (4,30) In order to detect a smaller change (e.g. 7%), the outcome measure requires a smaller SDD. This can be achieved by increasing the \( N \) of measurement occasions. For example, for a polio adult, 4 occasions are required to detect a 7% change when net EC is used (Figure 2). In terms of clinical practicality this is certainly a drawback, because it requires more measurements in an individual patient. However, an important advantage is that it results in a greater possibility to detect a true change. The choice for a larger CRC (e.g. 15%) with a clear advantage of fewer measurements might be justified by the specific decision under study. If walking efficiency is one of several elements in a decision, the clinician is more likely to opt for a practical design (less occasions) and accept a larger CRC.

The presented decision scheme may guide the process of valid clinical decision-making in evaluating interventions in individual patients. However, it must not be considered a golden standard. Also, generalization of these results to all groups of patients with locomotion disorders cannot be warranted, because the amount of variability will not be the same in all groups.
5. Conclusion

The use of gross EC, rather than net EC, in adults and children with lower extremity disorders seems to be a more reproducible measure of walking efficiency. However, methodological options can be used to improve the reproducibility of net EC, as a result of which this outcome measure becomes suitable for detecting clinically relevant changes at the individual level. In this study two options for improving the reproducibility of net EC were evaluated: optimizing the protocol for data-analysis and using a multiple repetition study design. Both were found to be effective, and can be used to adjust the SDD of net EC towards a certain CRC, therewith improving its clinical utility.

References


Methodological considerations for improving measurement reproducibility


Chapter 6

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

Merel-Anne Brehm, Jaap Harlaar, Michael Schwartz

Submitted
Abstract

Purpose: The aim of this study was to determine the effect of ankle-foot orthoses (AFOs) on walking efficiency and gait in a heterogeneous group of children with cerebral palsy (CP).

Design: A retrospective study.

Methods: Barefoot (BF) and AFO data of 181 children with spastic CP (mean age, 9yrs) were compared. These data consisted of: speed, net non-dimensional (NN) energy cost of walking (cost), NN cost as a percentage of speed-matched controls (normalised cost), the Gillette Gait Index (GGI), and 3D gait kinematics and kinetics.

Results: Speed was 9% faster ($p < 0.001$), NN cost was 6% lower ($p=0.007$), and normalised cost was 9% lower ($p = 0.022$) when walking with an AFO. The GGI remained unchanged ($p = 0.607$). Both changes in minimal knee flexion in stance and in terminal swing were found to be significantly related to the change in normalized cost ($p = 0.013$ and $p = 0.022$, respectively).

Conclusions: The use of AFOs causes a statistically significant decrease in cost of walking. This is related to both a faster and more efficient gait pattern. The improvements in efficiency were reflected in changes of stance- and swing-phase knee motion, i.e. those children whose knee flexion angle improved toward the typical normal range demonstrated a decrease in normalized cost, and vice versa.
Introduction

Cerebral palsy (CP) is primarily characterized by central nervous system abnormalities, such as loss of selective motor control, abnormal muscle tone, and deficient equilibrium reactions. As a result of growth, these primary characteristics often lead to secondary deficits, including bony deformities, muscle contractures, and gait abnormalities. (1) Gait abnormalities in children with spastic CP have shown to increase the energy cost (EC) of walking more than twofold when compared to healthy children. (2-5) Such increases in walking energy have a negative influence on their level of physical activity (6), thereby predisposing them to early fatigue in performing daily-life activities. Medical treatments and therapy programmes are used in an attempt to reduce gait abnormalities.

Orthotic treatment, and specifically the use of ankle-foot orthoses (AFOs), is a frequently prescribed intervention modality, which plays an important role in the management of gait abnormalities. (7) The most typical use of AFOs is to optimise the normal dynamics of walking by applying a mechanical constraint (control moment) to the ankle to control motion, and at the same time produce a more efficient gait. (8) The solid AFO (SAFO) achieves the maximum orthotic control by restricting the movements of both plantar flexion and dorsiflexion in stance and swing phase. Its rigid construction prevents ankle rocker function in stance. (8) Solid AFOs are generally prescribed to reduce excessive plantar flexion in stance, and to prevent or eliminate an equines position. (9,10) The posterior leaf spring AFO (PLS) allows plantar flexion as well as dorsiflexion in stance phase, though both motions are attenuated by a counteracting control moment. Its posterior trim line promotes normal ankle rocker function to create a more dynamic gait. (11) Solid AFOs can reasonably be thought of as one extreme of the PLS family (i.e. minimal or non-existent trim line). Both types of orthoses have been studied with respect to their effect on gait, although mainly assessed in small samples of CP children. (9-19) Among these studies, a distinction can be made between studies that have evaluated the effects of an AFO on the pattern of gait, by using three-dimensional gait analysis.
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(10,11,13,14), and those that have evaluated the effect of an AFO on the efficiency of gait, by using measurements of heart rate or oxygen consumption during walking. (11-13,15,16) It appears that only two studies have investigated both pattern and efficiency effects of an AFO in children with CP. (12,13) Such combined information is relevant in order to gain more insight into what changes in the gait pattern are associated with changes in walking efficiency.

The purpose of this study was twofold: to determine the effect of AFOs on walking efficiency in a heterogeneous group of children with spastic CP, and to examine what changes in the gait pattern, related to the wearing of the AFO, are associated with the change in walking efficiency.

2. Methods

Ethical approval was obtained (University of Minnesota IRB) and all relevant privacy laws (HIPAA) were followed in the conduct of the study. A written informed consent statement was obtained from all participants and their parents.

2.1. Study population

A retrospective study design was applied on pre- (barefoot) and post- (AFO) intervention data. These data had been collected between 1992 and 2002 in the Center for Gait and Motion Analysis at Gillette Children's Specialty Healthcare (GCSH) in St Paul, MN, USA. The cohort of subject data for this study was extracted from the existing database, based on the following criteria:

1. Confirmed diagnosis of spastic CP,
2. Aged between 4 and 18 years,
3. Barefoot (BF) and AFO measurements performed on the same day,
4. No use of assistive devices.

This resulted in a group of 181 children with spastic CP (110 male, 71 female): 23 hemiplegics, 103 diplegics, 37 triplegics, and 18 quadriplegics. Their ages ranged
from 4.6 to 18.4 years (mean, 9 y; SD, 3 y), their body mass ranged from 14 to 81 kg (mean, 29 kg; SD, 12 kg), and their body mass index (BMI) ranged from 12 to 34 kg/m² (mean, 17 kg/m²; SD, 4 kg/m²).

2.2. AFO intervention
Selected children used either a SAFO or a PLS orthosis. The main function of both orthoses is to prevent plantar flexion motion, while the amount of dorsiflexion allowed depends on the specific type. (14) All AFOs had been fabricated by a CPO at the Assistive Technology Department of GCSH (St Paul, Minnesota, USA), or at one of their five other locations throughout Minnesota.

2.3. Test procedures
In order to evaluate the effect of the AFO intervention, the following assessments were used: oxygen consumption during walking, walking speed, and three-dimensional (3D) biomechanics of gait. These assessments were completed in two sessions: 1) walking BF followed by 2) walking with AFOs and shoes. Between these two sessions the child was allowed to rest for approximately 10 minutes.

A breath-by-breath gas-analysis system (CPXD, Medical Graphics Corporation, St. Paul, MN, USA) was used for the assessment of oxygen consumption. Each assessment consisted of a resting test, followed by a walking test. The children were first seated in a comfortable chair, and the equipment and the facemask were put on. The fitting of the facemask was carefully inspected for leakage. The children were given specific instructions not to eat or drink 3.0 hours prior to testing, not to talk or laugh, and to fidget as little as possible. During the resting test the children sat quietly for 10 minutes watching a video movie. This test was followed by the walking test, which consisted of walking for 6 minutes on an indoor route with a length of 80 metres. Subjects were asked to walk at their usual, self-selected, comfortable speed. Throughout the resting test and the walking test breath-by-breath
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Oxygen uptake ($VO_2$) values were registered. The walking speed was simultaneously measured by using a calibrated wheel attached to the gas-analysis equipment.

For the biomechanical analysis of gait the child walked at a self-preferred, comfortable speed along a ≈10 m walkway. Data was captured using a six-camera VICON 370 or twelve-camera VICON 512 system (VICON Motion Systems, Lake Forest, CA, USA), and four AMTI force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA). A total of 6 walking trials (3 barefoot trials followed by 3 AFO trials) were collected for each child. Kinematics and kinetics were derived using the standard VICON clinical model based on Davis et al. (20)

2.4. Data-analysis

Steady state values for resting oxygen consumption and walking oxygen consumption were computed for the BF and AFO sessions using Kendall’s tau-b. (21) Breath-by-breath oxygen consumption data was analysed in three-minute intervals. The breath closest to the center of the interval was assumed to be at steady state ($H_0$). Rejection of $H_0$ over the interval at the 0.10 level using a two sided test indicated non-steady data. Steady state consumption values and steady state walking speed were then subjected to normalisation, according to the net non-dimensional scheme of Schwartz et al. (22), and the following outcome measures for analysis were derived: non-dimensional speed (speed), net non-dimensional energy cost of walking (NN cost), and NN cost as a percentage of speed-matched control data (normalised cost). Speed-matched control data was drawn from an able-bodied reference population previously measured in Center for Gait and Motion Analysis at GCSH. (23) Changes in NN cost and normalised cost were considered to be a clinically relevant change (CRC) if they met or exceeded 10%. This level was chosen based on a previous reproducibility evaluation made in children with CP. (24)

3D gait kinematics was used to quantify the overall deviation of a subject’s gait from normal gait, expressed as the Gillette Gait Index (GGI, formerly defined as normalcy index [NI] 25). Furthermore, 3D gait data was used to calculate seven
specific gait parameters directly related to functions that are meant to be addressed by orthotic control: dorsiflexion at IC; peak dorsiflexion in stance; minimal knee flexion angle in stance; minimal knee flexion angle in terminal swing; minimal knee moment in stance; peak ankle power in stance; and minimal ankle power in stance. Changes in these parameters were categorised into two final AFO-response levels (improved toward the typical normal range or worsened from the typical normal range).

2.5. Statistical-analysis
Paired t-tests were used to assess the differences between the BF and AFO condition for speed, NN cost, normalised cost, and GGI. Differences were analysed for the total group, and for subgroups, based on 1) AFO-type, i.e. children walking with a SAFO versus children walking with a PLS, and 2) involvement pattern, i.e. children with hemiplegia, diplegia, triplégia, and quadriplegia. Baseline (i.e. BF) characteristics for subgroups were analysed with student t-tests. Relationships between the change in normalised cost and changes in gait parameters were analysed with Mann-Whitney U tests.
Furthermore, a subgroup analysis was performed based on AFO-response in normalised cost, i.e. good responders versus bad responders. A subject was defined as a good responder if improvement in normalised cost exceeded 10%, and he was defined as a bad responder if normalised cost worsened with more then 10%. As mentioned above, the rational for this 10% difference as a criterion for good vs. bad responders was based on a previous reproducibility evaluation. (24). Student t-tests were used in order to distinguish a difference in the baseline (i.e. BF) characteristics between these two groups. Differences in AFO-response between the good and bad responders were analysed with Kruskal-Wallis tests for the seven specific gait parameters and with multivariate ANOVA for speed, NN cost, normalised cost, and GGI.
SPSS (11.5) for Windows was used for the statistical analysis. The alpha level of significance for all statistical tests was set at $p < 0.05$. 

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3. Results

Out of 181 children, a total of 172 children completed the oxygen consumption measurements and 80 of these children also underwent 3D gait analysis. Significant differences for the total group were found between the BF condition and the AFO condition for speed and both cost parameters. Speed was 9% faster ($p < 0.000$), NN cost was 6% lower ($p = 0.007$), and normalised cost was 9% lower ($p = 0.023$) when walking with an AFO, compared to BF walking. The GGI remained unchanged ($p = 0.607$). In Figure 1 the NN cost of BF/AFO walking is presented for different change possibilities (i.e. ”movements”) on the speed vs. NN cost plot.

Figure 1. Speed versus NN cost plot of BF/AFO walking (upper left) for decrease in speed and increase in NN cost, (upper right) for increase in speed and increase in NN cost, (lower left) for decrease in speed and decrease in NN cost, (lower right) for increase in speed and decrease in NN cost. Data is presented in relation to speed-matched control cost (----).
Subgroup analyses for AFO-type showed that the baseline characteristics were not significantly different between the SAFO and PLS group. With regard to the intervention outcomes, speed improved significantly by 8.2% in the SAFO group ($p<0.001$) and 9.0% in the PLS group ($p<0.001$) after intervention. NN cost and normalised cost improved significantly in the PLS group (8.1%, $p=0.006$, and 13%, $p=0.013$, respectively), while in the SAFO group the two cost measures remained unchanged ($p=0.188$ and $p=0.298$, respectively). The changes in GGI were not statistically significant; with worsening of 10% in the SAFO group ($p=0.159$) and improvement of 5% in the PLS group ($p=0.279$). Subgroup analyses for involvement pattern showed significant speed improvements in all of the four groups ($p<0.001$). Both cost measures only improved significantly in the triplegia group (8.1% for NN cost, $p=0.005$, and 22% for normalised cost, $p=0.009$), (Figure 2). The GGI remained unchanged in all four groups.

![Figure 2](image.png)

**Figure 2.** Change in normalised cost for involvement pattern subgroups. Negative values represent improvement in normalised cost and positive values represent worsening. * = Significant change in normalised cost
The results of the Mann-Whitney U tests showed significant relationships between change in normalised cost and change in minimal knee flexion angle in stance phase of walking \( (p = 0.013) \), and between change in normalised cost and change in minimal knee flexion angle in terminal swing phase \( (p = 0.022) \) (Figure 3).

