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WALKING, ORTHOSES AND HEALTH-RELATED QUALITY OF LIFE IN CHILDREN WITH ARTHROGRYPOSIS MULTIPLEX CONGENITA

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Walking, orthoses and health-related quality of life in children with arthrogryposis multiplex congenita
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To all children in my studies, you have taught me so much!

Abstract

Arthrogryposis Multiplex Congenita (AMC) describes the presence of multiple joint contractures at birth. Muscle weakness is often associated with the joint contractures, and orthoses are often used to enable or facilitate ambulation. The overall aim of this thesis is to evaluate ambulatory function, orthosis use and health-related quality of life (HRQoL) in children with AMC. In the different studies, the children were designated to three different groups depending on the need for joint stabilization due to muscle weakness and joint contractures: 1) use of knee-ankle-foot orthoses with locked knee joints (KAFO-LK), 2) use of knee-ankle-foot orthoses with open knee joints (KAFO-O) or ankle-foot orthoses (AFO) 3) use of shoes. In Study I-III, gait in children walking with their habitual orthoses or shoes was evaluated. In Study I, gait kinematics was evaluated with three dimensional (3D) gait analysis in 15 children with AMC. The children walking with KAFO-LK used greater trunk movements in the frontal and transverse planes than those walking with KAFO-O/AFOs and shoes. Those walking with KAFO-LK were able to compensate for the inability to flex their knees during swing due to their locked orthoses knee joints. In Study III, gait dynamics, including kinematics, moments, and mechanical work, were evaluated with 3D gait analysis in 26 children with AMC and 37 typically developing (TD) children. Excessive trunk movements were found in children who walked with orthoses, particularly in those walking with KAFO-LK. The frontal plane joint moments showed only small differences between the groups in hip abduction and knee valgus moments. The joint work analysis indicated greater contribution from the hip muscles to overall positive work in AMC children, particularly in those with KAFO-LK, than in TD children, which illustrates their reliance on hip musculature. In Study II, energy effort with measurement of oxygen consumption and functional exercise capacity measured with the six-minute walk test (6MWT) were evaluated in 24 children with AMC and in 25 TD children. All AMC groups showed higher oxygen cost than TD children, but only those walking with AFOs/KAFO-O had significantly higher oxygen cost. All AMC groups walked shorter distances than TD children during the 6MWT. In Study IV, 33 children and their parents answered questionnaires that investigated HRQoL (CHQ-PF50 and EQ-5D-Y) and satisfaction with orthoses (QUEST 2.0). The results from the CHQ-Parent Form were compared to those from a Swedish reference group of 60 healthy children. Children with AMC had lower physical functioning than the reference group, particularly in those who were dependent on orthoses for walking. With EQ-5D-Y, no difference was found between children walking with orthoses or with only shoes. Satisfaction with orthoses was high, but the group who were dependent on orthoses for walking was less satisfied with the weight of the orthoses than the group who were not dependent on orthoses. With adequate orthotic support, children with AMC, even with severe weakness and contractures, can achieve walking. The gait pattern deviated in children who walked with orthoses from those walking with shoes and from TD children, and evaluation of the energy effort indicated a less efficient gait in children with AMC than in TD children. The HRQoL was lower, particularly in subscales related to physical health, in children with AMC than in the healthy control group when reported by the parents.

List of scientific papers

The thesis is based on the following original articles and manuscripts. Every paper will be referred to in the text by its Roman numerals.

I. **Eriksson M,** Gutierrez-Farewik E M, Broström E, Bartonek Å. Gait in children with arthrogryposis. Journal of Children's Orthopaedics. 2010; 4:21-31.

II. **Eriksson M,** Villard L, Bartonek Å. Walking, orthoses and physical effort in a Swedish population with arthrogryposis. Journal of Children's Orthopaedics. 2014; 8:305-312.

III. **Eriksson M,** Bartonek Å, Pontén E, Gutierrez-Farewik E M. Gait dynamics in the wide spectrum of children with arthrogryposis: a descriptive study. Accepted in BMC Musculoskeletal Disorders, 26 of November 2015.

IV. **Eriksson M,** Bartonek Å, Villard L, Kroksmark AK, Jylli L. Health-related quality of life and satisfaction with orthoses in a Swedish population of children with arthrogryposis. Manuscript.

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List of abbreviations

3D	Three dimensional
6MWT	Six-minute walk test
AFO	Ankle-Foot Orthosis
AMC	Arthrogryposis Multiplex Congenita
CHQ-PF50	Child Health Questionnaire – Parent Form 50
EQ-5D-Y	EQ - 5 Dimensions - Youth version
GDI	Gait Deviation Index
HRQoL	Health-related quality of life
KAFO	Knee-Ankle-Foot orthosis
KAFO-LK	Knee-Ankle-Foot orthosis with locked knee joint
KAFO-O	Knee-Ankle-Foot orthosis with open knee joint
N	Nondimensional
NNconsumption	Net nondimensional consumption
NNcost	Net nondimensional cost
PEDI	Pediatric Evaluation of Disability Inventory
QUEST	Quebec User Evaluation of Satisfaction with Assistive Technology
SD	Standard deviation
TD	Typically-developing children

1 Introduction

Arthrogryposis multiplex congenita (AMC) is a descriptive term rather than diagnostic. It is used to describe a heterogeneous group of patients and disorders, all of whom have multiple congenital contractures. In children with AMC, one of the goals with treatment is to achieve and improve ambulatory function. This thesis studies different aspects on walking in children with AMC.

1.1 Definition

The main characteristics in AMC are multiple joint contractures in different body areas that are present at birth [1]. The first clinical description of arthrogryposis in the medical literature is thought to be by AW Otto in a textbook from 1841 [2]. The term arthrogryposis was probably first used by Rosencrantz in 1905 and arthrogryposis multiplex congenita by Stern in 1923 [3]. In 1932 Sheldon used the term amyoplasia congenita as he believed that the cause was due to aplasia or hypoplasia of muscle groups [3]. Still today AMC is used to describe conditions with non-progressive multiple joint contractures. AMC can be a part of a large number of other syndromes [4]. Arthrogryposis or AMC has been used synonymously with the term Multiple Congenital Contractures [5].

1.1.1 Contractures, deformities and muscle weakness

Joint contractures and deformities are the main characteristics in the newborn child with AMC [1]. A contracture is a limitation of movement in the joint, and in children with AMC the contractures have occurred before birth [6]. Staheli has divided the deformities into primary, positional and recurrent deformities based on the time of onset [7]. Primary deformities are formed early in fetal life and are characterized by severe stiffness and a tendency to recur after treatment and therefore continuous treatment is needed throughout childhood. Positional deformities occur late in fetal life and are usually mild [7]. Related to the contractures and deformities many types of AMC have decreased muscle mass, hypoplastic muscles, or loss of muscles [4].

Hip joint involvement in subjects with AMC varies in two different reviews; Bevan reports between 51-85% [8] and Stilli reports between 56-90% [9]. Likewise, knee joint involvement is reported as 60-90% [8] and as 38-90% [10]. The hip deformity is characterized by flexion and abduction contractures, and by dislocations [8, 9]. Knee flexion contractures are more common than knee extension contractures, 48% vs 21% respectively [8]. The feet are involved in 80-90% of persons with AMC, with clubfoot as the most commonly reported deformity [8]. Spine involvement has been reported in 22-40% of persons with AMC [11, 12] and in approximately 30% of children with amyoplasia and both scoliosis and lordosis have been found [13, 14].

1.1.2 Heterogeneous group of disorders

Multiple congenital contractures has been described as a part of more than 400 specific conditions [4, 5], occurring both hereditary and sporadically [15]. To identify a specific type of AMC, joint range of motion, muscle strength, associated anomalies, pregnancy and family history are documented. Genetic assays and muscle biopsies will also contribute to an accurate diagnosis, which could be found in more than half of the individuals with AMC [4].

In 2009 Bamshad et al. proposed a classification of AMC that is commonly used today [16]:

- Amyoplasia
- Distal arthrogyposis (DA)
- Syndromic which is further divided in a) central nervous system etiology, and b) progressive neurological etiology.

Amyoplasia, often referred to as "classical arthrogryposis" is the most frequently observed AMC condition, representing one third of all cases. It is characterized primarily by symmetrical limb involvement with decreased muscle mass. Muscle defects are sometimes also found in the abdominal wall [17, 18]. Distal arthrogryposis (DA) is probably the second most common type of AMC of which ten different types DA have been described [16, 19]. DA is characterized by involvement of foot and hand, sometimes also of proximal joints [16]. The third syndromic group includes Larsen syndrome, several types of pterygium syndromes, and various genetic syndromes and chromosomal anomalies [4]. Recently, many muscle proteins have been found to be involved in conditions previously thought to be neuropathic [20].

1.1.3 Etiology

Decreased fetal movement is the main common background factor for all different forms of AMC [1, 5]. Potential causes and etiologies to decreased fetal movements are suggested as pathology in the peripheral or central nervous system, pathology in muscles or in connective tissues, defects in neuromuscular transmission, limitation of space for fetal movements within uterus, maternal illness, external factors like medication, or compromised vascular supply to the fetus [1, 4, 5].