Baseline characteristics and outcomes for good responders and bad responders are summarized in Table 1. The results of comparing baseline characteristics showed that there were no significant differences between the two subgroups, except for both cost parameters. These were significantly higher at baseline for the good responders \( (p < 0.001 \) for NN cost and normalised cost). With regard to AFO-response, the outcome for minimal knee flexion angle in stance was significantly different between the groups \( (p = 0.037) \). In the good responder group 22 children \( (56\%) \) showed improved knee flexion during stance, compared to 17 children \( (44\%) \) who showed a decline. In the bad responder group, 7 children \( (29\%) \) showed improved flexion during stance compared to 17 children \( (71\%) \) who showed a decline. Second, also the outcome for minimal knee flexion angle in swing was
Table 1. Subgroup analysis based on AFO-response in normalised cost: good versus bad

<table>
<thead>
<tr>
<th></th>
<th>Good responders (n=77)</th>
<th>Bad responders (n=55)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFO-type</td>
<td>43 PLS</td>
<td>25 PLS</td>
</tr>
<tr>
<td></td>
<td>34 SAFO</td>
<td>24 SAFO</td>
</tr>
<tr>
<td></td>
<td>0 none</td>
<td>6 none</td>
</tr>
<tr>
<td>Sex</td>
<td>48 male</td>
<td>30 male</td>
</tr>
<tr>
<td></td>
<td>29 female</td>
<td>25 female</td>
</tr>
<tr>
<td>Age</td>
<td>9.0 (2.9)</td>
<td>9.1 (3.4)</td>
</tr>
<tr>
<td>MSS</td>
<td>9.2 (4.7)</td>
<td>10.8 (4.7)</td>
</tr>
<tr>
<td>SES</td>
<td>18.4 (4.5)</td>
<td>18.6 (5.0)</td>
</tr>
<tr>
<td>SPA</td>
<td>12.9 (3.6)</td>
<td>13.7 (3.9)</td>
</tr>
<tr>
<td>Initial contact ankle angle</td>
<td>3.0 (6.0)</td>
<td>2.9 (6.7)</td>
</tr>
<tr>
<td></td>
<td>6.4 (6.0)</td>
<td>8.1 (7.6)</td>
</tr>
<tr>
<td></td>
<td>Resp 23% ☯</td>
<td>Resp 29% ☯</td>
</tr>
<tr>
<td></td>
<td>77% ☯</td>
<td>71% ☯</td>
</tr>
<tr>
<td>Peak stance ankle angle</td>
<td>15.3 (6.7)</td>
<td>14.0 (6.3)</td>
</tr>
<tr>
<td></td>
<td>15.7 (6.6)</td>
<td>16.8 (6.7)</td>
</tr>
<tr>
<td></td>
<td>59% ☯</td>
<td>52% ☯</td>
</tr>
<tr>
<td></td>
<td>41% ☯</td>
<td>48% ☯</td>
</tr>
<tr>
<td>Min stance knee flexion</td>
<td>9.8 (11.3)</td>
<td>11.3 (10.5)</td>
</tr>
<tr>
<td></td>
<td>9.6 (9.9)</td>
<td>13.0 (11.2)</td>
</tr>
<tr>
<td></td>
<td>56% ☯</td>
<td>29% ☯</td>
</tr>
<tr>
<td></td>
<td>44% ☯</td>
<td>71% ☯</td>
</tr>
<tr>
<td>Min swing knee flexion</td>
<td>29.5 (9.1)</td>
<td>29.1 (8.9)</td>
</tr>
<tr>
<td></td>
<td>26.6 (11.4)</td>
<td>27.1 (12.1)</td>
</tr>
<tr>
<td></td>
<td>51% ☯</td>
<td>21% ☯</td>
</tr>
<tr>
<td></td>
<td>49% ☯</td>
<td>79% ☯</td>
</tr>
<tr>
<td>Min stance knee moment</td>
<td>-0.30 (0.13)</td>
<td>-0.31 (0.16)</td>
</tr>
<tr>
<td></td>
<td>-0.28 (0.13)</td>
<td>-0.27 (0.16)</td>
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<tr>
<td></td>
<td>53% ☯</td>
<td>53% ☯</td>
</tr>
<tr>
<td></td>
<td>47% ☯</td>
<td>47% ☯</td>
</tr>
<tr>
<td>Peak stance ankle power</td>
<td>1.40 (0.56)</td>
<td>1.30 (0.47)</td>
</tr>
<tr>
<td></td>
<td>0.89 (0.44)</td>
<td>0.98 (0.37)</td>
</tr>
<tr>
<td></td>
<td>22% ☯</td>
<td>20% ☯</td>
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<tr>
<td></td>
<td>78% ☯</td>
<td>80% ☯</td>
</tr>
<tr>
<td>Min stance ankle power</td>
<td>-0.74 (0.46)</td>
<td>-0.78 (0.35)</td>
</tr>
<tr>
<td></td>
<td>-0.62 (0.33)</td>
<td>-1.0 (0.79)</td>
</tr>
<tr>
<td></td>
<td>60% ☯</td>
<td>45% ☯</td>
</tr>
<tr>
<td></td>
<td>40% ☯</td>
<td>55% ☯</td>
</tr>
<tr>
<td>GGI</td>
<td>238 (115)</td>
<td>208 (118)</td>
</tr>
<tr>
<td></td>
<td>244 (145)</td>
<td>244 (195)</td>
</tr>
<tr>
<td></td>
<td>2.5% *</td>
<td>16% *</td>
</tr>
<tr>
<td>Speed</td>
<td>0.312 (0.09)</td>
<td>0.320 (0.08)</td>
</tr>
<tr>
<td></td>
<td>0.343 (0.08)†</td>
<td>0.348 (0.07)†</td>
</tr>
<tr>
<td></td>
<td>9.5% *</td>
<td>8.4% *</td>
</tr>
<tr>
<td>NN cost</td>
<td>0.677 (0.24)*</td>
<td>0.503 (0.20)</td>
</tr>
<tr>
<td></td>
<td>0.538 (0.17)†</td>
<td>0.596 (0.27)†</td>
</tr>
<tr>
<td></td>
<td>-23% *</td>
<td>17% *</td>
</tr>
<tr>
<td>Normalised cost</td>
<td>278 (84)*</td>
<td>213 (80)</td>
</tr>
<tr>
<td></td>
<td>288 (69)†</td>
<td>254 (97)†</td>
</tr>
<tr>
<td></td>
<td>-20% *</td>
<td>18% *</td>
</tr>
</tbody>
</table>

Abbreviations: AFO, ankle-foot orthosis; Resp, AFO-response; PLS, posterior leaf spring; SAFO, solid AFO; MSS, muscle strength sum; SES, selectivity sum; SPS, spasticity sum; ☯, percentage improved; ☯, percentage worsened; GGI, Gillette gait index.
*Differences are percentages (%), calculated as (AFO-BF/(AFO+BF/2))*100%
* = Baseline values of good responders significantly different (p<0.001) from bad responders
† = AFO condition significantly different (p < 0.001) from barefoot condition
‡ = AFO-response of good responders significantly different (p < 0.037) from bad responders
significantly different between the groups ($p = 0.017$). In the good responder group 20 children (51%) showed improved knee flexion during swing compared to 19 children (49%) who showed a decline. In the bad responder group, 5 children (21%) improved and 19 children (79%) worsened. The other outcomes did not show a significant difference with regard to the AFO-response.

4. Discussion

This study evaluated the effect of two types of AFOs on walking efficiency and gait in a large population of children with spastic CP. The use of AFOs causes a statistically significantly decrease in the EC of walking in both absolute and normalised sense.

The 6% decrease in absolute cost of AFO walking (NN cost) is in agreement with the findings of previous studies that were based on small samples sizes (12,13,15), and was related to a faster gait pattern, i.e. to an increased speed of AFO walking. Subgroup-analyses for AFO-type showed a significant decrease in NN cost only for PLS walking (8%), whereas NN cost for SAFO walking remained unchanged. These findings could best be compared with two studies of Buckon et al. (12,13), which are the only studies that also investigated the effect of different AFO types on walking efficiency at a self-selected, comfortable speed. Their first study (12) evaluated the effectiveness of AFOs in children with spastic hemiplegia, and showed a non-significant reduction of 4% and 7% in absolute cost of PLS and SAFO walking, respectively. A comparison of AFO types in children with spastic diplegia showed a significant reduction of 13% in absolute cost of PLS walking and of 17% for SAFO walking. (12) These improvements were much larger compared to our findings. The difference may be related to the fact that we evaluated a total group of CP children (i.e. hemi-, di-, tri- and quadriplegics), while Buckon et al. (13) performed analysis for a subgroup consisting of only diplegics. Hence, our group results may have been attenuated in comparison, as intervention effects can be
expected to be less significant for less involved children (hemiplegics). This was supported by our results of subgroup analyses for involvement pattern, which clearly showed an increasing trend of efficiency improvement with an increasing pattern of involvement. (Figure 2)

Apart from an absolute improvement, EC of walking also improved in normalized sense, i.e. as a percent of speed-matched controls (normalized cost). Using normalised cost as an outcome measure enables to separate the changes in energy cost in two distinct areas. That is, improvements that are solely due to increases in speed (which would occur at a constant normalized cost) can be distinguished from those that are due to a shift of the gait pattern toward a more efficient gait (which would occur at a decreased normalized cost). It may be helpful to think of different “movements” on the speed vs. NN cost plot (Figure 1). Improvements due to speed increases are represented by a movement along a direction tangent to that of the average control subject, and improvements due to a shift in the gait pattern are represented by a movement straight down. Any change in NN cost can be thought of as a sum of these two (generally non-orthogonal) components, and can provide indications to evaluate the gait more profoundly; giving further insight into what changes in the gait pattern did occur to cause an efficiency shift.

In the present study, both the GGI, characterizing gait in a global sense, as well as certain specific features of the gait pattern were analysed in order to explain the change in normalized cost. Interestingly, it was found that the displayed shift in gait efficiency was not reflected in the GGI, which remained unchanged. The probable explanation for the discrepancy between GGI and normalized cost is that the GGI only examines overall gait kinematics. It might be plausible that gait patterns that are more efficient from an energetic viewpoint, are not any closer to the average gait pattern exhibited by subjects without pathology. This finding also suggests that global measures such as the GGI may not exhibit the appropriate specificity and sensitivity for evaluating effects of targeted interventions. (26)
While the improvement in gait efficiency was not manifested as a global shift towards the control data, some specific changes at the knee did seem to be energetically favourable. Both changes in the minimal knee flexion angle in stance and in terminal swing-phase were found to be significantly related to the change in normalized cost, i.e. those children whose knee flexion angle improved toward the typical normal range demonstrated a decrease in normalized cost (good responders), and vice versa. An earlier study of Waters et al. (27) showed a similar trend in healthy adults, i.e. cost of walking decreased with decreasing knee flexion angles (45°, 30°, 15°, and 0°, respectively) Both findings support the hypothesis that an improvement in knee flexion angles reflects a reduction in the required muscle forces during stance-phase of walking, thus explaining to some extent the benefit in energy expense. (28,29) At the ankle level a reduction of peak ankle power during terminal stance was observed. This observation is in line with the existing literature (11,13), as well as with a very recent study (14), which indicates that applying an AFO can improve the gait pattern, at the expense of a reduced power generation at push-off. Interestingly, the reduction of power generation was not found to be a significant detriment to walking efficiency.

Although, the outcomes for minimal knee flexion angle in stance and terminal swing were significantly different between good responders and bad responders, our analyses did not reveal much difference in the baseline characteristics between both groups. This indicates that it is plausible that differences in AFO configuration (i.e. design, type of material, alignment, stiffness, combination with footwear, etc) might have had a significant effect on walking efficiency. It could be true that in case the AFO configuration was adequate, the effect on walking efficiency was positive, but at the same time the effect could have been negative when the configuration was inadequate. Because this study used a retrospective analysis of walking energy and 3D gait data to assess the efficacy of AFOs, we did not have any information regarding AFO configuration and prescription goals (e.g. to reduce foot drop, for mid-stance support, to promote normal ankle rocker function, etc.). This is a serious limitation of this study and therefore careful consideration must be taken in
generalizing the present results to all children with CP and to all types of solid and PLS orthosis. Secondary, retrospective data collection included subjects seen over nearly 10 years. As a result, the protocol for all subjects was not identical. The primary protocol change consisted of going from a 3-minute to a 10-minute rest, and using statistical methods for determining steady state. The current protocol (described above) has been found to be more reliable (smaller variability) but to give the same results, on average, as previous protocols.

5. Conclusion

The use of AFOs causes a statistically significantly decrease in the EC of walking. This is related to both a faster and more efficient walking pattern. The improvements in efficiency were not profoundly reflected in changes in gait parameters, except for stance- and swing-phase knee motion. Future research on the effects of AFOs in children with CP should focus on large-scale prospective studies, in which specific hypotheses related to the goals and design of the AFO prescription, in combination with footwear design, are analysed.

Acknowledgements

The study was supported by a grant from the Ter Meulen Fund, the Netherlands.

References


Chapter 7

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

Merel-Anne Brehm, Anita Beelen, Caroline Doorenbosch, Cees Noppe, Jaap Harlaar, Frans Nollet

Submitted
Abstract

Purpose: The aim of this study was to investigate the effects of total contact fitted carbon-composite knee-ankle-foot orthoses (KAFOs) on energy cost of (EC) walking and gait in adults with polio residuals who normally wear a conventional leather/metal KAFO or a plastic/metal KAFO.

Design: A prospective uncontrolled study with a multiple baseline and follow-up design. The follow-up measurements continued until 26 weeks after the intervention.

Setting: Outpatient clinic of a university hospital.

Participants: Twenty adults with a history of poliomyelitis (mean age 55 years, SD 9.2 yrs).

Intervention: Each participant received a new custom-made carbon-composite locked knee-joint KAFO, fitted according to a total contact principle, which resulted in a very rigid, light-weight and well fitting KAFO.

Outcomes: Primary, EC of walking; secondary, walking speed, biomechanics of gait, physical functioning (PF), and patient satisfaction.

Results: Net EC decreased significantly, without any learning effects, with respectively 7% and 8%, compared to the original KAFO. Furthermore, the surplus in net EC above normal was reduced by 18% when walking with the carbon-composite KAFO. An improvement in mean knee flexion, 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. Walking speed and PF remained unchanged.

Conclusion: In former polio patients, carbon-composite KAFOs are superior to conventional leather/metal and plastic/metal KAFOs with respect to improving walking efficiency and gait, and are, therefore, important in reducing overuse and maintaining functional abilities in polio survivors, and especially in those suffering from PPS.
Chapter 7

Introduction

Persons with a history of poliomyelitis often exhibit gait abnormalities, due to residual lower extremity pareses and joint deformities. Gait abnormalities in former polio patients have been shown to result in an increased energy cost (EC) of walking, being positively associated with lower extremity muscle weakness. (1,2) Many polio survivors experience new or increased muscle weakness later on in life, together with increased fatigue, pain, and reduced endurance. These new neuromuscular symptoms are referred to as the ‘postpoliomyelitis syndrome’ (PPS). (3) PPS often leads to a decline in functional abilities, with a decrease in walking ability as the most prominent problem. (4-6) Moreover, persons with PPS are predisposed to premature fatigue in carrying out mobility-related activities of daily-life, due to overuse of reduced muscle capacity (7-10), in combination with an increased EC of walking. (2) Both the gait abnormalities and the decline in physical performance can be expected to increase over time, due to PPS, aging, and progressive joint deformities. (11)

Lower extremity orthoses are often prescribed for former polio patients to reduce gait abnormalities, to enable standing and walking, and to maintain or improve physical performance. A population-based study reported the need for lower extremity orthoses in approximately 16% of the polio survivors. (6) A much higher percentage of 48% has been reported among patients visiting a post-polio clinic. (5) These patients had either worn orthotic devices since their recovery from acute polio in childhood, or started wearing them later on as part of the treatment for PPS. A substantial number of the patients wore knee-ankle-foot orthoses (KAFOs). In general, these KAFOs are rather heavy, and the construction methods for fabricating them have not changed for decades. Yet, it has been recognized that innovations are needed (12), and that orthoses should be made of the lightest possible, yet durable materials to make walking energy-efficient. (12) This would suggest the use of other materials than leather and metal. Orthoses based on plastic, such as polypropylene, usually in combination with metal parts, are frequently manufactured to reduce
weight. A disadvantage of such devices, however, is the limited rigidity of plastic materials. Therefore, carbon seems to be more promising, since it is both light and rigid. Carbon can be used to reinforce KAFOs made of resin-hardened acrylics or thermoplastics. Such carbon KAFOs have been reported to be more corrective, and also appreciated more by their users. (13,14) Carbon-composite, consisting of woven carbon pre-impregnated with resin, may be even more promising, as it can be used to make full carbon KAFOs that are lightweight, rigid and strong, and enable total contact fitting. The effectiveness of such carbon-composite KAFOs has not yet been objectively quantified with regard to the energy efficiency and biomechanics of gait, which are especially relevant in view of the late functional decline that is due to PPS.

This prospective study was set up to investigate the effects of total contact fitted carbon-composite KAFOs on the EC of walking in former polio patients who normally wear a conventional leather/metal (LM) KAFO or a conventional plastic/metal (PM) KAFO. We also investigated whether changes in the biomechanics of gait were associated with the change in EC of walking.

2. Methods

2.1. Study population

Adults with a history of poliomyelitis participated in the study. They were recruited from outpatient clinics of rehabilitation departments in (university) hospitals and rehabilitation centers, from the Dutch Neuromuscular Diseases Association, and from the manufacturers of orthoses. The inclusion criteria were: (1) ability to walk for at least 4 minutes at a self-preferred comfortable speed; (2) age between 18 and 70 years; and (3) using a conventional locked knee-joint KAFO made of LM or PM, with no technical deficits, for at least 2 years.
2.2. Intervention

On inclusion in the study, each participant received a new custom-made carbon-composite KAFO with a locked knee-joint, and fitted according to a total contact principle. These design properties resulted in a very rigid, lightweight and well-fitting KAFO, thus enabling the improvement of orthotic control options in comparison with existing KAFO. Achievable improvements included three control options that applied to the whole study group: (i) postural correction, (ii) reduction of deformity during weight bearing, and (iii) application of a dorsiflexion stop in the ankle-joint to improve the foot rocker. A fourth control option, (iv) ischial weight-bearing, applied only to half of the group (Table 1). Furthermore, reduction in KAFO weight was an improvement option that also applied to half of the group, and in general to those who wore a LM KAFO. Noppe Orthopedie BV (Noordwijkerhout, The Netherlands) manufactured the new KAFOs. Prior to the manufacture, the configuration of the KAFO was carefully determined on the basis of the results of physical examination and clinical movement analysis, for which the multi-media Sybar® system (16) was used.

2.3. Study design and procedures

In order to evaluate differences between the new and the old KAFO, the following assessments were made: 1) EC of walking, 2) biomechanics of gait, 3) physical functioning, and 4) patient satisfaction. To determine any learning effects with regard to these assessments, the study design contained three baseline measurements with the old KAFO, each separated by an interval of 2 weeks (B1, B2, B3), and three follow-up measurements with the new KAFO that were performed at 4, 12, and 26 weeks after the intervention (I1, I2, I3). The follow-up period started when the patients were wearing their new KAFO permanent, without any complaints. Biomechanics of gait was assessed at B1 and I3. Furthermore, technical deficits were recorded as they occurred, and once more they were listed with a questionnaire one year after delivery.
Table 1. Biomechanical gait parameters

<table>
<thead>
<tr>
<th>New KEVO control options</th>
<th>Improvement objectives on biomechanics of gait</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved postural correction <em>(total contact fitting)</em></td>
<td>Decrease in mean sagittal knee angle in midstance</td>
</tr>
<tr>
<td></td>
<td>Decrease in mean frontal knee angle in midstance</td>
</tr>
<tr>
<td>Reduction of deformity during weight bearing <em>(stiffness)</em></td>
<td>Minimization of change in sagittal knee angle in loading response</td>
</tr>
<tr>
<td></td>
<td>Minimization of change in frontal knee angle in loading response</td>
</tr>
<tr>
<td></td>
<td>Minimization of mean sagittal knee moment in midstance</td>
</tr>
<tr>
<td></td>
<td>Minimization of mean frontal knee moment in midstance</td>
</tr>
<tr>
<td></td>
<td>Minimization of change in hip joint center vertical motion and trochantor major vertical motion during stance</td>
</tr>
<tr>
<td>Improved ankle rocker function by applying a dorsi-flexion stop at the ankle hinge <em>(biomechanical action)</em></td>
<td>Increase in forward center of pressure excursion in midstance</td>
</tr>
<tr>
<td></td>
<td>Minimization of change in dorsiflexion angle in terminal stance</td>
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<tr>
<td></td>
<td>Increase in peak sagittal ankle moment in terminal stance</td>
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<td>Optimisation of timing peak ankle moment in terminal stance</td>
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<td></td>
<td>Increase in peak ankle power in terminal stance</td>
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<td></td>
<td>Optimisation of timing peak sagittal ankle power in terminal stance</td>
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<tr>
<td>Improved ischial weight bearing <em>(biomechanical action)</em></td>
<td>Minimization of mean sagittal hip moment in stance</td>
</tr>
<tr>
<td></td>
<td>Minimization of mean lateral trunk sway in stance</td>
</tr>
</tbody>
</table>

Abbreviations: Stance (0-100%): loading response (0-30%); midstance (30-70%); terminal stance (70-90%) (Based on gait cycle phases according to Perry [24]).
2.4. Measurements

**EC of walking**

A lightweight, portable gas-analysis system (VmaxST, Sensormedics, Bilthoven, the Netherlands), which has been shown to be accurate and reproducible in former polio patients (17,2), was used to determine EC of walking. The system consists of a facemask, a triple volume transducer, a gas-sample line, and a battery-operated unit (650g) that is worn on the shoulders. All the measurements and calibration procedures were conducted in accordance with the manufacturer’s instructions, including specific instructions not to eat or drink anything during a 1.5-hour period prior to testing. (17) Each measurement included a resting test and a walking test. The resting test consisted of sitting quietly for 10 minutes, and was followed by a 5-minute walking test on a marked indoor oval track (50m). During the walking test the subjects were asked to walk at their own, self-preferred, comfortable speed. Throughout both tests breath-by-breath oxygen uptake ($VO_2$) and carbon dioxide production ($VCO_2$) values were registered. The distance covered during the last 2 minutes of the walking test was also registered in order to calculate the speed.

**Biomechanics of gait**

For the biomechanical analysis of gait, the subject, wearing the KAFO and shoes and using customary walking aids, walked at a self-preferred comfortable speed along a 10m walkway. A 3D-movement analysis system (OPTOTRAK, Northern Digital, Inc., Waterloo, Canada) was used to measure the trajectories of active markers placed on the body (100 Hz). An 8-segment model of the human body was applied: left and right foot, lower legs, upper legs, pelvis and trunk. Rigid clusters of 3 markers were tightly attached to each segment. Simultaneously, the ground reaction force ($GRF$) was recorded at 1000 Hz from a force plate (Advanced Mechanical Technology, Inc., Watertown, USA). A total of 3 walking trials with the KAFO-leg stepping on the force plate were captured for each subject. Previous to these walking trials, the marker clusters were calibrated by probing 28 anatomical landmarks during a static trial, in order to define the co-ordinate systems for joints involved. (18,19)
Physical functioning and patient satisfaction

Physical functioning (PF) was assessed with the Short Form-36 (SF36), a multi-dimensional generic measure of health status, which contains 36 items organized into 8 multi-item scales. (20) Only the PF scale of the SF36 was used for analysis. PF is summarized from 10 items, each assessing limitations in physical activity due to health problems. An individualized satisfaction evaluation was made to quantify patient-specific improvements on various aspects of KAFO-use. At baseline, the patients were asked to name 5 self-chosen improvement items, and to rate these items for satisfaction with regard to the old KAFO on a 10-point Likert scale (1 = extremely unsatisfied, 10 = extremely satisfied). At follow-up, the patients were asked to rate the items again with regard to the new KAFO.

2.5. Data-analysis

EC of walking

For the resting and walking test, respiratory exchange ratios (RERs) were calculated for each breath as the ratio of VCO$_2$ to VO$_2$. Breath-by-breath RER and VO$_2$ values in minute 5-7 for resting and minute 3-5 for walking were then used to calculate the average steady state energy consumption (ECS) values. Here fore, the equation of Garby&Astrup was used ((4.960*RER+16.040)*VO$_2$). (21) A standard mass normalization procedure was applied, and the following parameters were calculated: resting ECS, gross ECS, and net ECS (net = gross – resting), expressed in Joules/kg/min. Finally, the primary outcomes, i.e. gross and net EC of walking, were calculated, expressed in Joules/kg/m. Gross and net EC were also expressed as increments above norm values, which were drawn from an able-bodied reference group. (2) Walking speed was calculated as the mean speed during the last 2 minutes of the walking test.

Biomechanics of gait

For the synchronization and reduction of the biomechanical gait data, a MATLAB-based software programme was used (BodyMech, Matlab®, The Mathworks [www.bodymech.nl]). First, 3D joint angles were calculated from the raw marker
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data. The joint co-ordinate systems were anatomically calibrated according to the CAMARC convention. (19) After synchronization, the GRF signals were used to calculate the center of pressure of the force under the foot. 3D net moments around the hip, knee and ankle were calculated as the cross product of the GRF and distance from the joint centres to that vector. (22,23) Finally, for each trial, this first analysis resulted in individual data on trunk movements, joint angles and net moments of hip, knee and ankle of one gait cycle, i.e. the gait cycle during which GRF signals were present. Subsequently, for each trial the data were time-normalized to the stance phase of that gait cycle (presented from 0-100%) and those data were then averaged for the 3 trials per subject. These individual data sets were used to compare the biomechanical output during gait with the old and the new KAFO with respect to 15 gait parameters (based on the gait phases according to Perry [24]) that were considered to be relevant (Table 1, column 2).

2.6. Statistical analyses

From pilot data and a previous study (2), the EC of walking for polio patients with a conventional KAFO was 25-35% higher than for healthy controls. As a clinical significant change a reduction of 25% of the extra energy expenditure was chosen, which means a reduction of 7.5% in total energy expenditure. It was calculated that a minimum sample size of 20 participants was required to detect such a change with a power of 80% and p < 0.05.

To study the effect of the intervention, a repeated measurement analysis, i.e. Generalized Estimated Equations (GEE), was applied. (25) GEE is a linear regression analysis that takes into account the dependency of the observations within one patient, and that can handle unequal time-intervals. It allows all longitudinal data to be used, and not only the data of complete cases. GEE was used to test for changes in gross EC, net EC, walking speed, and PF. Furthermore, GEE analysis was used to investigate whether changes in gross and net EC were associated with changes in biomechanical gait parameters and KAFO weight. GEE analysis was performed in STATA (version 7).
Paired t-tests were used to assess the differences between the old and the new KAFO for the biomechanical gait parameters and the patient-specific outcomes. Paired t-tests were performed in SPSS for Windows (version 11.5), with p < 0.05.

3. Results

Between October 2002 and October 2004, 23 former polio patients were included in the study (14 men, 9 women); 14 of them were diagnosed with PPS according to the Halstead criteria (3). During the course of the study, one person was lost to follow-up, and two people withdrew from the study because they found the burden of participation too high. A total of 20 people completed the study (13 men, 7 women, 13 PPS, 7 non-PPS). Their mean age was 55 years (SD, 9.2yrs), their mean body-mass was 72 kg (SD, 11.8 kg), and their mean body-mass index was 25.9 (SD, 4.1), 25.8 for men and 26 for woman. The mean weight of the old KAFO and the new KAFO was, respectively, 2.1 kg (SD, 0.8 kg) and 1.4 kg (SD, 0.3 kg). Table 2 presents the clinical condition of this group. The muscle strength sum (MSS) presented in this table is a lower extremity strength sum score (based on manual muscle-testing of the left and right hip flexors, hip extensors, hip abductors, hip adductors, knee flexors, knee extensors, dorsal flexors, and plantar flexors) that was calculated according to the method described by Nollet et al. (6)

3.1. Technical deficits

In general, the new KAFO was very well appreciated. The main issue that was reported by 7 patients included a technical deficit regarding the hinge at the ankle or knee (i.e. a crack of the clinch-nail). However, this deficit could easily be repaired. One non-technical issue that 7 patients reported included wear to the cloth upholstery inside the KAFO. One patient needed a replacement of the orthosis, due to a break of the KAFO.
Table 2: Clinical condition of subjects on inclusion

<table>
<thead>
<tr>
<th>Paretic body parts</th>
<th>Lower extremity strength (MSS†)</th>
<th>Walking devices</th>
<th>Material, weight (kg) old KAFO</th>
<th>Weight (kg) new carbon KAFO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 L</td>
<td>16.0</td>
<td>KAFO L</td>
<td>LM, 1.8</td>
<td>CC, 1.3</td>
</tr>
<tr>
<td>2 L, R</td>
<td>8.0</td>
<td>KAFO R + cane</td>
<td>LM, 4.1</td>
<td>CC, 1.7</td>
</tr>
<tr>
<td>3 L, R</td>
<td>5.0</td>
<td>KAFO R + cane</td>
<td>LM, 3.1</td>
<td>CC, 1.4</td>
</tr>
<tr>
<td>4 L, R</td>
<td>13.0</td>
<td>KAFO R + cane</td>
<td>LM, 1.8</td>
<td>CC, 1.6</td>
</tr>
<tr>
<td>5 R</td>
<td>14.0</td>
<td>KAFO R</td>
<td>PM, 2.3</td>
<td>CC, 1.5</td>
</tr>
<tr>
<td>6 L, R, T</td>
<td>5.0</td>
<td>KAFO R + 2 canes</td>
<td>LM, 2.9</td>
<td>CC, 2.1</td>
</tr>
<tr>
<td>7 R</td>
<td>18.0</td>
<td>KAFO R</td>
<td>PM, 1.1</td>
<td>CC, 1.2</td>
</tr>
<tr>
<td>8 R</td>
<td>8.5</td>
<td>KAFO R</td>
<td>LM, 2.3</td>
<td>CC, 1.4</td>
</tr>
<tr>
<td>9 L</td>
<td>17.5</td>
<td>KAFO L</td>
<td>LM, 2.6</td>
<td>CC, 1.2</td>
</tr>
<tr>
<td>10 L, R</td>
<td>8.5</td>
<td>KAFO L + cane</td>
<td>LM, 1.7</td>
<td>CC, 1.2</td>
</tr>
<tr>
<td>11 L, R</td>
<td>5.5</td>
<td>KAFO R</td>
<td>LM, 2.2</td>
<td>CC, 1.3</td>
</tr>
<tr>
<td>12 L, R, T</td>
<td>6.0</td>
<td>KAFO R + 2 canes</td>
<td>LM, 2.2</td>
<td>CC, 1.3</td>
</tr>
<tr>
<td>13 L</td>
<td>16.5</td>
<td>KAFO L</td>
<td>LM, 2.6</td>
<td>CC, 1.9</td>
</tr>
<tr>
<td>14 L, R</td>
<td>23.0</td>
<td>KAFO R</td>
<td>LM, 2.2</td>
<td>CC, 1.2</td>
</tr>
<tr>
<td>15 L, R</td>
<td>10.0</td>
<td>KAFO R</td>
<td>LM, 2.4</td>
<td>CC, 1.5</td>
</tr>
<tr>
<td>16 L, R</td>
<td>15.0</td>
<td>KAFO L + cane</td>
<td>PM, 1.4</td>
<td>CC, 1.3</td>
</tr>
<tr>
<td>17 L</td>
<td>11.0</td>
<td>KAFO L + cane</td>
<td>PM, 1.6</td>
<td>CC, 1.3</td>
</tr>
<tr>
<td>18 R</td>
<td>16.0</td>
<td>KAFO R + cane</td>
<td>LM, 1.2</td>
<td>CC, 1.2</td>
</tr>
<tr>
<td>19 R</td>
<td>17.0</td>
<td>KAFO R + cane</td>
<td>LM, 1.5</td>
<td>CC, 0.9</td>
</tr>
<tr>
<td>20 R</td>
<td>11.5</td>
<td>KAFO R</td>
<td>PM, 1.0</td>
<td>CC, 1.1</td>
</tr>
</tbody>
</table>