There is a relationship between an early onset of decreased fetal movements and the severity of contractures at birth [1, 5]. Deposition of connective tissue around the joints may inhibit the range of motion [1, 21, 22] and lead to an abnormal development of joint surfaces [23]. The muscles may be formed normally during fetal development but can then be replaced by fibrous and fatty tissues [1, 15].

1.1.4 Epidemiology

The occurrence of AMC or multiple congenital contractures has varied in several studies. The incidence of AMC was reported to be one in 3,000 live births in a Finnish study from 1966 [24], one in 66,000 live births in a Scottish study from 1976 [25], one in 12,000 live births in a study from

Western Australia from 1976 [26], and one in 4,300 live births in a study from Alberta, Canada from 2010 [27].

The incidence of multiple congenital contractures in western Sweden has been reported as one in 5,100 live births in a study from 2002 [28]. The incidence for amyoplasia has been reported as one in 10,000 live births in a study from USA from 1983 [17].

1.1.5 Limb involvement

Four-limb involvement is more common than only lower limb or upper limb involvement in arthrogryposis [22]. Various frequencies of limb involvement in amyoplasia has been reported; four-limb involvement is reported in 63-84% [17, 29, 30, 31] , lower limb involvement is reported in 5-13% [17, 29, 31], and upper limb involvement is reported in 11-24%, [17, 29, 31].

1.1.6 Motor development

Due to contractures and muscle weakness, motor development in AMC is often delayed, which reduces the child's ability to function at an age-appropriate level [4, 32]. The motor milestones may be delayed or some children with AMC may not be able to perform these milestones as the typically-developed child [33, 34]. When the child is between 6 and 12 months of age, gross motor skills, such as sitting balance and mobility skills should be evaluated, according to Graubert [33]. After achieving a stable sitting on the floor, some children learn to slide on their bottoms instead of crawling on their hands and knees. Other children learn to roll their body for mobility [33]. When the child shows interest of an upright position, orthoses may be needed to support the lower extremities in an adequate alignment [34].

In most children with AMC, walking function is, however, achieved though with some delay [7]. Fassier and collaborators found that some ambulators were immediate walkers without any support at a mean age of 1.5 years while others needed support of orthoses and walking aids and achieved walking at a mean age of 2.5 years [30]. Kroksmark and collaborators reported independent walking at a median age at of 18 months in a group who later became community ambulators [29]. Another group achieved independent ambulation at a median age of 42 months and they later became household ambulators [29]. In a group of five children with AMC treated for clubfoot deformity, walking was achieved at a mean age of 17 months, wherein three of the children used orthoses for walking [35]. Sells et al. reported that 85% of children in their study had achieved walking at the age of 5 years [31].

1.2 Treatment towards walking

As AMC is a complex disorder, a multi-disciplinary team management is required. Treatment of the contractures and deformities in children with AMC is performed with physiotherapy, occupational therapy, and orthopaedic and orthotic management in combination. Achieving best function possible is one goal of AMC treatment [23]. In the lower limbs, management is focused on stability and symmetry [7]. Contractures are most severe at birth, and some improvements can be expected during the first 3-4 months [8]. The first four months of life can be seen as an important period to increase range of motion and to avoid further muscle atrophy [4, 8, 29]. The treatment can vary during childhood with more intensive treatment during the first year. During childhood, there is a risk that contractures will recur, thus treatment is often required until skeletal maturity [36]. This thesis studies children who have achieved a walking function.

1.2.1 Physiotherapy

Initial treatment usually consists of physiotherapy with intensive stretching of the joints just after the birth [31]. The physiotherapist commonly instructs parents how to perform passive stretching. Physiotherapy with stretching in combination with use of orthoses has been reported to increase range of motion, wherein better results are achieved with early starts [37]. During the first year of life physiotherapy includes improving passive range of motion of the joints and treatment of contractures, evaluation of muscle contractions and stimulation of the child's gross motor functions, and preparing the child for first standing [33, 34].

During childhood physiotherapy treatment continues with further improving of passive range of motion of the joints and treating of contractures, increasing muscle strength, and enhancing functional ambulation with orthoses and mobility in different environments [33, 34].

1.2.2 Orthoses

Orthoses (splints) are used to maintain joint position after stretching [37]. After serial casting or orthopaedic surgery orthoses should be used to maintain the achieved correction [37]. Ankle-foot orthoses (AFO), knee orthosis (KO), and knee-ankle-foot orthoses (KAFO) in thermoplastic material without knee joints and ankle joints are frequently used for treatment of contractures. Club foot treatment with the Ponseti method includes the use of foot abduction orthoses [38, 39] but also use of AFOs has been described [40, 41].

Around the age of 12 months, when children often show intention to stand upright, orthoses are introduced often in combination with a standing frame [33, 34]. These first orthoses are often KAFOs without knee joints [7, 34]. If there is an uncertainty about the child's ability to maintain an upright position of the trunk, the first orthoses for standing might be a hip-knee-ankle-foot orthoses (HKAFO) with locked hip joints and without knee joints [34]. When the child starts to walk, KAFOs are often beneficial [7]. As contractures have a tendency to recur during childhood, especially knee flexion contractures and club foot deformities, night-time orthoses are recommended [7, 42].

1.2.3 Orthopaedic management

Despite efforts to prevent contractures and deformities, further treatment in the form of serial casting and/or orthopaedic surgery is often needed [36]. Lower limb deformities that will prevent the child from standing or walking should be dealt with before the age of about 18 months [43, 44].

Mild hip flexion contractures may improve with stretching [42]. If the hips are dislocated an open surgical reduction can be performed, ideally between six and 12 months of age [36, 42, 45]. In a walking child, hip flexion contractures will generally require release or extension osteotomies in order to improve gait [8, 36, 42, 46, 47]. Unilateral dislocations should be reduced to facilitate mobility and limit pelvic obliquity [9, 47]. In the case of bilaterally dislocated hips surgery is more controversial, but is proposed by some authors [47, 48, 49, 50, 51].

In children born with knee hyperextension and knee dislocation good results have been reported with early serial casting often in combination with orthopaedic surgery [52]. Mild knee flexion contractures in infants can usually be treated with stretching [7, 42, 53]. More severe knee flexion contractures can be treated by guided growth, achieved by long-term compression of the distal femoral physis, using 8-plates fixed to the distal femur [54]. If there is not enough growth remaining for correction with guided growth, the flexion deformity can be treated by distal femoral osteotomies [36, 55, 56] or with gradual correction with an external fixator [56, 57].

Clubfoot deformity could, especially in a young child, be treated with serial casting according to a modified Ponseti method, which is a combination of a primary percutaneous Achilles tenotomy followed by serial casting and a re-Achilles tenotomy if needed [38, 39, 41, 58]. Before the Ponseti method was introduced, many different surgical procedures were used in order to obtain a plantigrade foot, e.g. soft-tissue release, triple arthrodesis, correction with an external fixator and talectomy [8, 36, 44]. These surgeries may be needed if the modified Ponseti method fails. However, even relapsed club foot deformities have in recent years been shown to be treatable with yet another Ponseti casting series and re-tenotomy of the Achilles tendon [39].

Spine deformities in AMC are usually characterized by rigidity [12]. Hip flexion contractures contribute to increased lordosis and hip dislocation can contribute to pelvic obliquity [8]. Night bracing should be commenced when scoliosis with an axial rotation is detected [12]. Different surgical procedures have been described for correction of scoliosis [12, 59].

1.2.4 Occuptional therapy

For the child’s ability to improve independence, it is important to treat the upper extremities [8, 33, 42]. In order to improve range of motion, stretching of contractures, in combination with use of orthoses, is initiated in newborn children [37, 60, 61]. Orthoses for hands and wrists are often used at night to maintain range of motion. Many children with AMC have muscle weakness in the hand and poor grasping skills, and different activities can help to strengthen the muscles [33]. For those with severe lower limb involvement, the upper limbs may be needed for use of a walker or crutches [62].To allow weight-bearing through forearms instead of hands, wrist support can be attached to the walker. Lester has described the basic functions of the upper limbs as being able to eat independently and taking care of personal hygiene [62]. Different surgical procedures have been described to improve function in the upper limbs [60].

1.3 Walking function and orthoses

1.3.1 Walking ability

The ability to walk depends on severity of contractures and degree of muscle weakness in the lower limbs [30, 36, 46]. Requirements for functional ambulation have been identified as hip flexion and knee flexion contractures less than 20-30°, hip extensor strength grade 4-5, and knee extensor strength grade 4-5 or use of knee-ankle-foot orthosis with locked knee joint.

Muscle strength has been reported to have a greater impact on walking ability than joint contractures [29]. Additional upper limb involvement may also have an influence on walking ability [30, 36, 46] due to poor protective responses of the upper limbs [34]. Severe spine involvement has reported to negatively influence walking ability [30, 46].