Abbreviations: L, left leg; R leg, right; T, trunk; MSS, muscle strength sum; KAFO, knee-ankle-foot orthosis; LM, leather/metal; PM, plastic/metal.
† MSS range: (0-32), calculation described in detail elsewhere (6)
3.2. Outcomes

EC of walking

For all parameters, data of complete cases were used, except for net EC of walking that was missing for 2 cases at B1. No significant learning effects were found for the EC parameters (Figure 1) or for walking speed. (Table 3) The gross and net EC of walking were significantly lower for the new KAFO, than for the old KAFO: 7% ($p<0.001$) and 8% ($p<0.001$), respectively. The increments in gross and net EC above norm values with the old KAFO were both reduced by 18% during walking with the new KAFO. Walking speed itself remained unchanged ($p=0.226$). (Table 3)

![Figure 1. Averaged data and standard errors over all subjects for net energy cost (EC) of walking on six different study visits. The visit numbers represent: B1 (week -6); B2 (week -4); B3 (week -2); I1 (week +4); I2 (week +12); I3 (week +26). Dotted line represents the moment of carbon composite KAFO intervention in the group (n=20). Dashed line represents the normative net EC value (2.4 J/kg/m) of healthy subjects. The arrow represents the 18% reduction in net EC of walking towards normative.](image-url)


Table 3: Results for EC of walking and walking speed; the means (SD) are given for the old and the new KAFO

<table>
<thead>
<tr>
<th></th>
<th>Old KAFO</th>
<th>New KAFO</th>
<th>Mean change †</th>
<th>95% CI ‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (m/min)</td>
<td>51.0 (12.4)</td>
<td>52.8 (12.4)</td>
<td>1.8 (3 %)</td>
<td>[-4.35, 0.57]</td>
</tr>
<tr>
<td>Gross EC (J/kg/m)</td>
<td>6.11 (1.4)</td>
<td>5.70 (1.3)</td>
<td>-0.42 (-7%)</td>
<td>[-0.63, -0.21]</td>
</tr>
<tr>
<td>Net EC (J/kg/m)</td>
<td>4.66 (1.0)</td>
<td>4.30 (1.0)</td>
<td>-0.36 (-8%)</td>
<td>[-0.54, -0.18]</td>
</tr>
<tr>
<td>Gross EC, above norm †</td>
<td>2.69 (1.4)</td>
<td>2.42 (1.3)</td>
<td>-0.47 (-18%)</td>
<td>[-0.27, -0.67]</td>
</tr>
<tr>
<td>Net EC, above norm †</td>
<td>2.24 (1.0)</td>
<td>1.87 (1.0)</td>
<td>-0.37 (-18%)</td>
<td>[-0.19, -0.55]</td>
</tr>
</tbody>
</table>

Abbreviations: EC, energy cost; KAFO, knee-ankle-foot orthosis.
† Mean differences are presented in absolute units and as a percentage (%); % are calculated as ([new-old]/[new + old]/2)*100%
‡ 95% confidence interval of the difference
• Norm values used: 3.2 J/kg/m for gross EC and 2.4 J/kg/m for net EC (2)
* = Significantly different (p < 0.001) from the old KAFO

Physical functioning and patient satisfaction
The results of the SF36 showed no significant difference in physical functioning (PF) between the old and the new KAFO (p = 0.593). With regard to patient satisfaction, a total of 26 different items were mentioned. On average, mean subject satisfaction scores were 48% higher for the new KAFO, compared to the old KAFO (p < 0.001). Items that were most frequently indicated for improvement were weight, fitting, and cosmesis of the KAFO, stability, and walking performance.
Table 4: Results for gait parameters; the means (SD) are given for the old and the new KAFO

<table>
<thead>
<tr>
<th>Biomechanical gait parameters (part of stance phase in %)</th>
<th>Old KAFO</th>
<th>New KAFO</th>
<th>p-value</th>
<th>Association with decrease in net EC: y/n (p-value)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Improved postural correction</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sagital knee angle (40-60%)</td>
<td>-10.3º (8.1)</td>
<td>-8.0º (4.8)</td>
<td>0.187</td>
<td>Yes (0.040)</td>
</tr>
<tr>
<td>Frontal knee angle (40-60%)</td>
<td>8.2º (9.4)</td>
<td>11.4º (9.0)</td>
<td>0.279</td>
<td>No (0.678)</td>
</tr>
<tr>
<td><strong>Reduction of deformity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Change in sag knee angle (0-30%)</td>
<td>-8.4º (4.4)</td>
<td>-6.2º (3.7)</td>
<td>0.003*</td>
<td>No (0.491)</td>
</tr>
<tr>
<td>Change in frontal knee angle (0-30%)</td>
<td>-5.1º (2.8)</td>
<td>-5.6º (3.0)</td>
<td>0.369</td>
<td>No (0.931)</td>
</tr>
<tr>
<td>Sagital knee moment (40-60%)</td>
<td>0.21Nm/kg (0.17)</td>
<td>0.16Nm/kg (0.12)</td>
<td>0.128</td>
<td>No (0.572)</td>
</tr>
<tr>
<td>Frontal knee moment (40-60%)</td>
<td>0.18Nm/kg (0.08)</td>
<td>0.19Nm/kg (0.15)</td>
<td>0.731</td>
<td>No (0.429)</td>
</tr>
<tr>
<td>Change in HJC and TM vertical motion (0-100%)</td>
<td>33 mm (9)</td>
<td>31 mm (13)</td>
<td>0.457</td>
<td>No (0.169)</td>
</tr>
<tr>
<td><strong>Improved ankle rocker function</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forward COP excursion (30-70%)</td>
<td>73 mm (39)</td>
<td>86 mm (27)</td>
<td>0.020*</td>
<td>Yes (0.037)</td>
</tr>
<tr>
<td>Change in dorsiflexion angle (70-90%)</td>
<td>-6.5º (2.6)</td>
<td>-4.6º (2.4)</td>
<td>0.003*</td>
<td>No (0.546)</td>
</tr>
<tr>
<td>Sagital ankle moment (70-90%)</td>
<td>0.59Nm/kg (0.34)</td>
<td>0.76Nm/kg (0.24)</td>
<td>0.003*</td>
<td>Yes (0.011)</td>
</tr>
<tr>
<td>Timing sagital ankle moment (70-90%)</td>
<td>84.2% (3.2)</td>
<td>82.7% (3.8)</td>
<td>0.145</td>
<td>Yes (0.047)</td>
</tr>
<tr>
<td>Sagital ankle power (70-90%)</td>
<td>21.0 (14.9)</td>
<td>15.7 (9.2)</td>
<td>0.129</td>
<td>No (0.181)</td>
</tr>
<tr>
<td>Timing sag ankle power (70-90%)</td>
<td>83.5% (6.0)</td>
<td>81.4% (6.2)</td>
<td>0.291</td>
<td>Yes (0.003)</td>
</tr>
<tr>
<td><strong>Improved ischial weight bearing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sagital hip moment (0-100%)</td>
<td>0.20Nm/kg (0.13)</td>
<td>0.18Nm/kg (0.16)</td>
<td>0.580</td>
<td>No (0.068)</td>
</tr>
<tr>
<td>Lateral trunk sway (0-100%)</td>
<td>84 mm (41)</td>
<td>83 mm (36)</td>
<td>0.791</td>
<td>No (0.703)</td>
</tr>
</tbody>
</table>

All values are mean (SD). Percentages between brackets refer to the time normalized part of the stance phase. Stance = 0-100%; loading response = 0-30%; midstance = 30-70%; mid midstance = 40-60%; terminal stance = 70-90%. COP, centre of pressure; EC, energy cost; KAFO, knee-ankle-foot orthosis; HJC, hip joint centre; TM, trochantor major.

* = Significantly different from the old KAFO
Chapter 7

Biomechanics of gait

The results of the paired t-tests showed significant improvements in change of knee angle during the loading response ($p = 0.003$), forward excursion of the centre of pressure (COP) during midstance ($p = 0.020$), change in dorsiflexion angle during terminal stance ($p = 0.003$), and peak ankle moment during terminal stance ($p = 0.003$) (Table 4). GEE analysis showed that a decrease in the knee flexion angle during midstance was found to be significantly associated with the decrease in EC ($p=0.030$ and $p=0.040$ respectively for gross and net EC). Furthermore, an increase in forward COP excursion ($p=0.001$ and $p=0.020$ for gross and net EC, respectively), peak ankle moment during terminal stance ($p=0.012$ and $p=0.011$ respectively for gross and net EC), and timing of peak ankle power during terminal stance ($p=0.001$ for both gross and net EC) were significantly associated with the decrease in EC. (Figure 2, Table 4)

The reduction in KAFO weight was not significantly associated with the decrease in EC ($p=0.814$ and $p=0.863$ for gross and net EC, respectively).

Figure 2. Averaged data over all subjects for:
(upper) Sag knee angle during midstance;
(middle) Forward excursion of the COP;
(lower) Sag ankle moment during terminal stance. Data are shown for the old KAFO (thin lines) and new KAFO (bold lines). Arrows represent the direction of improvement.
4. Discussion

This study evaluated the effect of carbon-composite KAFOs on walking efficiency and gait in persons with polio residuals who wore either a conventional LM KAFO or conventional PM KAFO. The major finding was that carbon-composite KAFOs reduced the physical effort of walking with clinical significance by decreasing the increment in net EC above norm values by 18%. In view of the lack of causal therapy for PPS (26), the optimisation of KAFOs deserves serious consideration in order to reduce overuse and to improve or retain walking ability. A comparison of the EC results with the findings of previous studies is not possible, because this was the first study to focus on the EC of walking. So far, the effectiveness of carbon KAFOs in polio has only been investigated by means of structured questionnaires. (13,14)

In order to investigate possible causes of improvement in the EC of walking, 15 biomechanical gait parameters were analyzed. The choice of these parameters was based on expected outcomes in relation to improved orthotic control options. (Table 1) First, the application of a dorsiflexion stop at the ankle joint, in combination with a footplate that was stiffened until the metatarsophalangeal joints, resulted in a significantly larger ankle moment (Figure 2) and an improved timing of peak ankle power during terminal stance, compared to the conventional KAFO. Its mechanism is based on improving the forward COP excursion in the 2\textsuperscript{nd} (i.e. ankle) rocker of stance phase, thereby enhancing the 3\textsuperscript{rd} (i.e. foot) rocker. The result is a more effective push-off. Bennett et al. (27) described a similar line of reasoning with regard to the impact of ankle-foot orthoses (AFOs) on the forward COP excursion in children with cerebral palsy. They observed a trend of increased ankle moments during AFO walking, which was explained by a change in the COP motion, such that the relative phasing of potential and kinetic energies improved. The result was a more pendulum-like gait. Within an inverted pendulum model (28), this is expected to reduce the EC of walking. Although Bennet et al. (27) have not quantified such a relationship yet, the present study supports this assumption.
Apart from changes at the foot and ankle, significant changes also occurred at the knee. The change in knee flexion during the loading response decreased with the new KAFO, compared to the old KAFO. This was obtained by the combination of the total contact fitting of the new KAFO and its stiffness, resulting in less postural deformity in response to weight bearing. Yet, this change did not contribute to the improvement of walking efficiency. A possible explanation for this is that during loading response the function of the knee is more important in providing adequate shock absorption (24), than in controlling the EC of walking. Although the improvement in walking efficiency was not related to less postural deformity, adequate postural correction appeared to be of energetic benefit. As expected, the total contact fitting and the rigidity of the construction enabled the subjects to remain in a more upright position, demonstrated by a decrease in the knee flexion angle during mid-stance (Figure 2).

No significant changes were found at the hip and trunk. However, we did observe a trend of a reduced EC of walking in association with a reduced hip flexion moment ($p=0.068$). The finding that this association did not reach significance might be due to the fact that the control option related to the aimed hip improvement, i.e. ischial weight-bearing, was only applied in 10 cases. The same holds for the reduction of KAFO weight, established in 9 cases, which was not a significant contributor to the reduction in EC.

The results described above clearly indicate that improved orthotic management can influence the gait pattern, which, in turn, improves walking efficiency. This relationship might support arguments proposed in a previous study, i.e. that EC of walking in PPS individuals is strongly related to the extent of lower extremity muscle weakness, explaining 71% of the variance in EC. (2) It was argued that orthotic and walking devices might have contributed to the unexplained variance, and that this will, in part, depend on the quality of the device, i.e. if the orthotic quality is insufficient, EC will be increased, and visa versa. The latter was supported by the present study; improved orthotic quality increased the efficiency of walking. However, this observation of improved walking efficiency was not reflected by a
The effect of knee-ankle-foot orthosis on walking efficiency and gait in polio

reduction of perceived limitations in PF, which remained unchanged. This is suggested to be due to the fact that the SF36-PF can only detect large changes in clinical status that might not be adequately responsive to intervention effects in polio and PPS. (6,29,30). As pointed out by Horemans et al. (31), it might also indicate that former polio patients do not necessarily adapt their daily-life behavior to their physical capacities, because this is also determined by environmental and personal factors. Ambulatory monitoring of daily activities may be helpful in future outcome studies, to quantify changes in actual daily-life physical performance.

Satisfaction with the new KAFO increased impressively. All of the patients were satisfied with the new orthosis, and averaged satisfaction scores for patient-specific improvement items increased with almost 50%, compared to the old KAFO. Improvement items that were most frequently indicated were weight, fitting, and cosmesis of the KAFO, stability, and walking performance. Even though these items were individually chosen, similar items were mentioned and similar results were found in two previous studies (13,14).

Some limitations of this study should be considered. First, it is difficult to decide to what extent the improvement in energy efficiency of walking is due to the application of carbon-composite. With conventional materials such as leather/metal or plastic/metal optimisation of the orthosis might have been possible to a certain extent as well. However, we believe that this can be achieved better with carbon-composite, because of its unique combination of properties: rigid, strong, lightweight and well mouldable. Another limitation is that for the two types of existing devices studied, weight and rigidity were related, that is, the PM KAFO was light and not rigid while the LM KAFO was rigid and heavy. Together with the limited number of subjects we were not able to determine the precise contribution of the alteration of these factors to the improved energy efficiency of walking.
5. Conclusion

This study demonstrates that for former polio patients carbon-composite KAFOs were superior to conventional LM and PM KAFOs with regard to walking efficiency, i.e. the increment in net EC above norm values was decreased by 18%. Improvements in the knee flexion angle, forward excursion of the COP, peak ankle moment, and timing of peak ankle power were significantly associated with the decrease in net EC. These improvements could be achieved due to the properties of carbon-composite.

The optimization of KAFOs to decrease the EC of walking, by using carbon-composite designs and improving their biomechanical action, results in an important option to reduce overuse and to maintain functional abilities in polio survivors, and especially in those suffering from PPS.

Acknowledgements

This study was supported by a grant from the Anna Fonds (02/07) and ZonMw (014-32-031), The Netherlands. We are very grateful to all the patients for their dedicated and enthusiastic participation in this study, and also to Tanneke Vogelaar (Department of Rehabilitation Medicine, VU University Medical Center, in Amsterdam) for her assistance in the data-collection for the study.

References


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Chapter 8

General discussion

Merel-Anne Brehm
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. (1) 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. (2,3)

In this thesis the clinical application of EE assessment in patients with gait pathology was evaluated. Two aspects were the focus of study. The first was to examine the methodological quality of currently available measurement instruments and protocols that are used for the evaluation of pathological gait. The second was the use of EE assessment in clinical gait studies to evaluate the effect of orthotic interventions. Related to these aspects, two research questions were formulated:

1. “Is the methodological quality of EE assessment appropriately sufficient in patients with gait pathology, 1) to apply this tool in rehabilitation management, and 2) to evaluate clinical interventions or monitor changes over time?”

2. “Can the assessment of EE of walking capacity, as an activity assessment tool, contribute to the rehabilitation management of patients with gait pathology?”
The first of these two questions will be addressed by reflecting on requirements for the usefulness of EE assessment, and its position in comparison to other clinical assessment tools, and the second question will be addressed by discussing the clinical usefulness of EE assessment, i.e. describing its role for clinical decision-making. Some recommendations will also be made for future research and clinical practice.

**Requirements for usefulness**

**Accuracy and reproducibility**
As a first requirement for usefulness, the accuracy and reproducibility of EE measurements in pathological gait were examined in Chapters 2-5. A practical and feasible instrument, the VmaxST system, was used to assess the EE of gait, and it was found that the accuracy of this instrument is sufficient for use in clinical gait studies. Next, the reproducibility of the EE outcomes that are most commonly used in clinical gait studies was evaluated. This demonstrated that an energy cost (EC) measure is more reproducible than an energy consumption (ECS) measure, and that the reproducibility of a gross evaluation protocol is superior to that of a net evaluation protocol.

Based on these results, it was concluded that gross EC of walking, being the most stable and sensitive measure, should be used in the evaluation of pathological gait. However, from the recent literature has become clear that net EC, compared to gross EC, has several important advantages, because it is independent of resting ECS levels. (4-6) This makes net EC a clinically more meaningful measure. Therefore, methodological options were proposed and presented in a decision scheme (page 83), to demonstrate that the reproducibility of net EC can be substantially increased, as a result of which this outcome measure becomes more suitable for evaluating the effectiveness of clinical interventions that are aimed to improve gait.
Additional requirements for usefulness

By having assessed the accuracy and reproducibility of EE measurements in pathological gait, it can be concluded that two important methodological requirements for the usefulness of EE assessment have been established. Such is a definite requisite when using this tool in evidence-based clinical practice. (7,8) However, other requirements for usefulness must also be met. (7-9) Rephrasing the statement made by Brand and Crowninshield (10): Any biomechanical evaluation tool will be useful (and thus gain widespread acceptance) if, and only if, the technique meets the following criteria:

1. The measured parameter correlates well with the patient’s functional capacity.
2. The measured parameter is not directly observable and semi quantifiable by the physician or therapist.
3. The measured parameter clearly distinguishes between normal and abnormal.
4. The measurement technique does not significantly alter the performance of the evaluated ability.
5. The measurement is accurate and reproducible.
6. The results are communicated in a form that is readily identifiable in a physical or physiological analogue.

Although Brand formulated these criteria for biomechanical evaluation tools, they are not solely limited to this application. Therefore, the five criteria other than the criterion of accuracy and reproducibility are discussed below, in order to more completely assess the usefulness of EE assessment as a capacity evaluation tool.

Criterion 1

From the existing literature it is known that several indices of (gait) functionality correlate with EE measures. (11-14) Johnston et al. (11) reported a strong correlation between EC of walking and level of Gross Motor Function Classification System (GMFCS; [14]) in children with cerebral palsy (CP): i.e. more involved children with higher GMFCS levels place a greater demand on their metabolic system while
walking. A similar relationship was found between EC of walking and score on the
Gross Motor Function Measure (GMFM). (12) It has further been demonstrated that
the metabolic demands of walking correlate with the patient’s functional capacity in
the reproducibility studies presented in this thesis: (Chapter 3) EC of walking in
former polio adults is strongly related to the extent of muscle weakness, as
quantified by an overall muscle strength score (MSS) of the lower extremities, and
(Chapter 4) EC of walking in children with CP is related to the degree of severity, as
defined by their pattern of involvement.

Another overall index of gait functionality is the Gillette Gait Index (GGI, (15)).
The GGI is postulated to be a representative method of determining the amount by
which the overall kinematics of gait deviates from normative values. (13,15,16)
Schwartz (16) quantified a linear relationship between GGI and EC of walking,
which further supports the hypothesis that the metabolic demands of walking and
overall gait pathology are related. It was also proposed that the strong relationship
between the GGI and EC supports the use of these global measures in outcome
studies. (16)

**Criterion 2**
The requirement that the measured parameter is not directly observable by the
clinician is, in the case of EE assessment, self-evident. ECS and EC are determined
by many different factors. These include primary diagnosis characteristics (e.g. loss
of selective motor control, abnormal muscle tone), secondary deficits (e.g. skeletal
deformities, muscle contractures, gait abnormalities), and compensatory
mechanisms, as well as relevant physiological and anthropometrical aspects. The
influence of all these factors on ECS and EC is not directly observable, and an
evaluation tool is required to quantify them.

**Criterion 3**
For diagnostic purposes, it is also a requirement that the measured parameter
distinguishes between normal and abnormal. The studies presented in Chapters 3
and 4 clearly showed that EE outcomes are capable of doing so. An evaluation of
walking EE in persons with polio residuals showed that ECS and EC were, respectively, 9% and 40% higher than in healthy persons (Chapter 3). ECS and EC of walking in children with CP were, respectively, 19% and 36% higher than in children with a typical development (Chapter 4).

**Criterion 4**
As a fourth requirement, Brand stated that the measurement technique should not affect the function it is measuring. This aspect is related to the practical feasibility of the measurement instrument. Currently, EE can be assessed, without encumbrance to the patient, with lightweight, portable gas-analysis systems. Such systems enable the measurement of gas-exchange during walking over level ground, which allows subjects to walk at their own, self-preferred speed (with or without walking aids). For patients with gait abnormalities this is often the most feasible mode of walking, and therefore affects their walking function the least.

**Criterion 6:**
The final requirement for methodological usefulness states that the outcome parameter must be reported in terms analogous to clinical concepts. The best analogue with regard to evaluating the physical effort of walking is to report the outcome parameter in energy equivalents, such as kcal or Joules. Accordingly, based on the Garby and Astrup equation (17), EE outcomes were calculated in Joules per unit of time (ECS) and Joules per unit of distance (EC).

**Methodological considerations**
Although the above evaluation of requirements for valid clinical testing clearly demonstrates the potential usefulness of EE assessment in rehabilitation management, certain methodological issues deserve further consideration: clinical relevant change (CRC) and the variability of net EC.
First, the reproducibility studies described in Chapters 3-5 provided insight into the amount of experimental and biological variability of EE measurements in both normal and pathological gait. Hereby, a reference was made to whether a CRC can be detected. According to the existing literature (18-20), changes in EE are considered to be clinically relevant if they meet or exceed 10%; an assumptive value, essentially based on clinical opinion. Because the smallest detectable difference (SDD) for gross EC in all of the study groups was less than 10%, it was concluded that this outcome measure is sufficiently sensitive to detect changes at the individual level. Yet, this conclusion might be considered arbitrary, because the use of subjective clinical opinion as an external criterion for defining a CRC is one of several constructs. Stratford et al. (21) defined a CRC as “the smallest change that is important to patients”, which indicates that the subjective patient opinion is also important. “Because no single construct represents a true gold standard for change, the use of multiple constructs appears to be preferable.” (22) Therefore, in future research we intend to use additional constructs, such as global rating scales or measurements of walking performance, to define a CRC more precisely, and also to investigate whether clinical relevance differs between groups of patients.

The second methodological issue concerns the variability of net EC. Although the SDD of gross EC was less than 10%, the variability of net EC was much greater, primarily due to variations in resting ECS between days. Two options for reducing the variability of net outcomes (Chapter 5) were therefore evaluated: optimizing data-analysis procedures of the resting protocol, and using multiple repetition designs. Both strategies were found to be effective, and can be used to adjust the SDD of net EC towards a certain CRC, therewith improving its clinical utility.

Another option to reduce the variability of net EC, however, would be to explore potentially more valid methods for the measurement of resting ECS. This could, for example, include measuring resting ECS in the supine/semi-supine position, rather than the 10 minutes of sitting that was used in our studies. Further research is needed to examine these, and other alternatives, in order to develop a more reproducible, though practical and feasible method for the measurement of resting ECS.
General discussion

Comparison with other clinical assessment tools

Further support for the usefulness of EE assessment in the rehabilitation management of pathological gait will be given by discussing the potential value of this tool in comparison to other clinical assessment tools. Based on the model of the International Classification of Functioning, Disability and Health (ICF), measurements of EE of walking are compared to other capacity measurements of walking effort, and to measurements of walking performance and measurements of impairments and gait abnormalities.

Measurements of the physical effort of walking

The measurement of EE of walking capacity is considered to be the criterion tool for estimating the physical effort of walking at the patient-relevant level of activity limitations. (2,3) However, other assessment tools are also used to evaluate walking effort. Among these, a distinction can be made between subjective assessment tools, e.g. hierarchical scales such as the Borg scale (2,3,23), and objective assessment tools such as heart rate (HR) monitoring. (2,3,24,25)

While all these measurements represent a method with which to estimate the physical effort of walking, it has been argued that they measure different aspects. (2,3,26,27) More specific, subjective methods, which rely on self-report, measure a patient’s perceived physical exertion/fatigue, while objective and criterion-based methods measure actual exertion. (26) Other differences between the methods become evident when comparing their strengths and weaknesses. (2,3,27) For example, it has been shown that the reproducibility of self-report measures (27,28) and HR measures (29,30) is poor, and that their ability to detect changes at the individual level is limited. In the choice of an appropriate tool to estimate the physical effort of walking, such limitations should be taken into account. (2) As has been shown in this thesis, the assessment of EE of walking capacity currently seems to be the best tool for this, i.e. it is objective, accurate, reproducible, and sensitive enough to detect clinically relevant changes in an individual patient.
Measurements of walking performance

Most of the clinical gait evaluations to date rely on measurements of capacity, because these are the most practical and feasible tools to work with in a hospital or rehabilitation setting. However, the interpretation of capacity measurements, such as timed walking tests and measurements of EC of walking, only reflect what a person is capable of achieving in a standardized situation, and the real-life relevance for the individual’s physical mobility in the community can only be estimated. (33) Information about what a person actually does in daily-life requires additional measurements in the individual’s own environment, i.e. measurements of walking performance. Ambulatory activity monitoring (AM) has been found to be a useful and objective tool for this purpose (34-36), and also observational video-analysis. (37) Furthermore, subjective information about physical walking performance can be ascertained by means of questionnaires, such as the Functional Ambulation Categories (FAC) score (38) or the Gillette Functional Assessment Questionnaire (FAQ). (39)

Measurements of impairments and gait abnormalities

Although in patients with gait pathology capacity measurements are necessary to objectify their limitations in walking and to evaluate any changes at this patient-relevant level, for clinical decision-making it is necessary to have information that reveals the underlying causes of a certain limitation. Therefore, the assessment of impairments is needed, which is at the ICF level of body functions and structures. (40) The impairments can, for example, be assessed with three-dimensional (3D) gait-analysis (1,40), which makes it possible to quantify the effects of impairments on the biomechanics of gait (i.e. gait abnormalities). (41)

Subsequently, by relating these impairment outcomes to capacity outcomes possibly valuable relationships between the two domains may become clear, e.g. underlying causes of walking limitations or mechanisms underlying treatment effects. In the outcome studies presented in Chapters 6 and 7, such relationships between impairment (i.e. biomechanics of gait) and capacity outcomes were investigated. Relationships in each study that revealed valuable information are described below.
1. The outcome study on AFO treatment (Chapter 6) demonstrated a valuable relationship between impairment and capacity outcomes through a significant association between EC of walking and knee kinematics: i.e. those children whose knee flexion angle improved toward the typical normal range, as a result of wearing an AFO, demonstrated a decrease in EC, and *vice versa*.

2. In the outcome study on KAFO treatment (Chapter 7) relationships were demonstrated through significant associations between EC of walking and ankle kinetics, i.e. the improvement in EC, as a result of optimizing KAFO treatment, was explained by an improvement in forward excursion of the center of pressure under the foot, peak ankle moment, and timing of peak ankle power. These results imply important linkages between impairments and capacity outcomes, i.e. they imply underlying mechanisms for orthotic treatment effects in the functional activity domain. Although the studies did not demonstrate cause and effect relationships between impairments/gait abnormalities and walking limitations, they do provide information that can help clinicians in orthotic decision-making.

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**Figure 1.** The ICF model, visualizing the relating of activity and impairment outcomes on the one hand, and activity and performance (participation) outcomes on the other hand.
Summary 1

From the above considerations, the following two conclusions can be drawn:

1. The clinical assessment of EE of walking capacity in pathological gait is adequately validated, i.e. the requirements for usefulness of this tool in rehabilitation management are met.

2. The EE of walking, as an activity outcome, holds an important position between impairment outcomes, on the one hand, and performance outcomes on the other hand, i.e. it has the potential to reveal valuable relationships between these two adjacent domains (Figure 1). With regard to outcomes in the impairment domain, such relationships were established, and provided information that can be used to optimize orthotic treatment. Further work is needed to investigate any potential relationships between capacity and performance outcomes.

Based on these conclusions, the first research question formulated in this thesis can be answered: “The methodological quality of EE assessment is appropriate and adequate in patients with gait pathology, 1) to apply this tool in rehabilitation management, and 2) to evaluate clinical interventions or monitor changes over time”.

Clinical usefulness

The answer to the second research question formulated in this thesis, “Can the measurement of EE of walking capacity, as an activity assessment tool, contribute to the rehabilitation management of patients with gait pathology”, is based on the concept of clinical usefulness. This concerns the role of this tool in clinical decision-making, when the patient-relevant problem is an increase in the physical effort of walking. There are two aspects involved. The first is related to the question “Will the result of EE assessment suggest a different treatment outcome than would be suggested without the use of this tool”. The second is related to the question “Will the result of EE assessment suggest different treatment than would be recommended
without the use of this tool”. The potential usefulness of EE assessment in the process of clinical decision-making will be evaluated on the basis of these two questions.

To answer the first question, the results of three clinical gait studies that used EC of walking as the primary measure to evaluate treatment outcome will be taken into consideration (Chapter 6 and 7, and [43]). These concern results on EC effect-size.