Some children with AMC will not achieve an ambulatory function, and a wheelchair will therefore be required. Fassier et al. found no correlation between joint involvement at birth and ambulatory function at skeletal maturity [30], while Kroksmark et al., in contrast, found that joint position and joint contractures at birth have an impact of achievement of motor function [29]. In another study group, hip flexion contractures were found to be a predictor for walking function in a study by Eamsobahna [63].

1.3.2 Levels of functional ambulation

Hoffer has classified the walking ability in persons with AMC into four levels: community ambulators (CA) can walk with or without aids in the community and do not need wheelchairs, household ambulators (HA) walk at home with aids and use wheelchairs in the community, non-funtional ambulators (NF) can only walk with support and aids, such as walkers or parallel bars, and non-ambulators (NA) are unable to walk in any situation [46].

Various levels of functional ambulation are reported in children with AMC. In a study by Hoffer, 14 of 36 individuals were CA, seven HA, six NF, and eight were NA [46]. Of 29 patients, Kroksmark et al. reported 11 with CA and HA respectively, and seven of NA [29]. Of 11 individuals, Fassier reported that 8 were CA, and one each HA, NF, and NA [30]. Of 51 individuals, Eamsobahna et al. reported 31 with CA, three with HA, three with NF, and 14 with NA [63]. This variation indicates that ambulatory level varies among individuals and may reflect the heterogeneity among the persons with AMC.

1.3.3 Activity level

Dillon et al. measured activity in children with AMC with a step activity monitor, and found that they took fewer daily steps and spend less time at high activity levels than typically-developing (TD) children [64]. Lower endurance in youths with AMC than in TD children has been reported [64], and a powered wheelchair may therefore provide more efficient ambulation [33].

1.3.4 Gait pattern

Three dimensional (3D) gait analysis has shown that hip abductor weakness can lead to excessive trunk movements in the frontal plane in AMC [65]. This gait pattern alters the moments around the hip and the knee joints [65]. Böhm and collaborators have proposed that excessive frontal plane trunk movements may also be a compensation for weak hip flexors in order to clear the foot during swing [66].

1.3.5 Health-related quality of life

In a study reporting health-related quality of life (HRQoL) in children with various motor disorders, including ten children with AMC, participants reported their perceived health with EQ-5D Youth version (EQ-5D-Y) [67]. The children with AMC reported more problems in the dimensions ‘mobility’, ‘looking after myself’, ‘doing usual activities’, ‘having pain or discomfort’, and ‘feeling worried, sad or unhappy’ than a Swedish reference group of TD children [67].

1.4 Orthoses for walking

In children with AMC, orthoses are commonly used to enable or facilitate walking. Various types of orthoses can be used to compensate for muscle weakness and to support the lower limbs in an aligned position [7, 34].

1.4.1 Definition of orthoses

The International Organization for Standardization (ISO) has established a vocabulary of terms to be used in the field of external orthotics. An orthosis or an orthotic device is defined as “an externally applied device used to modify the structural and functional characteristics of the neuromuscular and skeletal systems” [68]. A lower limb orthosis is defined as “orthosis applied to the whole or part of the lower limb” [68]. ISO has a vocabulary of terms used in the field of external orthotics and defines terms relating to external orthoses that encompass joints [69].

1.4.2 Types of orthoses

Commonly used orthoses for walking in children with AMC are AFOs and KAFOs [7, 34, 70]. When the aim is to stabilize the knee joints in frontal and transverse plane, while not restricting knee flexion, KAFOs with open knee joints (KAFO-O) can be used [70, 71]. For persons with knee extensor weakness, KAFOs should have a locked knee joint (KAFO-LK) in order to stabilize the knee joint in the sagittal plane during walking [7, 34, 46, 70]. AFOs are used to stabilize the foot and ankle joints [70]. Use of AFOs has also been described to prevent recurring clubfoot deformities [34] and to provide a better weight-bearing surface [33]. The most commonly reported AFO in AMC are solid AFOs [7, 33, 34], but use of hinged AFOs with limited dorsiflexion and some allowance of plantarflexion has also been reported [70]. For those with plantarflexor weakness, AFOs and KAFOs with a carbon fiber spring ankle joint improve kinematic gait parameters, stride length, and walking speed [70, 72]. Ankle plantarflexion moment, ankle power generation, and ankle positive work are significantly higher with the carbon fiber ankle joints than with AFO with solid ankle joints [70, 72]. Contractures that interfere with stable standing may be optimized with use of compensations in orthoses and/or with external shoe wedges [70, 71]. Various levels of ambulation have been reported in persons walking with KAFOs ranging from community ambulators to non-functional ambulators [29, 30]. In those walking with bilateral KAFOs with locked knee joints, walking aids are often required [33]. Use of KAFOs including pelvis and hip joint (HKAFO) has also been described for walking in AMC [9, 10].

1.5 Rationale with the thesis

To achieve walking, children with AMC go through treatments such as physiotherapy and orthotic and orthopaedic management. Many children use orthoses both to treat contractures, as well as to facilitate and enable walking. Even though there are several studies reporting the children's functional ambulatory level, there is a lack of studies quantitatively measuring gait and energy effort with respect to orthosis use. The studies in this thesis will provide an understanding of gait pattern, energy expenditure, as well as perception of health and orthoses.

2 Aims

The general aims of this thesis were to evaluate ambulatory function, orthosis use and health-related quality of life in children with AMC.

The specific aims of the studies were:

Study I

To describe gait pattern among individuals with AMC wearing their habitual orthotic devices.

Study II

To evaluate energy expenditure and exercise capacity during walking in children with AMC wearing their habitual orthotic devices.

Study III

To describe gait dynamics in children with AMC during walking wearing their habitual orthotic devices.

Study IV

To describe health-related quality of life and satisfaction with orthoses in a group of ambulatory children with AMC.

3 Methods

Several outcome measures were used in the four studies that comprise the present thesis. They will be presented more in detail below each method.

3.1 Participants

The entire study group included 40 children with AMC and 62 TD children without disabilities as controls. The distribution of the participants with AMC and of controls are presented in Table 1.

Table 1. Distribution of participants in Study I – Study IV.

Study	N of subjects	Mean age (years)	Category and Gender	Children with AMC recruited from
I	15	12.4 (range 4.7 - 17.7)	AMC 8 m, 7 f	Karolinska University Hospital, Stockholm
II	24	11.1 (range 5.1 - 17.0)	AMC 16 m, 8 f	Karolinska University Hospital, Stockholm Uppsala University Hospital, Uppsala
	25	11.4 (range 5.1 - 16.8)	Controls 17 m, 8 f	
III	26	10.5 (range 5.0 -17.8)	AMC 17 m, 10 f	Karolinska University Hospital, Stockholm Uppsala University Hospital, Uppsala
	37	10.4 (range 5.1 - 17.6)	Controls 11 m, 26 f	
IV	33	10.5 (range 5.0 - 17.0)	AMC 18 m, 15 f	Karolinska University Hospital, Stockholm Uppsala University Hospital, Uppsala Regional Habilitation Center, Gothenburg

m, male; f, female

3.2 Clinical characteristics

3.2.1 Joint contractures and joint involvement

Passive range of motion (ROM) of the hip, knee, and ankle joints was measured in a supine position with a goniometer and assessed according to recommendations of the American Academy of Orthopaedic Surgeons [73]. Hip flexion contracture was measured using Thomas' test [74]. In Study I, II, and IV, hip and knee flexion contractures were defined as ≥10° from a neutral position. In Study III, hip and knee flexion contractures were defined as >0° from neutral position. Plantarflexion contractures were defined in Study I, II, and III as >0° and in Study IV as ≥5° from neutral position. Hyperextension was defined in Study II >10° and in Study III ≥10° from neutral. Prevalence of hip dislocation was obtained from the medical record in Study III. Contractures or deformities in the upper limb joints were documented as present or not.

3.2.2 Muscle strength

In Study I–IV, muscle strength in the lower limbs was tested manually on a six-graded scale in the available range of motion. Grade 0 indicates no muscle strength, grade 1 indicates activity traces, grade 2 indicates gravity-eliminated movement, grade 3 indicates movement against gravity, grade 4 indicates movement against gravity with some manual resistance, and grade 5, indicates normal strength[75]. In Study I–IV, muscle strength in hip extensors, hip abductors, knee extensors, and plantarflexors were tested. Muscle strength in hip flexors were tested in Study I and III, muscle strength in dorsiflexors was tested in Study I–III.

3.2.3 Orthopaedic surgery history

In Study I and II, orthopaedic surgery was reported as bony or soft tissue procedures in each joint of lower limb. Spine fusion was reported in Study I and II. In Study III and IV, the number of orthopaedic procedures in lower limbs and spine was retrieved from medical records.

3.3 Orthosis subgroups

In Study I–III:
Participants were designated to different subgroups according to which orthoses they required, based on presence of muscle weakness and need for joint stabilization. The orthosis subgroups represent 1) knee and ankle joint stabilization for knee extensor weakness grade ≤3, 2) ankle joint stabilization for plantarflexor and dorsiflexion weakness grade ≤3, and 3) only foot stabilization.

Four children in Study I, three children in Study II, and five children in Study III used KAFO-LK, which stabilize the ankle in the sagittal plane and the knee in the sagittal, frontal and transverse planes. In Study I they were defined as Group 1, and in Study II and III as AMC1. Eight children in Study I, eleven children in Study II, and ten children in Study III used KAFO-O or AFOs. AFOs stabilize the ankle in the sagittal plane and the KAFOs stabilize the knee in the frontal and transversal planes without limit knee flexion. In Study I they were defined as Group 2, and in Study II and III as AMC2. Three children in Study I, ten children in Study II, and eleven children in Study III used shoes and in some cases additional foot orthoses (FO). In Study I they were defined as Group 3, and in Study II and III as AMC3.

In Study IV:
Nine children were dependent on orthoses for walking and they were designated as group Ort-D, nine children used orthoses but were able to walk short distances indoors without orthoses and they were designated as group Ort-ND. Fifteen children did not use orthoses and they were designated as group Non-Ort.

Distribution of orthoses in the subgroups in all four studies are shown in Table 2.

3.4 Types of orthoses

The types of orthoses used for walking as well as additional heel heights on orthoses and/or shoes were documented in Study I–IV (Table 2). The most frequently used orthosis models in the AMC orthoses groups are shown in Figure 1.

Figure 1 a-c. The most frequently used types of orthoses in the AMC groups: a) KAFO-LK and carbon fiber ankle joint (KAFO-LK-C), b) KAFO-O with carbon fiber ankle joint (KAFO-O-C), c) AFO with carbon fiber ankle joint (AFO-C).

a) b) c)

Table 2. Distribution of types of orthoses in Study I–IV.

	Study I			**Study II**			**Study III**			**Study IV**		
	Group 1 n=4	Group 2 n=8	Group 3 n=3	AMC1 n=3	AMC2 n=11	AMC3 n=10	AMC1 n=5	AMC2 n=10	AMC3 n=11	Ort-D n=9	Ort-ND n=9	Non-Ort n=15
KAFO-LK	2			1	1		3			4		
KAFO-LK-C	2			2			2			2		
KAFO-O-C		2			3			2		1		
KO-LK										1		
AFO-S		1			2			2		1	1	
AFO-H		1			2			2			2	
AFO-C		4			2			2			2	
AFO-FC					1			2			3	
Shoes			3			10			11			15

KAFO: knee-ankle-foot orthosis, LK: locked knee joints, C: carbon fiber ankle joint, O: open knee joints, KO: knee orthosis, AFO: ankle-foot orthosis, S: solid, H: hinged. FC: flexible carbon fiber.

3.4.1 Usage time

The children's daily use of their orthoses was documented in Study I-IV.

In Study 1–III, all children used their orthoses more than eight hours a day. In Study IV, 14 of the children used them more than eight hours a day, two children between five to eight hours a day, and two children less than five hours a day.

3.5 Functional ambulation

In Study I – IV, the ambulatory function was assessed according to a five-level scale that has previously been used in children with myelomeningocele: Level I: community ambulators with no need for a wheelchair, Level II: community ambulators requiring a wheelchair for long distances outdoors only, Level III: household ambulators requiring a wheelchair outdoors and for long distances indoors, Level IV: household ambulators requiring a wheelchair both outdoors and indoors, and Level V: non-functional ambulators and wheelchair use for mobility [76].

3.6 Functional mobility and self-care

In Study IV, functional skills of mobility and self-care were assessed by the Pediatric Evaluation of Disability Inventory (PEDI) [77]. In a parent-report questionnaire that was administered in an interview session, the parents were asked about their child's ability to perform functional skills of the mobility domain (59 questions) and of the self-care domain (73 questions).

3.7 Gait analysis

Three dimensional (3D) gait analysis provides detailed information about a person's gait pattern [78]. Data is collected by placing reflective markers on various landmarks on the person; the markers reflect the light from several infrared cameras when the person walks in the gait laboratory. Kinematics is the term used to describe joint and segment motion. The ground reaction forces acting on the body during walking can be measured with force plates mounted on the floor of the walkway. The internal moment can be computed from the ground reaction force and the kinematics [78]. Kinetics is the term used to describe joint moments, forces, and powers. During gait analysis, time and distance parameters are often collected, e.g. walking speed, stride length, step length, cadence, step width, and limb support time.

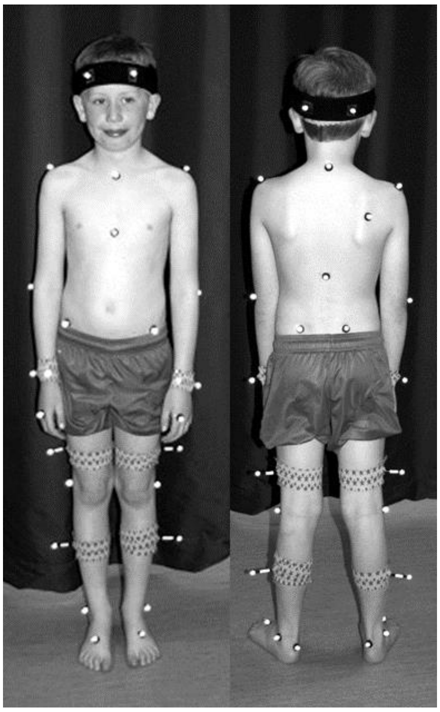
In both Study I and III, 3D gait analysis using an eight-camera reflective marker system (Vicon©, Oxford, UK) was used to measure joint and segment angles during gait. In both studies, a full body marker set with 35 markers was used (Figure 2). Markers were placed on specific anatomical positions or on orthoses and shoes. In Study III, data from two embedded force plates (Kistler©, Winterthur, Switzerland) were used to measure ground reaction forces. In both studies, children were asked to walk at a self-selected pace along a 10-meter walkway until complete information of several gait cycles for each side was collected. All children walked in their habitual orthoses or shoes. In Study I, gait analysis was also performed in those five children who were able to walk without orthoses. All 3D gait analyses were conducted at the Motoriklab, Karolinska University Hospital, Stockholm.

3.7.1 Biomechanical model

In both Study I and III, the lower body was modeled as seven segments (pelvis, two thighs, two shanks, and two feet) according to the Vicon Plug-In-Gait model [79]. The upper body was modeled as the thorax, upper and lower arms, hands, and head according to the Plug-In-Gait model (Vicon).

Trunk and pelvis segment angles in all planes and foot progression angles are described in global coordinates whereas all hip and knee angles, and sagittal ankle angles are described relative to the proximal segment.

Figure 2. Marker placement during 3D gait analysis used in Study I and Study III.



3.8 Energy effort

A method to measure energy effort during walking is indirect calorimetry. The oxygen consumption is measured during a walking test and the oxygen cost is calculated. Oxygen consumption refers to as physical effort, and oxygen cost is referred to as gait efficiency [80].

In Study II, oxygen consumption was measured during walking at a self-selected speed (O_2-walking test) using the portable telemetric system Cosmed $K4b^2$ (Cosmed Srl, Rome, Italy) (Figure 3). The Cosmed system $K4b^2$ has been reported to be a valid and reliable method to measure energy effort during walking in children with disabilities [81]. All O_2-walking tests were conducted on a 21-meter oval walking track at the Motoriklab, Karolinska University Hospital, Stockholm. Oxygen cost and walking speed was calculated from the time and the distance walked during the test.

Figure 3. A child equipped with a Cosmed $K4b^2$ in Study II.

3.9 Functional exercise capacity

In Study II, functional exercise capacity was measured with the 6MWT, which is a valid and reliable method for assessing endurance and exercise tolerance in healthy children [82] as well as in children with disabilities [83]. The heart rate was registered with a Polar heart rate monitor (Polar Electro Oy, Kempele, Finland). The walking distance during six minutes of continuous walking was documented and walking speed was calculated.

3.10 Health-related quality of life

Two questionnaires were used to measure perception of HRQoL, of which one was answered by the parents and the other by the children.

3.10.1 Child Health Questionnaire – Parent Form

In Study IV, the parents' perception of their children's HRQoL was reported with the Child Health Questionnaire – Parent Form (CHQ-PF50). The CHQ-PF50 is a generic instrument constructed to measure children's physical and psychosocial well-being using a multi-item scale [84]. Eight health concepts are measured: physical functioning (PF), bodily pain/discomfort (BP), limitations in school work and activities with friends due to physical health (RP), general health perceptions (GH), limitations in schoolwork and activities with friends due to emotional behavioral difficulties (REB), mental health (MH), general behavior (GH) and self-esteem (SE). There are four concepts addressing the parents only: parental time impact (PT), parental emotional impact (PE), family activities (FA) and family cohesion (FC) [84]. A four-week recall is used for all scales except for the family cohesion (FC) item and the general health (GH) scale [84]. The scores range from 0 to 100, with a higher score indicating better health [84]. The CHQ-PF50 is a valid and reliable questionnaire to report HRQoL in children with disabilities in the age 5-18 years [85, 86, 87]. There is a Swedish reference group consisting of 60 healthy 6-18 years old children [85].