1. In Chapter 6, in the AFO study, we found a small overall treatment effect on EC. However, sub-group analyses for involvement pattern (i.e. severity of the disorder) showed that EC of walking only improved significantly and achieved clinical relevance in the severely involved groups (triplegia), whereas in the mildly involved groups (diplegia and hemiplegia) EC remained unchanged. Moreover, the mean changes in the mildly involved groups were under 10%, which, according to the existing CRC definition (18-20), cannot be considered as clinically relevant.

2. A recent randomized controlled clinical trial on the effect of multi-level botulinum toxin A in children with CP reported similar results. (43) Although the children in that study were selected on the basis of an energy-inefficient gait pattern (i.e. hip and knee flexion), no overall treatment effect on EC was found. However, more involved children who used walking aids (GMFCS III) did improve significantly, while less involved children (GMFCS I and II) remained unchanged. (43)

3. The polio patients in the KAFO study (Chapter 7), who also used walking aids, were mainly moderately to severely involved, with baseline EC values up to twice that compared to normal. The EC effect-size of the intervention applied in this group was considerably large, and was both significant and clinically relevant (i.e. an 18% change).

The probable explanation for the above differences in EC effect-size is that more involved patients (with much higher baseline EC values, compared to normal) have more potential to improve. Less involved patients, on the other hand, seem to be non-responsive to change in EC, since their gait pattern is not that energy inefficient. Accordingly, the treatment effects can be expected to be less significant for the less
involved patients. This emphasizes the importance of considering EE assessment in the process of clinical decision-making, i.e. when an intervention is aimed at addressing gait abnormalities to decrease limitations in walking and to reduce the physical effort of walking, one must establish baseline EC values and compare these with normal values. Only then can a scope for change be identified, providing an indication of treatment outcome, i.e. providing an indication of potential functional gain, as well as possible risks for functional loss. James Gage stated that, “such is invaluable when counseling patients about their current function and future function with or without treatment intervention.” (42)

Because EE assessment provides information about treatment outcome, i.e. functional gains, the result of this assessment can, accordingly, suggest a different treatment than would be recommended without the use of this tool. For instance, if the disadvantages that medical treatment inherently brings about outweigh the functional gains, then a patient might prefer to have no treatment, or the clinician might recommend no treatment and/or suggest a different treatment.

**Summary 2**

From the above considerations the following conclusion can be drawn:

More involved patients (with much higher baseline EC values, compared to normal) have more potential to improve. Less involved patients seem to be non-responsive to change in EC, since their gait pattern is not that energy inefficient. Therefore, when treatment is aimed at addressing pathological gait to reduce the physical effort of walking, one must establish baseline EC values and compare those with normal values. 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.

This answers the second research question formulated in this thesis: “The measurement of EE of walking capacity, as an activity assessment tool, does contribute to the rehabilitation management of patients with gait pathology”.

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Recommendations for future research

In the different paragraphs of this chapter a number of recommendations for future research were already made. Here, some remaining recommendations are discussed.

1. Capacity assessment tools, such as EE assessment, that are used for the measurement of activity limitations in walking provide information about what a patient does in a standardized laboratory environment. Although the current technology of gas-analysis systems makes measurement in the home environment possible, this is not commonly done, and might be regarded a limitation because the outcomes in a laboratory situation do not generalize to what patients actually do in their daily life, nor do they provide information about other, more complex activities. To measure this kind of performance, AM has been found to be a suitable tool (34-36). Future intervention studies aimed at decreasing activity limitations in walking could possibly combine EE capacity outcomes and AM performance outcomes. This might offer indications as to whether changes in walking EE will also result in changes in the performance of functional, purposeful daily life activities. (Figure 1, dashed box)

2. Reducing the physical effort of walking is an important treatment goal in rehabilitation management. However, if the underlying principles of increased physical walking demands are more clearly understood, then treatment can focus more specifically on ways to achieve such improvements. Chapters 3 and 4 presented an evaluation of the physical demands of walking in persons with polio residuals and children with CP, and showed that sub-maximal EE levels could be considerably increased. However, relationships with the underlying principles were not studied. As stated by Stout (42), if one wishes to understand the mechanisms of increased EE levels in pathological gait, the mechanical properties of muscles and mechanical power estimates cannot be ignored. All these factors need to be investigated further in future research in order to achieve better understanding of the mechanisms underlying increased sub-maximal EE levels in pathological gait.
3. Another recommendation concerns the investigation of maximal aerobic capacity levels in pathological gait. Several previous studies have reported that the level of aerobic capacity (i.e. maximal EE levels) was lower in children with CP than in healthy children (44-46). Furthermore, it has been reported that children with CP are considerably less physically active than their healthy peers (47,48). Accordingly, it may be assumed that such inactivity will lead to further deterioration in aerobic capacity levels, which consequently increases the relative physical strain of walking (i.e. the sub-maximal EE as the proportion of maximal EE). Therefore, providing training programs to increase aerobic capacity levels might also be a means to improve walking capacity. Future research should focus on the assessment of maximal EE levels, preferably measured during functional walking test (e.g. the shuttle-run test (49)), in combination with sub-maximal walking EE levels, 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.

**Recommendations for clinical practice**

The clinical assessment of EE in pathological gait has now been adequately validated, and, although some aspects need further study, it is recommended that this tool 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 to decide whether treatment will be beneficial. Secondly, it can serve as a tool for *patient evaluation*, to determine whether an applied treatment was, indeed, effective. Therefore, the necessary development of an implementation plan will be initiated in our department in the near future. The following step would then be to implement the tool in other specialized rehabilitation centers, thereby contributing to a more broad quality enhancement of rehabilitation care.
References


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.
Samenvatting

Het klinisch testen van het energieverbruik tijdens lopen
Introductie

De capaciteit om te kunnen lopen is vaak een belangrijke voorwaarde voor de uitvoering van activiteiten in het dagelijks leven. Echter, veel patiënten met aandoeningen aan het bewegingsapparaat ervaren beperkingen in het lopen. Deze kunnen de fysieke mobiliteit beperken, en derhalve leiden tot een significante handicap.

Het doel van revalidatiebehandeling is de beperkingen die een patiënt ondervindt in de uitvoering van activiteiten in het dagelijks leven te minimaliseren. Hoewel dit vaak behandeling vereist op stoornis niveau, is evaluatie van de behandeling op het patiëntrelevante niveau van activiteit beperkingen ook belangrijk. Wanneer dergelijke activiteit beperkingen gerelateerd zijn aan verminderde mobiliteit op basis van een verhoogde fysieke inspanning van het lopen, dan is meting van het energieverbruik tijdens lopen een zeer geschikt evaluatie-instrument.

Het energieverbruik kan, zonder al teveel hinder op te leveren voor de patiënt, gemeten worden met computergestuurde draagbare gas-analyse apparatuur. Het gebruik van dergelijke systemen biedt de mogelijkheid om de zuurstof opname ($VO_2$) en koolstof dioxiedafgifte ($VCO_2$) te meten tijdens een veldtest, hetgeen de patiënt in staat stelt om op een eigen zelfgekozen snelheid te lopen. Dit is voor patiënten met loopafwijkingen vaak de meest prettige en uitvoerbare manier van lopen. Tevens hebben diverse studies aangetoond dat het lopen op een zelfgekozen snelheid meestal resulteert in een comfortabele loopsnelheid, die dicht bij de meest efficiënte snelheid van de patiënt ligt. Dit levert uiteindelijk een uitkomstwaarde op die een valide vergelijking van data binnen en tussen patiënten toestaat.

Om de computergestuurde draagbare apparatuur toe te passen voor het doel van klinisch testen op individueel niveau, is het van essentieel belang dat de methodologische kwaliteit voldoende toereikend is. Dit betekent dat naast het vaststellen van de nauwkeurigheid van de meetapparatuur er tevens informatie bekend moet zijn over de reproduceerbaarheid van de uitkomstmaten.
Samenvatting

Het energieverbruik tijdens lopen wordt over het algemeen uitgedrukt met twee uitkomstmaten, de energie consumptie (ECS) en energie kosten (EK). De ECS verwijst naar de intensiteit van fysieke inspanning tijdens lopen, en de EK naar de hoeveelheid energie die gebruikt wordt om de loopactiviteit uit te voeren. De ECS en EK kunnen vervolgens gerapporteerd worden in termen van bruto verbruik (= totale verbruik) of netto verbruik (= bruto verbruik – rust verbruik). Informatie over de reproduceerbaarheid van deze verschillende uitkomstmaten is beperkt, vooral in klinische populaties, almede informatie over de nauwkeurigheid van de meetapparatuur. Beide studieonderwerpen worden dan ook in de hoofdstukken 2-5 behandeld.

De beoordeling van het energieverbruik wordt niet alleen geëvalueerd voor het doel van klinische testen op individueel niveau, maar ook in de context van klinische uitkomst studies, om zodoende bewijsvoering voor de doeltreffendheid van revalidatiebehandelingen te verkrijgen. In de hoofdstukken 6 en 7 worden twee klinische uitkomst studies gepresenteerd, waarin de EK als primaire uitkomstmaat wordt gebruikt om het effect van orthese interventies te evalueren, en om de relatie met afwijkingen in het looppatroon te bepalen.

**Doelstelling van het proefschrift**

Het doel van dit proefschrift is om de klinische toepasbaarheid van het beoordelen van het energieverbruik tijdens lopen, als klinisch meetinstrument op het patiëntrelevante activiteiten niveau, te evalueren. Aanvankelijk wordt deze evaluatie gedaan voor het doel van klinische testen op individueel niveau, en omvat het bepalen van de methodologische kwaliteit van de huidige meettechnieken en meetmethodes die in de praktijk van revalidatiegeneeskunde gebruikt worden. Het tweede deel betreft de toepassing van metingen van het energieverbruik in klinische uitkomst studies, om zodoende de doeltreffendheid van interventies, zoals de orthese behandeling, in patiënten met aandoeningen aan het bewegingsapparaat te evalueren.
**Hoofdstuk 2: de validatie van het mobiele VmaxST systeem voor meting van de zuurstof opname**

Het energieverbruik tijdens lopen kan, zonder al te veel hinder op te leveren voor de patiënt, bepaald worden met geautomatiseerde draagbare gas-analyse systemen, die zowel de VO$_2$ als de VCO$_2$ meten. Om dergelijke systemen in de klinische praktijk van revalidatiegeneeskunde te gebruiken, is het belangrijk dat de meetapparatuur voldoende accuraat is. In deze studie is de nauwkeurigheid van het mobiele VmaxST systeem gevalideerd aan de Douglas Bag (DB) methode voor de toepassing in klinische gangbeeldd studies. De metingen voor deze nauwkeurigheidsevaluatie werden uitgevoerd bij 10 gezonde volwassenen tijdens 5 minuten rustig zitten en tijdens 5 minuten fietsen op een belasting van 80Watt (d.w.z op een energiebelastingniveau dat gemiddeld genomen wordt bereikt tijdens het lopen op basis van loopafwijkingen)

De resultaten laten zien dat er significante verschillen zijn tussen het VmaxST systeem en de DB methode voor de uitkomstmaten VO$_2$ en energieverbruik, in zowel de rust conditie als de fiets conditie. Echter de grootte van deze verschillen was kleiner dan 7.5%, hetgeen in fysiologische en klinische termen niet van belang is voor de meeste doeleinden. Op basis hiervan kan geconcludeerd worden dat het VmaxST systeem een accuraat instrument is voor het bepalen van het submaximale energieverbruik tijdens lopen bij patiënten met loopafwijkingen.

**Hoofdstuk 3: het energieverbruik tijdens lopen bij oud-poliopatiënten: de relatie met spierkracht en de reproduceerbaarheid.**

Voor diverse patiëntengroepen met aandoeningen aan het bewegingsapparaat is reeds aangetoond dat het energieverbruik tijdens lopen verhoogd is. Echter, de energie uitgaven tijdens lopen bij oud-poliopatiënten zijn nog niet uitgebreid beschreven. Zoals in hoofdstuk 2 werd genoemd, kan het energieverbruik tijdens lopen nauwkeurig worden gemeten met behulp van computergestuurde draagbare
Samenvatting

gas-analyse apparatuur. Echter, om het gebruik van energie uitkomsten als ECS en EK voor de klinische toepassing te overwegen, d.w.z om patiënten en de effecten van interventies te evalueren, is informatie over de reproduceerbaarheid noodzakelijk. De reproduceerbaarheid van ECS en EK werd geëvalueerd bij 14 voormalig polio patiënten en bij 14 gezonde volwassenen tijdens 10 minuten rustig zitten en tijdens 5 minuten lopen op een zelfgekozen comfortabele snelheid. De metingen werden vier keer herhaald op vier verschillende dagen, met een interval van 1 week tussen de meetdagen.

De resultaten laten zien dat de reproduceerbaarheid van de EK uitkomst superieur is ten opzichte van de ECS uitkomst. Verder is aangetoond dat de EK uitkomst beter reproduceerbaar is voor gezonden, dan voor oud-poliopatiënten. Toch kan geconcludeerd worden dat de EK tijdens lopen een voldoende gevoelige maat is om klinisch relevante veranderingen te detecteren in een individuele polio patiënt; d.w.z de meetfout ofwel ruismarge voor EK was kleiner dan 10%, terwijl een verandering als klinische relevant worden beschouwd wanneer deze groter is dan 10%. Wat verder geconcludeerd kan worden, is dat oud-poliopatiënten, in vergelijking met gezonden, veel meer energie verbruiken tijdens lopen, namelijk 40% meer per afgelegde meter. Deze verminderde loopefficiëntie is sterk gerelateerd aan de mate van spierzwakte in de onderste extremiteiten.

Hoofdstuk 4: een reproduceerbaarheidevaluatie van de bruto en netto loopefficiëntie bij kinderen met cerebrale pARESE.

In de evaluatie van de EK tijdens lopen, ofwel loopefficiëntie, is het gebruik van een bruto evaluatie protocol (d.w.z meting van het totale energieverbruik) algemeen gangbaar. Echter, sinds de laatste jaren wordt het gebruik van een netto protocol (bruto – rust) aanbevolen, vooral in de evaluatie bij kinderen. In de huidige klinische gangbeeld studies wordt het netto protocol dan ook in toenemende mate toegepast. Met deze groeiende toepassing, is het essentieel geworden om de reproduceerbaarheid van de netto uitkomsten te bepalen voor de juiste interpretatie.
van de resultaten. Vreemd genoeg, tot op heden is er niets bekend over de reproduceerbaarheid van het netto protocol versus het gangbare bruto protocol. Daarom werd een vergelijkend reproduceerbaarheidonderzoek van bruto en netto EK uitkomsten uitgevoerd bij 13 kinderen met cerebrale parese (CP) en 10 gezonde kinderen tijdens 10 minuten rustig zitten en 5 minuten lopen op een zelfgekozen comfortabele snelheid. De metingen werden vier keer herhaald op vier verschillende dagen, met een interval van 1 week tussen de meetdagen.

De resultaten van de reproduceerbaarheidsevaluatie tonen aan dat de EK uitkomst beter reproduceerbaar is voor gezonde kinderen, dan voor kinderen met CP. Verder blijkt de reproduceerbaarheid van de bruto EK uitkomst superieur t.o.v. de netto EK uitkomst, doordat de netto uitkomst meer intra-individuele variabiliteit bevat als gevolg van variaties in de rust ECS tussen de vier meetdagen.