3.10.2 EQ-5D-Youth (EQ-5D-Y)

The EQ-5D is a broadly used generic questionnaire originally designed to measure health-related quality of life in adults [88]. The adult version has been modified to suit a pediatric population (EQ-5D-Y) from the age of 8-16 years [89, 90]. It is valid and reliable for measuring self-reported HRQoL in children eight years and older [90] and has also been used in children with functional disabilities in Sweden [67]. EQ-5D-Y consists of five dimensions: 'mobility' (walking about), 'looking after myself', 'doing usual activities', 'having pain or discomfort', and 'feeling worried, sad or unhappy'. Each dimension has three response levels of severity: 'no problems', 'some problems', and 'a lot of problems'. No overall score can be calculated and data is often presented as the percentage of individuals reporting each level of problem for each item [89, 90]. The EQ-5D-Y also includes a visual analog scale (VAS) for rating overall health status on a vertical scale between 0 (worst imaginable health) and 100 (best imaginable health). All dimensions and the VAS refer to health state 'today'. The EQ-5D-Y has shown good psychometric properties when used in healthy children [89].

3.11 Satisfaction of orthoses

The Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST 2.0) questionnaire was used for evaluation of satisfaction of the children's orthoses and related services [91, 92, 93]. QUEST 2.0 consist of two parts; one part is related to satisfaction with children's satisfaction with their device, and the other part of satisfaction related to service delivery. The questionnaire is comprised of 12 items in total, of which eight relate to satisfaction with their assistive devices (dimensions, weight, ease of adjustment, safety, durability, simplicity of use, comfort, effectiveness), and four relate to service delivery (service delivery program, repairs and servicing, quality of professional services, follow-up services) [92, 93]. A five-level response scale is used to calculate a score for satisfaction with the device, service and a total score (not satisfied at all, not very satisfied, more or less satisfied, quite satisfied, very satisfied) [92]. Of the 12 satisfaction items, there is an opportunity to select the three most important items of the device and service [92].

QUEST 2.0 is a valid questionnaire for measuring satisfaction with assistive devices which has been developed for adults [92, 93]. A Swedish version of QUEST 2.0 is available and is distributed by the Swedish Handicap Institute [94]. In this thesis, the parents and the child together answered the questionnaire. Before using the QUEST 2.0, eight children with myelomeningocele using similar types of orthoses were tested in a pilot study with regard to their understanding of the questions.

3.12 Data analysis

Study I

Three kinematic gait cycles were analyzed for each child. Gait parameters were averaged for each side. Gait parameters were described in the frontal plane for the trunk, pelvis and hip, in the sagittal plane for the trunk, pelvis, hip and knee, and in the transverse plane for the trunk, pelvis, hip and foot. In Group 3, dorsiflexion and plantarflexion were analyzed. Cadence, step length, stride length, walking speed and step width were analyzed, wherein walking speed, step length and stride length were normalized to leg length.

Study II

Oxygen consumption during walking was measured and normalized by body weight per unit time (ml/kg/min) and oxygen cost per meter walked during the test (ml/kg/m) [80]. Due to the large difference in age among the participants (5 to 17 years), we normalized the oxygen data with using the nondimensional normalization scheme. The scheme includes a nondimensional scaling and thereby reduces the variability due to different statures of the children [95]. The net nondimensional consumption (NNconsumption) and net nondimensional cost (NNcost) were calculated from the last 2 minutes of the first resting period and the last 2 minutes of the walking period. The 6MWT was analyzed based on the distance walked and the mean walking velocity during walking. Walking velocity in both tests was normalized to leg length and gravity, and is presented as the normalized walking velocity (N walking velocity) [96].

Study III

At least three left and right gait cycles per side were collected and analyzed for each subject. Kinematic and kinetic gait parameters were obtained from each gait cycle and averaged for each side. Kinematic gait parameters were described in the frontal plane for the trunk, pelvis and hip, in the sagittal plane for the trunk, pelvis, hip, knee and ankle, and in the transverse plane for the trunk, knee, hip and foot. The Gait Deviation Index (GDI), which summarizes lower body kinematics into a multivariate measure of overall gait deviations, was computed for left and right sides independently. The GDI is based on kinematics from the pelvis and hip in all three anatomical planes, the knee and the ankle in the sagittal plane, and foot progression in the transversal plane. A GDI of approximately 100 reflects normal kinematics and each reduction represents one standard deviation from normal [97]. A reference GDI value was computed from the gait laboratory database of 37 TD children.

Internal joint moments were normalized to body weight. Joint moments (Nm/kg) were described in the frontal plane for the hip and knee, and in the sagittal plane for the hip, knee and ankle. Joint work was calculated as the integral of joint power with respect to time. Work (J/kg) was calculated in each joint in the lower extremities. Positive work done was calculated as the sum of positive power components, and negative work, as the sum of negative power components. Positive work contributions from the hip, knee and ankle were computed as percentages of total positive work in the lower extremities (hip + knee + ankle positive work).

Time and distance parameters were analyzed, wherein cadence, walking speed, stride length and step length were non-dimensionalized (N cadence, N walking speed, N stride length, and N step length) [96].

Study IV

For the CHQ-PF50 the raw scores was transformed and the physical and psychosocial summary scores were calculated according to the CHQ User Manual [84]. In EQ-5D-Y, the categories "some problems" and "a lot of problems" were combined into the severity level "problems" before statistical analysis. For functional mobility and self-care, the scores were transformed to scaled scores using the PEDI manual [77]. The results for satisfaction with orthoses were analyzed according to the Swedish manual of QUEST 2.0 [94].

3.13 Statistical analysis

In Study I, non-parametric statistical tests were used to determine differences between the three groups with children with AMC. In Study II, parametric statistical tests were used to determine differences between two groups of children with AMC and a group of TD children. One group (AMC1) was excluded from the analysis due to few participants. In Study III, non-parametric statistical tests were used to determine differences between three groups of children with AMC and a group with TD children. In Study IV, both parametric and non-parametric statistical tests were used to determine differences between orthoses groups and TD children. Commercially available software was used in all studies (SPSS, Chicago IL, USA). Significance level in all studies was set at $p<0.05$.

3.14 Ethical considerations

All studies were approved by the Regional Ethical Review Board in Stockholm, Sweden. All studies were conducted in accordance with the Declaration of Helsinki. Participation was voluntary. All children and the parents were given oral information, and the parents and children 10 years and older were given written information. Consent to participate was obtained from the parents.

4 Results and Discussion

Ambulatory children with AMC were investigated using various methods in order to evaluate gait pattern, energy effort, perception of HRQoL and how they perceived their orthoses. In Study I-III the participants were divided into three groups based on the orthoses they were prescribed at the time of the studies:

- Group 1/AMC1 used KAFO-LK
- Group 2/AMC2 used KAFO-O or AFOs
- Group 3/AMC3 used shoes

In Study IV the children were divided into criteria based on dependence of orthoses for walking ability:

- Ort-D were dependent on orthoses for walking
- Ort-ND used orthoses but were not dependent on them for walking
- Non-Ort used shoes

All children wore the same orthosis type in all studies they took part of, except one child who used AFOs in Study I and shoes only in Study II-IV.

4.1 Clinical characteristics

The children included in the thesis were classified with AMC with either four-limb involvement or lower limb involvement.

4.1.1 Joint contractures

At the time of the studies, hip flexion contractures were present in 25% of the children. None of the children had hip flexion contracture more than 20°, which is under the threshold that has been described to limit functional ambulation [7, 30, 36, 46]. Knee flexion contractures were present in 45% of the children and did not exceed 30° in any of the participants, except for one child with severe involvement on one side and a mild involvement on the other side (Study II and IV). Knee hyperextension of 20° or less were present in 43% of the children. Plantarflexion contractures ranging from 5 to 50° were present in 50% of the children. The most severe knee flexion and plantarflexion contractures were found in Group 1/AMC1. In Study IV, knee flexion and plantarflexion contractures were significantly more frequent in Ort-D than in Ort-ND and Non-Ort. None of the children had dislocated hips at the time of the studies.

In the total study population of all 40 children, 73% were also considered to have an upper limb involvement, which is in accordance with previous reported findings [17, 29, 31]. None of them, however, had solely upper limb and were included in the four-limb involvement group.

4.1.2 Muscle strength

Hip extensor strength grade 3 or less was present in 8% of the children. Hip abductor strength grade 3 or less was present in 20% of the children. Knee extensor strength grade 3 or less was present in 20% of the children, who required KAFO-LK to stabilize their knee joints during walking. Weakness of plantarflexors grade 3 or less was presented in 50% of the children, who required AFOs to stabilize their ankle joints.

Muscle strength assessment is based on movement through the entire available range of motion [75]. Because of the joint contractures in children with AMC, a proper muscle strength assessment may does not always be possible. The children with AMC, however, are reported to often be strong in the midrange of their joint motion [34]. This position could be achieved in all children in the present studies. In addition, a great effort was made to ensure a valid muscle strength measurement throughout each child's possible range of motion.

4.1.3 Orthopaedic surgical history

In the total study population of 40 children with AMC, hip surgery has been performed in 33%, knee surgery in 33%, and foot/ankle surgery in 73%. Spine surgery has been performed in two children.

In Study III, investigating gait dynamics, there was no difference in number of lower limb surgery procedures between the AMC groups. Despite various level of functional ambulation there were, thus, similar amount of performed orthopaedic surgery in the groups.

In Study IV, 29 of the 33 children had undergone orthopaedic surgery in lower limbs or spine surgery. The total number of lower limb orthopaedic surgical procedures were 127 with an average of 4.4 procedures in each child (range 1-10). Two previous studies reported an average of 4.3 and 5.7 procedures, respectively, including procedures of both lower and upper limbs [31, 63]. In this thesis, performed upper limb surgery was not documented.

In the Non-Ort group, significantly fewer procedures had been performed in the ankle joints than in both Ort-D and Ort-ND groups. There were no other differences in performed orthopaedic surgery procedures that could be related to perceived HRQoL.

4.2 Ambulation

When reporting functional ambulation in children with AMC, the predominantly used classification is a four-level classification [46]. We instead assessed the functional ambulation with a five-level classification modified from Hoffer [76]. This five-level scale discriminates between those who are community ambulators; with no need for wheelchair (Level I) and those who use wheelchair for long distances outdoors (Level II).

Functional ambulation, i.e. ability to walk with or without orthoses ranged from Level I to III in the study population. Most of the children in the studies had achieved community ambulation wherein children who used orthoses often used a wheelchair for longer distances outdoors. Those with KAFOs with locked knee joints were designated to Level III. This is in accordance with previous reported results that severe lower limb involvements decrease the ambulatory level [29, 30, 46]. The children in Group 1/AMC1/Ort-D had no walking ability without orthoses, however they obtained walking with adequate orthotic support. Two children used walking aids, one child in Study I (Group 1) at the school yard to prevent injuries, and one child in Study IV (Ort-D) used a rollator. Distribution of functional ambulation in groups and studies are shown in Table 3.

Table 3. Distribution of functional ambulation level in Study I – IV

	Study I	Study II	Study III	Study IV
Level I	2	11	11	13
Level II	8	8	8	11
Level III	5	5	7	9

Level I: community ambulators with no need for a wheelchair, Level II: community ambulators who require a wheelchair for long distances outdoors only, Level III: household ambulators and wheelchairs-users outdoors and long distances indoors.

4.3 Mobility and self-care

Thirty-three parents were interviewed about their child's functional capabilities in mobility and self-care with the Pediatric Evaluation of Disability Inventory (PEDI). Ort-D had lower functional mobility than Ort-ND. There was no significant differences between the groups in self-care. The range in the results of self-care were large within each group, which could be attributable to the presence of upper limb involvement in all groups. The functional skills in mobility and self-care were scored either as 'unable or limited capability to perform the item in most situations' or as 'capable of performing item in most situations' [77]. Children with AMC often develop compensatory strategies and they are therefore often capable to perform the item in their own way [34].

4.4 Walking

4.4.1 Gait pattern

In Study I, gait was recorded with 3D gait analysis while the children walked with their habitual orthoses or shoes. Children with AMC were found to have a heterogeneous gait pattern even if similarities were found in some of the gait parameters, particularly in Group 3. Group 1 had approximately three times greater range of trunk lateral sway and trunk rotation than Group 2 and Group 3 (Figure 4). Similar results of trunk lateral sway in AMC has later been reported in two other studies, but in contrast to our study, the children in those studies walked barefoot [65, 66]. The range of knee flexion/extension was significantly lower in Group 1 than in the other groups, which is a consequence of walking with KAFO-LK (Figure 5).

Figure 4. Range of trunk lateral sway (mean, SD) in AMC groups (Study I)

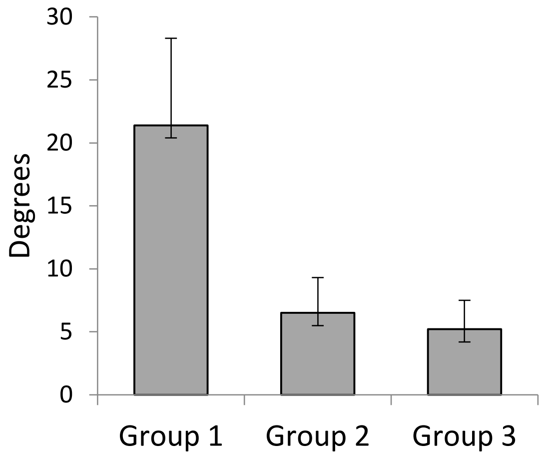
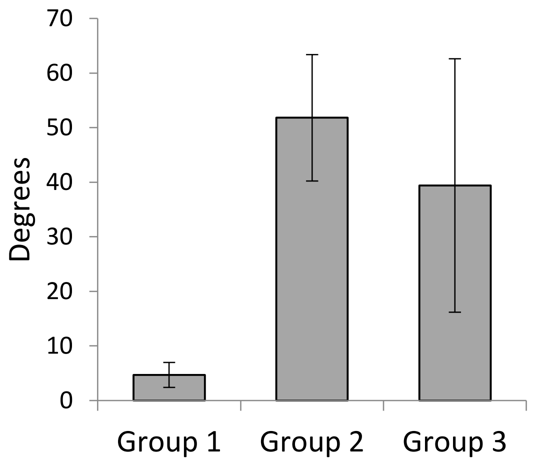


Figure 5. Range of knee flexion/extension (mean, SD) in AMC groups (Study I)

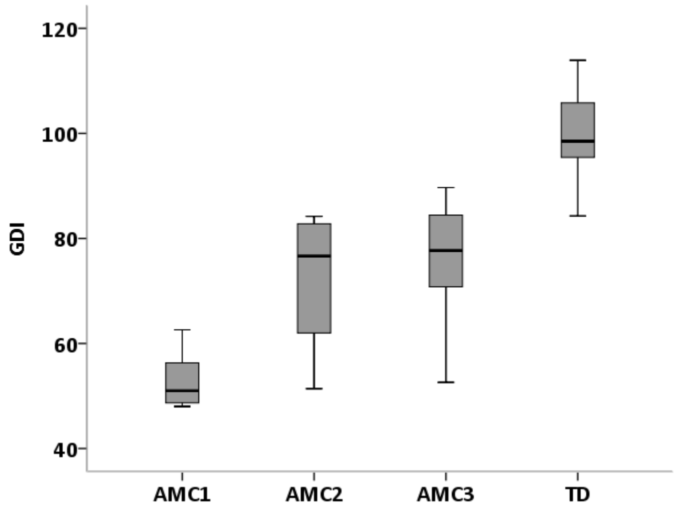


4.4.2 Gait pattern, joint moments and joint mechanical work

In Study III, gait dynamics, including gait pattern, joint moments and joint mechanical work was studied. Twenty-six children with AMC and a control group of 37 TD children participated. The children with AMC walked with their habitual orthoses or shoes.

As analyzed with GDI of the most affected limb, gait in children with AMC deviated significantly from that of TD children. The lowest GDI score was found in AMC1, whereas AMC2 and AMC3 had similar GDI scores (Figure 6). GDI describes the gait deviations of pelvis and lower limb joints without including the trunk movements [97]. Since large trunk movements are characteristic in children with AMC, an assessment excluding those, cannot fully describe their gait deviations. However, in this work the GDI was primarily used to define the most deviating limb for statistical purpose.

Figure 6. Gait Deviation Index (median, range) in AMC groups and TD children



The results from Study I of significantly greater trunk lateral sway and trunk rotation in children walking with locked KAFOs (AMC1) were likewise found in Study III. Unlike in Study I, significantly greater trunk lateral sway and trunk rotation were also found in AMC2 than in AMC3 and TD children (Figure 7 and 8). One possible reason of this finding could have been inclusion of new AMC2 participants in Study III. There were no other clear indications such as differences in step length, muscle strength nor in age that could explain this result.

In a group of children with AMC walking barefoot, the gait pattern with excessive trunk movements in the frontal plane was proposed to be a compensatory movement for hip abductor weakness [65], as has been previously described in children with myelomeningocele [98]. In the present Study III group, only three children had hip abductor weakness of grade 3 or less, of which two children were found in AMC1 and one child in AMC2. Furthermore, there was no significant difference between the groups in average hip abduction moment during stance, despite excessive trunk lateral sway (Figure 9). Boehm et al. reported a correlation between hip flexor weakness and excessive trunk lateral sway and suggested it to enable foot clearance during the swing phase [66], which has been previously described in biomechanical literature [99]. In the present work, hip flexion weakness of grade 3 or less was found in 3/5 children in AMC1. In accordance with previous authors, the interpretation of the present results is that excessive trunk lateral sway and trunk rotation in AMC1 helped to advance the limb during the swing phase and to propel the body forward.

Fig 7. Range of trunk lateral sway (median, range) in AMC groups and in TD children (Study III).