In conclusie, de bruto EK lijkt een gevoeliger uitkomst te zijn voor het detecteren van klinisch relevante veranderingen in de loopefficiëntie van individuele kinderen met CP, dan de netto EK uitkomst. Wat verder geconcludeerd kan worden is dat kinderen met CP, in vergelijking met gezonde kinderen, veel meer energie verbruiken tijdens lopen, namelijk 43% meer per afgelegde meter.

**Hoofdstuk 5: methodologische overwegingen voor het verbeteren van de reproduceerbaarheid van de netto loopefficiëntie voor toepassing in klinische gangbeeld studies**

In de huidige klinische gangbeeld studies, en vooral in de studies die het pathologische lopen van kinderen evalueren, wordt het gebruik van de netto EK uitkomst, veeleer dan de bruto EK uitkomst, aanbevolen. Echter, zoals in hoofdstuk 4 werd aangetoond, is de reproduceerbaarheid van de netto EK inferieur aan de reproduceerbaarheid van de bruto EK. Derhalve, lijkt de netto EK een minder gevoelige uitkomst om klinisch relevante veranderingen in de efficiëntie van het lopen te detecteren, hetgeen een nadeel is in de evaluatie van individuele patiënten. Niettemin, zijn er ook belangrijke voordelen verbonden aan het gebruik van de netto EK uitkomst, doordat deze uitkomst onafhankelijk is van de rust ECS. Dit maakt de
Samenvatting

Netto EK uitkomst in klinisch opzicht meer betekenisvol. Het doel van deze studie was dan ook om het potentieel te evalueren van twee methoden ter verbetering van de reproduceerbaarheid, om zodoende de bruikbaarheid van de netto EK uitkomst voor klinische doeleinden te vergroten. De reproduceerbaarheid van de brute en netto EK werd geëvalueerd bij 14 oud-polipatiënten, 14 gezonde volwassenen, 13 kinderen met CP en 10 gezonde kinderen tijdens 10 minuten rustig zitten en tijdens 5 minuten lopen op een zelfgekozen comfortabele snelheid. De metingen werden vier keer herhaald op vier verschillende dagen, met een interval van 1 week tussen de meetdagen.

De eerste methode voor verbetering van de reproduceerbaarheid bestond uit het optimaliseren van het protocol voor data-analyse. Op basis van het gebruikte rustprotocol van 10 minuten was het mogelijk om meerdere rust intervallen te selecteren voor het berekenen van de netto EK uitkomst. Zodoende kon voor elke groep een interval geselecteerd worden waarin de meetfout het kleinst was. Voor beide patiënten groepen als ook voor de gezonde proefpersonen blijkt de methode effectief met betrekking tot het reduceren van de meetfout. Naast data-analyse optimalisatie, kan een verdere reductie van de meetfout bereikt worden door veranderingen in het studieontwerp aan te brengen, d.w.z door het vermeerderen van het aantal metingen (zie Figuur 2 op pagina 84).

In conclusie, data-analyse optimalisatie en het gebruik van een multiple studie design kunnen de variabiliteit in de netto EK bij patiënten met aandoeningen aan het bewegingsapparaat wezenlijk verminderen. Hierdoor kan de klinische bruikbaarheid van deze uitkomst aanzienlijk worden vergroot.

Hoofdstuk 6: het effect van enkel-voet orthesen op de loopefficiëntie en het looppatroon bij kinderen met cerebrale pares.

Zoals in hoofdstuk 4 beschreven, kunnen loopafwijkingen bij kinderen met CP leiden tot een EK tijdens lopen die meer dan twee keer zo hoog is in vergelijking met gezonde kinderen. Een dergelijke vermindering van loopefficiëntie kan het
niveau van fysiek functioneren negatief beïnvloeden. Dat wil zeggen, kinderen met CP zijn ontvankelijk voor vroegtijdige en/of overmatige vermoeidheid tijdens het uitvoeren van hun dagelijkse activiteiten. De orthese behandeling, en specifiek de toepassing van enkel-voet ortheses (EVOs), is een veel toegepaste revalidatie interventie die een belangrijke rol speelt bij het verminderen van loopafwijkingen. Deze studie bevalueerde het effect van twee typen EVOs op de netto EK tijdens lopen in een heterogene groep van 181 kinderen met CP. Verder werd onderzocht welke veranderingen in het looppatroon, ten gevolge van het dragen van de EVO, mogelijk gerelateerd zijn aan veranderingen in de EK.

De resultaten laten zien dat het gebruik van een EVO resulteert in een significant verminderde van de netto EK, ten opzichte van het lopen op blote voeten. Dit interventie-effect is meer significant voor ernstig aangedane kinderen met CP (kinderen met een tripelgie), dan voor kinderen met een mindere vorm van CP (kinderen met hemiplegie en diplegie). De vermindering in EK is gerelateerd aan een sneller en een efficiënter looppatroon, alhoewel dit zich niet manifesteert als een prominente verandering in het looppatroon. Alleen een verandering in de kniehoek tijdens midstance en terminal swing is significant gerelateerd aan de verandering in de EK, d.w.z de groep kinderen bij wie de kniehoek verbetert in de richting van het normale patroon, laat een vermindering in EK zien, en visa versa. Deze bevinding ondersteunt de hypothese dat een afname in de mate van knieflexie tijdens de standfase zich vertaalt in een vermindering van de hoeveelheid geleverde spierkracht, hetgeen een deel van de efficiëntie verbetering zou kunnen verklaren.

Verschillen in de baseline karakteristieken van de groep kinderen die een afname in EK versus een verhoging in EK liet zien, werden niet gevonden. Dit wijst ertop, dat het aannemelijk is dat ook verschillen in de configuratie van de EVO (d.w.z het ontwerp, het type van materiaal + stijfheid, de combinatie met schoeisel, enz.) een significant effect op de loopefficiëntie kunnen hebben gehad. Toekomstig onderzoek naar het effect van EVOs in kinderen met CP zou zich moeten richten op (grootschalige) prospectieve studies, waarin specifieke hypotheses gerelateerd aan doelstellingen en de configuratie van het EVO voorschrift, in combinatie met schoeisel ontwerp, zouden moeten worden onderzocht.
Hoofdstuk 7: het effect van koolstofcomposiet knie-enkel-voet orthesen op de loopefficiëntie en het looppatroon bij oud-poliopatiënten.

Gewrichtsafwijkingen en de rest-parese in de onderste extremiteiten, als zijnde de late gevolgen van polio, leiden bij oud-poliopatiënten vaak tot loopafwijkingen. In Hoofdstuk 3 is reeds beschreven dat dergelijke loopafwijkingen kunnen resulteren in een verhoogde EK tijdens lopen. Zowel de verhoogde EK, als de loopafwijkingen als zodanig, kunnen de fysieke mobiliteit beperken, en derhalve leiden tot een significante handicap.

De orthese behandeling, zoals de toepassing van knie-enkel-voet orthesen (KEVOs), is een veel toegepaste interventie bij oud-poliopatiënten om de fysieke mobiliteit te handhaven of verbeteren. Voorheen, maar zeker ook nu nog, werden KEVOs gemaakt van leer en metaal (LM), waardoor orthesen vaak zwaar en onvoldoende corrigerend waren. De ontwikkeling naar KEVOs die gefabriceerd werden van plastic materialen, zoals polypropyleen, in combinatie met metaal (PM), resulteerde in lichtere orthesen. Echter, een nadeel van dergelijke塑料 materialen is de beperkte stijfheid, waardoor KEVOs mogelijk nog steeds onvoldoende corrigerend zijn. De meest recente orthopedische techniek is de toepassing van koolstofcomposiet voor het vervaardigen van KEVOs. Het gebruik van dit materiaal, in combinatie met een heel nauw sluitende fitting methode, resulteert in orthesen die heel licht, stijf en sterk zijn. Deze studie onderzocht het effect van koolstofcomposiet orthesen op de loopefficiëntie en het looppatroon bij oud-poliopatiënten die normaal een LM of een PM KEVO dragen.

De resultaten laten zien dat koolstofcomposiet KEVOs de fysieke moeite van het lopen met klinische significantie verminderen, door het surplus in de netto EK t.o.v. normaalwaarden te verminderen met 18%. Verbeteringen in de knieflexie hoek, de voorwaartse verplaatsing van het aangrijpingspunt van de grondreactie kracht onder de voet, het maximale enkel moment en de timing van het maximale enkel vermogen zijn significant gerelateerd aan de verbeterde loopefficiëntie. Deze
biomechanische veranderingen in het looppatroon konden worden bewerkstelligd door de eigenschappen van koolstofcomposiet.

In conclusie, het optimaliseren van KEVOs ter verbetering van loopefficiëntie, door de toepassing van een koolstofcomposiet ontwerp en verbetering van de biomechanische werking, biedt een belangrijke optie om de fysieke moeite van het lopen te reduceren en zodoende het zelfstandig functioneren te handhaven.

**Discussie**

De discussie in dit laatste hoofdstuk evalueert de klinische toepasbaarheid van het beoordelen van het energieverbruik tijdens lopen bij patiënten met loopafwijkingen, 1) door te reflecteren op 6 vereisten voor bruikbaarheid van het meetinstrument, 2) door de positie van het meetinstrument te vergelijken met andere klinische meetinstrumenten, en 3) door de rol van het meetinstrument voor klinische besluitvorming te bediscussiëren. Tevens zullen een aantal aanbevelingen worden gedaan voor toekomstig onderzoek en voor de klinische praktijk.

Om te bepalen of de beoordeling van het energieverbruik tijdens lopen bruikbaar is in de revalidatiebehandeling van patiënten met loopafwijkingen, werden zes vereisten voor bruikbaarheid geëvalueerd. Als een eerste vereiste voor bruikbaarheid werden in de hoofdstukken 2-5 de nauwkeurigheid en reproduceerbaarheid van metingen van het energieverbruik geëvalueerd. Deze evaluaties toonden aan dat:

1. Het VmaxST systeem, dat gebruikt werd om het energieverbruik tijdens lopen te meten, een nauwkeurig instrument is, dat geschikt is voor toepassing in klinische gangbeeld studies.
2. EK metingen beter reproduceerbaar zijn dan ECS metingen
3. Het gebruik van de bruto EK, in vergelijking tot de netto EK, een beter reproduceerbare maat lijkt te zijn voor de loopefficiency
4. De reproduceerbaarheid van de netto EK aanzienlijk verbeterd kan worden door optimalisatie van de data-analyse en het gebruik van een multiple studie design.
Samenvatting

Dit resulteert in een hogere gevoeligheid om klinische relevante veranderingen in individuele patiënten te detecteren. Deze resultaten zijn weergeven in een beslisboom (pagina 84).

Reflectie op de vijf andere vereisten voor bruikbaarheid liet zien dat energie uitkomsten en sterkte correlatie hebben met functionele capaciteit, ze niet direct waarneembaar zijn door de arts of therapeut, ze gemakkelijk identificeerbaar zijn in een fysieke of fysiologische analoog, en dat ze duidelijk onderscheid maken tussen normaal en abnormaal. Bovendien verandert de meettechniek de uitvoering van de geëvalueerde capaciteit niet beduidend.

Verdere ondersteuning voor de bruikbaarheid van energie metingen in de beoordeling van loopafwijkingen, kan worden gegeven door de waarde van het meetinstrument te vergelijken met andere klinische meetinstrumenten in de verschillende ICF domeinen. Deze vergelijking laat zien dat, in relatie tot andere capaciteit meetinstrumenten, de beoordeling van het energieverbruik tijdens lopen het meest geschikte instrument is om de fysische inspanning van het lopen te bepalen. Namelijk, het verstrekt een middel om de fysiologische belasting t.o.v. loopafwijkingen objectief te kwantificeren, en de uitkomsten zijn nauwkeurig, reproduceerbaar, en gevoelig genoeg om klinisch relevante veranderingen in een individuele patiënt te detecteren. Echter, omdat de interpretatie van capaciteit metingen alleen een indicatie geeft over wat een persoon kan in een gestandaardiseerde situatie, zijn performance metingen nodig om te bepalen wat een persoon daadwerkelijk in zijn/haar dagelijks leven doet. Ook metingen op stoornis niveau zijn nodig, om onderliggende oorzaken van een verhoogd energieverbruik te achterhalen. Kennis van de relaties tussen de uitkomsten in de verschillende ICF domeinen maakt het mogelijk om revalidatie behandelingen te optimaliseren, zodanig dat deze meest waarschijnlijk zal resulteren in een functionele verbetering. Met betrekking tot biomechanische gangparameters in het stoornis domein en energie uitkomsten in het capaciteit domein werden in de hoofdstukken 6 en 7 dergelijke relaties onderzocht, en verstrekten informatie die gebruikt kan worden om de orthese behandeling te optimaliseren. Verder onderzoek is nodig om mogelijke
relaties tussen energie uitkomsten in het capaciteit domein en uitkomsten in het performance domein te onderzoeken.

Op basis van de bovenstaande overwegingen kan geconcludeerd worden dat de methodologische kwaliteit van het beoordelen van het energieverbruik bij patiënten met loopafwijkingen geschikt is 1) als hulpmiddel in de revalidatie behandeling, om 2) klinische interventies te evalueren of veranderingen in tijd te monitoren.

De klinische bruikbaarheid van energie metingen, d.w.z de potentiële rol van energie metingen voor klinische besluitvorming, werd ook geëvalueerd. Het concept van klinische bruikbaarheid werd gerelateerd aan de vraag of het gebruik van de resultaten een energie meting een andere behandeluitkomst zal opleveren dan zonder gebruik van de resultaten. Deze vraag werd beantwoord na een reflectie op de uitkomsten van de hoofdstukken 6 en 7, die lieten zien dat metingen van het energieverbruik informatie verstrekken over de effectgrootte van een toegepaste interventie. Namelijk, ze verstrekken informatie over het behandelingresultaat op het domein van de fysieke inspanning van het lopen. Als zodanig, kan de beoordeling van het energieverbruik, als onderdeel van een meer uitvoerigere beoordeling, gebruikt worden in het proces van klinische besluitvorming om zodoende het potentieel voor functionele winst te bepalen. Omdat de beoordeling van het energieverbruik informatie verstrekt over potentiële functionele winst, kan het gebruik van dit meetinstrument daarmee ook een andere behandeling voorstellen dan dat zonder gebruik van het meetinstrument zou worden geadviseerd. Namelijk, wanneer de nadelen die een behandeling inherent met zich meebrengt groter zijn dan de functionele winst die bereikt kan worden, dan zou een patiënt kunnen kiezen om niet tot behandeling over te gaan, of de arts of therapeut zou kunnen adviseren om niet tot behandeling over te gaan, dan wel een andere behandeling adviseren.

Op basis van de bovenstaande overwegingen kan geconcludeerd worden dat de beoordeling van het energieverbruik tijdens lopen, als meetinstrument in het capaciteit domein, bijdraagt aan de revalidatie behandeling van patiënten met loopafwijkingen.
Tot slot worden drie aanbevelingen voor toekomstig onderzoek gedaan voor:


2. Klinische gangbeeld studies die de mechanische eigenschappen van spieren en berekening van het mechanisch vermogen onderzoeken, om zodoende de onderliggende mechanismen van het verhoogde submaximale energieverbruik tijdens pathologisch lopen beter te kunnen begrijpen.