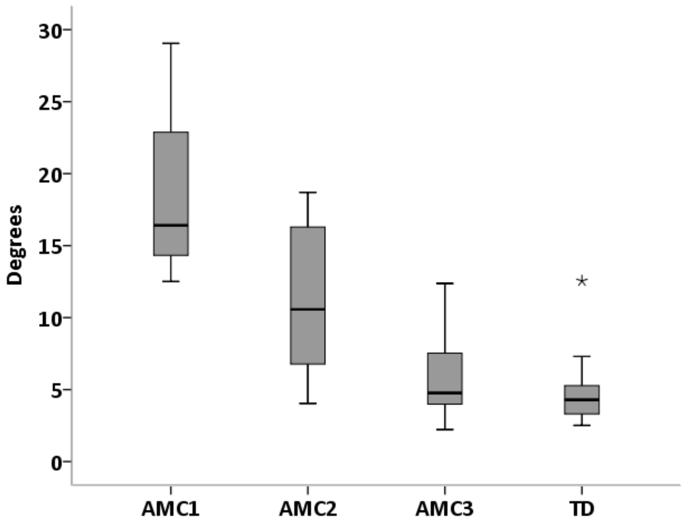


Figure 8. Range of trunk rotation (median, range) in AMC groups and in TD children (Study III).

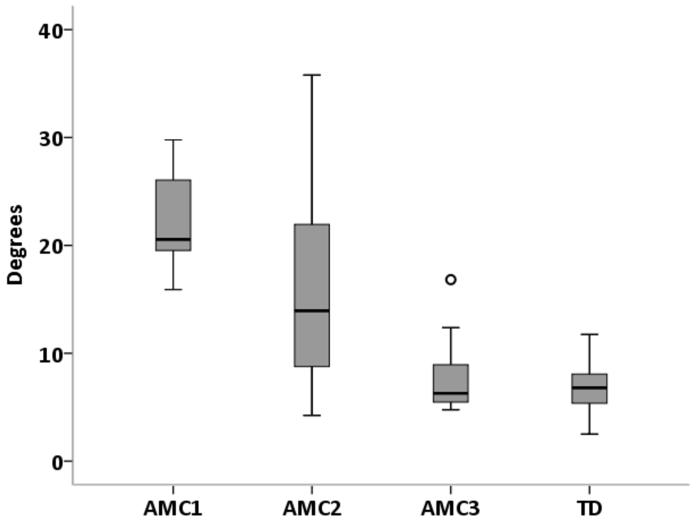
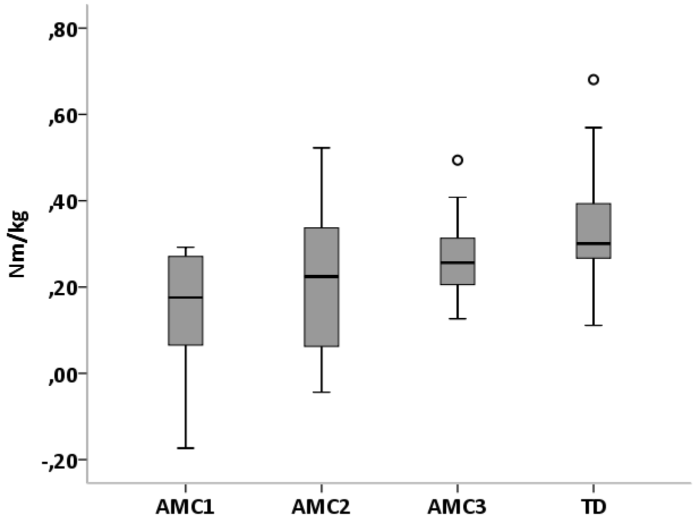


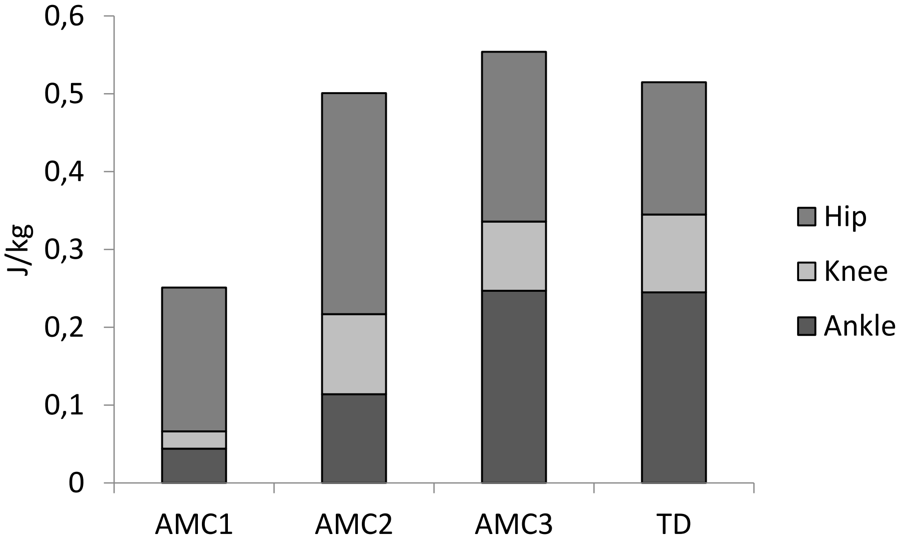
Fig 9. Average hip abduction moment during stance (median, range) in AMC groups and TD children.



In the sagittal plane, compared to the TD children, AMC1 had significantly less hip flexion moments, which was probably related to hip flexion contractures and reduced hip extensor strength in two of the children. In AMC1 and AMC2, the orthoses were able to provide plantarflexion moment, though less than in TD children. The plantarflexion moment in AMC3 was similar to TD children, which confirms no necessity of external stability of the ankle joint.

In normal walking, the ankle joint contributes to approximately 50% of the positive work [98, 100]. Orthoses were used in children with plantarflexor weakness to stabilize the ankle joint, which prevented the ankle from doing much positive work. This was compensated in AMC1 and AMC2 with a greater positive work done by the hip joint than was possible from the ankle (Figure 10). Similar results has been described in children with low lumbar myelomeningocele with plantarflexor weakness during walking with orthoses [98].

Fig 10. Positive work (median) in hip, knee and ankle joint in AMC groups and TD



4.4.4 Time and distance parameters

In both Study I and III, step length was similar between all groups despite the wide range of contractures and muscle strength between the groups. This finding may be attributable to good hip extensor strength in most of the participants. Of the children using both AFOs and KAFOs, 8/12 in Study I and 6/15 in Study III, had carbon fiber ankle joints, which probably contributed to the increased stride length, as reported in previous study [72]. In Study I, the walking speed differed significantly between the groups with the lowest in Group 1, and Group 2 walking slightly faster than Group 3. In Study III, AMC1 had somewhat lower N walking speed than the other groups, but without significant difference between the groups.

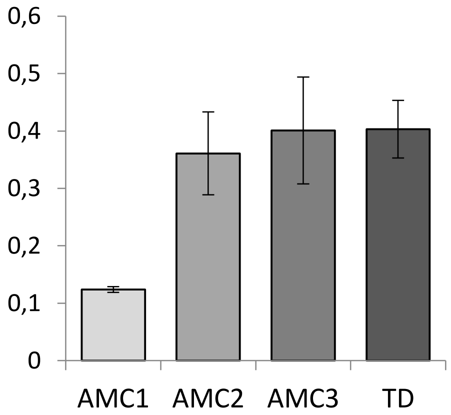
4.5 Energy effort

4.5.1 O_2-walking test

In Study II, energy effort was evaluated in twenty-two children with AMC and in twenty-five TD children with a similar age. All children were able to fulfill the O_2-walking test of 5 minutes.

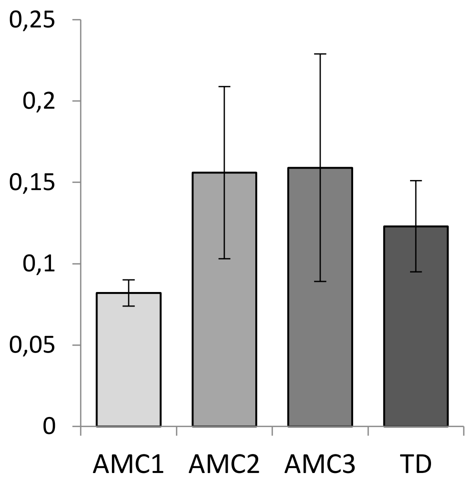
When comparing results from the O_2-walking test between AMC2, AMC3 and TD children the only significant difference was found in NNcost, which was higher in AMC2 than in TD children. We did not include AMC1 in the statistical analysis since there were only three participants. AMC2 and AMC3 walked with similar speed as TD children, and AMC1 had the slowest walking speed of all groups (Figure 11).

Figure 11. N walking velocity (mean, SD) in AMC groups and TD children (note: AMC1 were not included in statistical analysis).