3. Klinische gangbeeld studies die het maximale energieverbruik, bij voorkeur gemeten tijdens een functionele looptest zoals de shuttle-run test, in combinatie met het submaximale energieverbruik onderzoeken, om zodoende de relatieve fysieke belasting van het lopen te bepalen. Dit zou gedaan kunnen worden als onderdeel van het ontwikkelen van cardio-respiratoire trainingsprogramma’s, die wellicht een extra interventie mogelijkheid kunnen zijn in de behandeling van patiënten met loopafwijkingen.

Als aanbeveling voor de revalidatiepraktijk wordt bepleit dat het meten van het energieverbruik tijdens lopen onderdeel wordt van routine pre/post beoordeling van patiënten met een pathologische looppatroon wanneer het patiëntrelevante probleem gerelateerd is aan een verhoogde fysieke belasting van het lopen. Als zodanig, kan het als hulpmiddel voor selectie dienen, d.w.z om het potentiële voor functionele winst te bepalen en te beoordelen of behandeling van voordeel zal zijn. Ten tweede, kan het als hulpmiddel voor evaluatie dienen, om te bepalen of een toegepaste behandeling inderdaad tot een functionele verbetering heeft geleidt.
## List of abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADL</td>
<td>activities of daily living</td>
</tr>
<tr>
<td>AFO</td>
<td>ankle-foot orthosis</td>
</tr>
<tr>
<td>BF</td>
<td>barefoot</td>
</tr>
<tr>
<td>BMI</td>
<td>body mass index</td>
</tr>
<tr>
<td>CP</td>
<td>cerebral palsy</td>
</tr>
<tr>
<td>CRC</td>
<td>clinically relevant change</td>
</tr>
<tr>
<td>CWS</td>
<td>comfortable walking speed</td>
</tr>
<tr>
<td>DB</td>
<td>Douglas Bag method</td>
</tr>
<tr>
<td>D-study</td>
<td>decision study</td>
</tr>
<tr>
<td>EC</td>
<td>energy cost of walking</td>
</tr>
<tr>
<td>ECS</td>
<td>energy consumption of walking</td>
</tr>
<tr>
<td>EE</td>
<td>energy expenditure</td>
</tr>
<tr>
<td>FECO₂</td>
<td>fraction of expired carbon dioxide</td>
</tr>
<tr>
<td>FEO₂</td>
<td>fraction of expired oxygen</td>
</tr>
<tr>
<td>FICO₂</td>
<td>fraction of inspired carbon dioxide</td>
</tr>
<tr>
<td>FIO₂</td>
<td>fraction of inspired oxygen</td>
</tr>
<tr>
<td>GGI</td>
<td>Gillette Gait Index</td>
</tr>
<tr>
<td>GMFCS</td>
<td>Gross Motor Function Classification System</td>
</tr>
<tr>
<td>GMFM</td>
<td>gross motor function measure</td>
</tr>
<tr>
<td>ICC</td>
<td>intraclass correlation coefficient</td>
</tr>
<tr>
<td>ICF</td>
<td>International Classification of Functioning, Disability and Health</td>
</tr>
<tr>
<td>KAFO</td>
<td>knee-ankle-foot orthosis</td>
</tr>
<tr>
<td>MSA</td>
<td>muscle strength asymmetry</td>
</tr>
<tr>
<td>MSS</td>
<td>muscle strength sum</td>
</tr>
<tr>
<td>NN</td>
<td>net non-dimensional</td>
</tr>
<tr>
<td>Pb</td>
<td>barometric pressure</td>
</tr>
<tr>
<td>PF</td>
<td>physical functioning</td>
</tr>
<tr>
<td>PH₂O</td>
<td>vapour pressure</td>
</tr>
<tr>
<td>PLS</td>
<td>posterior leaf spring orthosis</td>
</tr>
<tr>
<td>PPS</td>
<td>postpoliomyelitis syndrome</td>
</tr>
<tr>
<td>PV</td>
<td>percent variability</td>
</tr>
<tr>
<td>RER</td>
<td>respiratory exchange ratio</td>
</tr>
<tr>
<td>SDD</td>
<td>smallest detectable difference</td>
</tr>
<tr>
<td>SEM</td>
<td>standard error of measurement</td>
</tr>
<tr>
<td>SAFO</td>
<td>solid AFO</td>
</tr>
<tr>
<td>ST</td>
<td>VmaxST system</td>
</tr>
<tr>
<td>VCO₂</td>
<td>carbon dioxide production</td>
</tr>
<tr>
<td>VE</td>
<td>minute ventilation</td>
</tr>
<tr>
<td>VE (ATPS)</td>
<td>volume measured at ambient temperature and pressure, saturated</td>
</tr>
<tr>
<td>VE (BTPS)</td>
<td>volume at body temperature and pressure, saturated</td>
</tr>
<tr>
<td>VE (STPD)</td>
<td>volume at standard temperature and pressure, dry</td>
</tr>
<tr>
<td>VO₂</td>
<td>oxygen uptake</td>
</tr>
</tbody>
</table>
Ruim zes jaar geleden was ik, in het kader van mijn opleiding Bewegingswetenschappen, op zoek naar een stage plek. Via een collega van Heliomare, waar ik toen werkzaam was als ergotherapeut, kreeg ik de tip om eens te informeren bij Jaap Harlaar en Jules Becher, twee enthousiaste heren vol met ideeën. Zo gezegd, zo gedaan. Ik maakte een afspraak, en inderdaad, de ideeën van de beide heren vloeiden over tafel. Een van die ideeën had betrekking op een nieuw apparaat, het VmaxST systeem, dat gebruikt moest gaan worden in de evaluatie van revalidatiebehandelingen. Met dit onderwerp ging ik aan de slag, onder de begeleiding van Jaap. Ik leerde alle kneepjes van het VmaxST apparaat, evalueerde vervolgens de botuline-toxine behandeling bij een groep kinderen met CP, en na 9 maanden had ik mijn stage succesvol afgerond. Tijd voor de zomervakantie.

Alhoewel, twee weken later ging de telefoon; of ik langs kon komen, want er waren problemen met het VmaxST apparaat. Een week later weer, en nog een week later weer. Een oplossing was nodig en die was snel bedacht. Jaap zocht een potje bij elkaar (potje 1) en in november 2001 kwam ik parttime in dienst van de afdeling Revalidatie Geneeskunde van het VUmc om onderzoek te doen naar de validiteit van het VmaxST systeem. Een half jaar later kwam potje 2 voor een onderzoek naar de reproduceerbaarheid en weer een half jaar later kwam potje 3.

Het was toen januari 2003. Frans Nollet en Anita Beelen, in samenwerking met Kees Noppe, waren net van start gegaan met een innovatief project naar het effect van koolstofcomposiet orthesen op het lopen bij oud-poliopatiënten, waarbij het VmaxST systeem als evaluatie instrument werd gebruikt. Echter, in die periode maakten Frans en Anita tevens de overstap naar het AMC, om de revalidatie afdeling aldaar nieuw leven in te blazen. En dus werd er iemand gezocht die het project vanuit de VU kon coördineren. Iemand die natuurlijk wel iets van het VmaxST systeem afwist… Inderdaad, ik kwam op het project (het KEVO project) en vanaf dat moment was het plan voor een promotie onderzoek definitief.

Ik schreef vervolgens zelf een subsidie aanvraag voor een onderzoek in het buitenland (potje 4) en in april 2005 ging ik van start in het zeer vooraanstaande
onderzoek instituut Gillette Children’s Specialty Healthy, St Paul, USA. Voor een periode van drie maanden heb ik daar gewerkt aan een onderzoek naar het effect van enkel-voet orthesen op het lopen bij kinderen met CP, onder de begeleiding van dr. Michael Schwartz. Bij terugkomst in Nederland volgde de laatste fase, het afronden van alle onderzoeken en het schrijven van de artikelen. En met behulp van potje 5 heb ik mijn werk kunnen afronden tot het proefschrift zoals het voor u ligt. Ik ben er trots op.

Allerbeste Jaap, met jou als mijn 1e begeleider heb ik de afgelopen jaren heel intensief samengewerkt, en al sinds de periode dat ik stage bij je liep ben ik onder de indruk van je ambitie en je enthousiasme. Met je enthousiasme heb je me weten te overtuigen dat het doen van wetenschappelijk onderzoek echt wel leuk kan zijn. Niks dingen uitpluizen in stoffige kamertjes. Door de vrijheid die je me gaf, had ik de kans om zelf mijn onderzoeken op te zetten, en daarmee om mijn eigen promotie werk in elkaar te draaien. Daar heb je me altijd met volle overtuiging in ondersteund. Ook in de plannen die ik had om onderzoek te doen in het buitenland. Nu, vijf jaar later, ben ik erachter dat het doen van wetenschappelijk onderzoek ondertdaad ontzettend leuk is. Vooral omdat het, in ons vakgebied, wat op kan leveren voor de patiënt. En daar gaat het uiteindelijk om. Beste Jaap, bedankt voor de leuke gesprekken die we vaak hadden tijdens onze overleggen, voor alles wat je me geleerd hebt, en voor het volste vertrouwen dat je altijd in me hebt gehad. Je was van zeer grote betekenis voor het slagen van dit proefschrift.

Professor doctor Frans Nollet, mijn 2e begeleider. Allerbeste Frans, ik ben je onttzettend dankbaar voor de mogelijkheid die je me hebt gegeven om samen met jou, Kees Noppe en Anita Beelen te werken aan het KEVO project. Een innovatief en omvangrijk project, dat uiteindelijk een aantal belangrijke en nieuwe inzichten heeft opgeleverd voor zowel de orthopedische instrumentmakerij als de revalidatie geneeskunde. Elke donderdag ochtend hadden we onze metingen in de VU, waar jij, Kees, Anita, en ik voor dag en dauw klaar stonden om de patiënten te ontvangen. Het was altijd fun; veel geouwehoer over dikke, snelle auto’s (Kees had net een
nieuwe Audi A8 gekocht en jij een Mercedes), over de duurste nieuwe gadgets, en over de liefde (ALTHANS, over het feit dat liefde, ik was toen net ongeloofelijk verliefd geworden op Erik, niet altijd rooskleurig blijft); maar nooit zonder de volle professionele aandacht voor de patiënten die van heinde en verre kwamen.

Frans, bedankt voor je tijd, inzet, enthousiasme en de fun tijdens de afgelopen 4 jaar. Ik heb ontzettend veel van je geleerd en dat is echt een hele goeie kans voor mij geweest om me tot de onderzoeker te ontwikkelen dus ik nu ben. Ik ben je zeer dankbaar ben voor deze kans en voor onze samenwerking. En ik hoop in de toekomst nog veel met je te werken! Bij deze wil ik ook Kees Noppe bedanken, altijd even vrolijk en enthousiast. Bedankt Kees voor de samenwerking en voor alle ondersteuning die ik van Noppe Orthopedie gekregen heb. Anita Beelen, ik bedank ook jou Anita voor de samenwerking binnen dit project. Ik heb je altijd enorm bewonderd vanwege je zeer brede expertise als onderzoeker. Je bent voor mij het voorbeeld van hoe een professionele senior onderzoeker zou moeten zijn. Daar neem ik, in het verdere verloop van mijn carrière, heel graag een voorbeeld aan. Dan Caroline Doorenbosch, Caroline, jij kwam pas halverwege op het project, maar je was absoluut een onmisbare schakel in het geheel. Met jou kennis over 3D gangbeeld analyse en met je precisie en doortastendheid wist jij als geen ander de juiste biomechanische output. Ook buiten het project hebben we veel samengewerkt, vooral in het kader van de ESMAC congresbezoeken en de JEGM feestcommissie. Ik denk hier met ongelooflijk veel plezier terug (Richard Babe, Captain Hook, en dwarf throwing 😊). En last, maar zeker niet least wil ik Tanneke bedanken voor alle hulp tijdens de vele metingen die we gedaan hebben.

Tot slot, mijn 3e en laatste begeleider, Michael Schwartz. Dear Mike, it has been a great opportunity and honor for me to work with you and all your colleagues in Gillette. I have never experienced such a great hospitality as with you and your family (Jacky, Phoebe and Reed). Everything was arranged when I came to visit Minneapolis; a house, a cubical at Gillette, a ride to work (inclusive a fresh cappuccino) at 5 in the morning, steak nights + GT’s, as well as a great trip to Lake
Geneva and Chicago together with Erik. Also professionally everything was worked out; twice a week we had a meeting, and for each question I asked, you conjured up a PowerPoint presentation that included the answer (at the VU we call this the Schwartz secret) Mike, thank you so much for receiving me with open arms. It has been of great importance to me!. We keep up that KARMA thing 🙏. Also a great thank you to all the other colleagues from Gillette: Tom Novacheck, James Gage, Adam, Sue, Jean, Roy, Rick, Pam, Joyce, and Cammy.

Het slagen van mijn promotie werk was ook zeker niet mogelijk geweest zonder de ondersteuning van Guus Lankhorst. Beste Guus, ontzettend bedankt voor alle mogelijkheden die je steeds weer voor me gecreëerd hebt om in dienst van de VU te blijven en om al mijn onderzoeken af te kunnen ronden. Ik bedank ook alle patiënten die hebben deelgenomen aan mijn onderzoeken. Zonder de enorme inzet van hen is het doen van wetenschappelijk onderzoek onmogelijk.

De collega’s van “De gouden gang” wil ik in het bijzonder bedanken. Bedankt Petra, Mirjam, Janine, Fred, Joost, Martijn, Annet, Vanessa en ook Vicky en Monique voor jullie interesse en voor al jullie bemoedigende woorden!! Vanes, af en toe kregen we er een punthoofd van, maar we hebben het gered. Ik vind het heel jammer dat je er 21 juni niet bij bent, maar we hebben het gered. Ik vind het dan ook geweldig dat jullie mij als paranimfen willen begeleiden.

De laatste dank, of eigenlijk een hele dikke zoen, gaat uit naar Erik, de liefde van mijn leven. Gewoon, omdat hij de mooiste, meest geweldige man op aarde is, die er elke dag met volle overtuiging voor zorgt dat onze liefde altijd rooskleurig is. x!!!
About the author

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1994:1995 Creatieve therapie, Hogeschool Nijmegen
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2002:heden Junior onderzoeker, VU Medisch Centrum, Amsterdam
2005 Onderzoekstage, Gillette Children’s Speciality Healthcare, St Paul, USA

Aandachtsgebieden binnen mijn functie als onderzoeker zijn inspanningsfysiologische metingen van het energieverbruik tijdens het normale en pathologische lopen en de evaluatie van de orthese behandeling bij CP kinderen en oud-poliopatiënten op basis van metingen van het energieverbruik en klinische gangbeeld analyse

Mijn meest geliefde hobby is basketbal. Deze sport heb ik zeer fanatiek beoefend totdat de knie het in 2002 begaf. Alternatieve hobby’s zijn nu hardlopen, tennissen en fitness

Ik woon op dit moment in Amsterdam samen met mijn vriend Erik Driessen
Publications

Abstracts


Full papers


4. Brehm MA, Knol D, Harlaar J. Study design considerations for improving the reproducibility of walking efficiency outcomes in clinical gait studies. Gait and Posture (accepted for publication, currently in press)