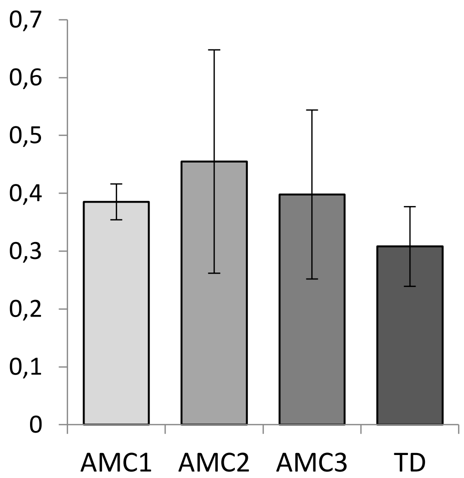
A linear relationship between oxygen consumption and walking speed has been described: when the walking speed increases the oxygen consumption will increase [101]. AMC1 had the lowest NNconsumption of all groups including TD children (Figure 12). A faster speed probably had increased the NNconsumption, so slowing down the walking speed may be a strategy to avoid exertion. In AMC2 and AMC3 NNconsumption was somewhat higher compared to TD children, though not significantly. Slightly reduction of the walking speed may have resulted in similar oxygen consumption. The ability to modify gait speed as done in AMC1 may also be attributable to age maturation, as compared to AMC2 and AMC3 who were of substantially younger ages.

Figure 12. NN consumption (mean, SD) in AMC groups and TD children (note: AMC1 were not included in statistical analysis).



Oxygen cost is the ratio of oxygen consumption and walking speed and is often used as a measure of gait efficiency [80]. NNcost was highest in AMC2 compared to TD children, which cannot be fully explained. From the kinematic data we know that some children in this group had excessive trunk and pelvic rotation, which has been described to increase the energy cost [99]. All AMC groups showed higher NNcost than TD children and thereby a less efficient gait (Figure 13). The gait pattern in AMC, particularly in those walking with orthoses led us to expect a greater difference in both oxygen consumption and oxygen cost compared to TD children, which could not be confirmed.

Figure 13. NNcost (mean, SD) in AMC groups and in TD (note: AMC1 were not included in statistical analysis).

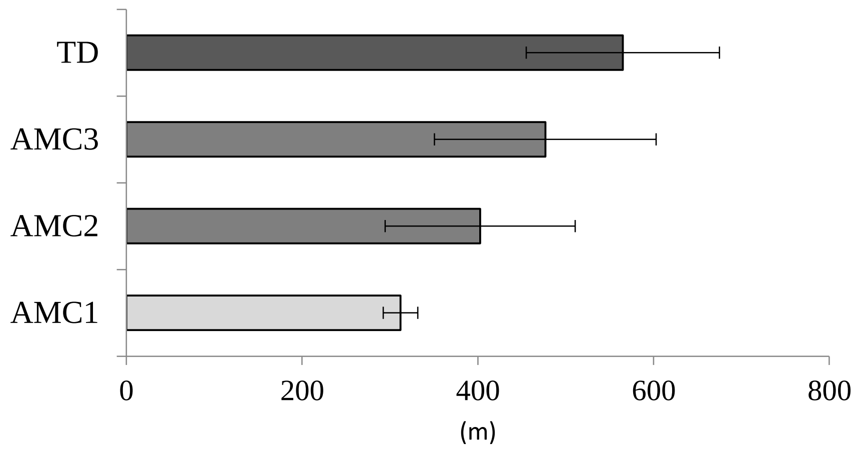


4.5.2 Functional exercise capacity

Functional exercise capacity were evaluated with the 6MWT in twenty-four children with AMC and in twenty-five TD children in a similar age. All children were able to fulfill the walking test during 6 minutes.

Children with AMC walked significantly shorter distance than TD children (Figure 14). AMC1 walked a shorter distance than the other groups, but this group of only three children was excluded from the statistical analysis. Even though values were not normalized, the results may express variations in exercise capacity between AMC2, AMC3 and TD children as these groups were of similar ages. This finding may explain that children with AMC are reported to need a wheelchair for efficient ambulation and to keeping up with peers [34].

Figure 14. Walked distance in the 6MWT (mean, SD) in AMC groups and in TD children (note: AMC1 were not included in statistical analysis).

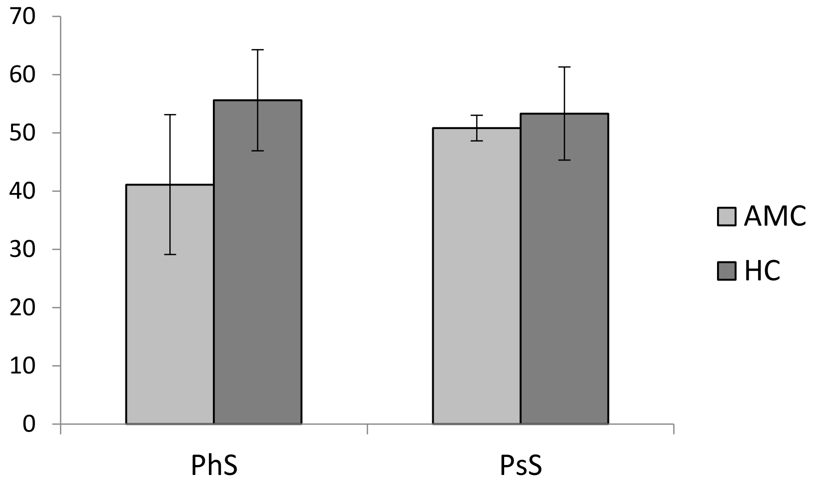


4.6 Perception of health-related quality of life

4.6.1 Parents perception of their children's health

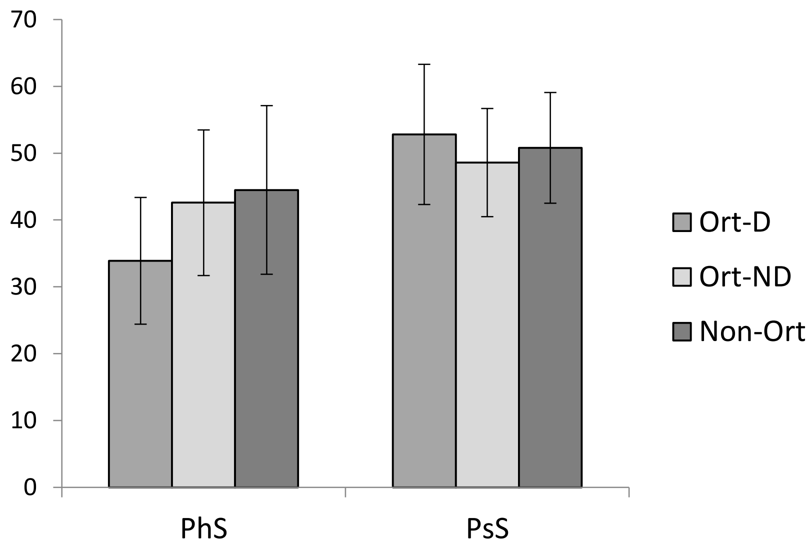
The parents' perception of their children's health was reported with the CHQ-PF. Parents of 33 children filled in the questionnaire. The results were compared to a Swedish reference group of 60 healthy controls (HC). Children with AMC had significantly lower CHQ scores in nine of 12 subscales compared to HC. The physical summary score (PhS) was significantly reduced in children with AMC compared to HC. The children with AMC did not differ from that of HC in the Psychosocial summary score (PsS), which indicates that psychosocial health in children with AMC are similar to that of healthy children (Figure 15).

Figure 15. Physical summary score (PhS) and psychosocial summary score (PsS) in AMC and healthy controls (HC) (mean, SD).



When comparing all groups, a significant difference was found in physical functioning (PF) with significant lower CHQ score in Ort-D, compared to Ort-ND and Non-Ort. In the physical summary score (PhS), Ort-D had slightly lower than Ort-ND and Non-Ort, but not significantly. The psychosocial summary score (PsS) did not differ between the groups (Figure 16). In this study group, joint contractures and performed orthopaedic surgery did not show any negative impact on the children's psychosocial health. Factors such as muscle strength, orthoses use and deviation in gait pattern are likely to have influenced differences between the groups in the physical functioning domain.

Figure 16. Physical summary score (PhS) and psychosocial summary score (PsS) in AMC orthoses groups (mean, SD).



4.6.2 The children's perception of health

The EQ-5D-Y was answered by 22 children in the age of eight years and older. When assessing EQ-5D-Y, all children using orthoses were grouped as Ort for statistical reasons, since the group numbers were too small to make between-group analyses. The Ort-group did not report more problems in any of the five dimensions than the Non-Ort group. The EQ-5D VAS scoring did not differ between Ort and Non-Ort.

When identifying the health profiles, both groups scored 'no problems' in all dimensions to the same extent (11111) (Table 4). Five children walked with orthoses with locked knee joints, of which three reported 'no problems' and two reported 'some problems'. This may surprise since walking with locked knee joints can be assumed to cause problem with mobility. As those children were totally dependent on orthoses for walking, they may not have experienced their orthoses use as negatively. The children with more severe upper limb involvement, both Ort and Non-Ort, reported more frequently problems in 'looking after myself' and 'doing usual activities', since everyday tasks usually requires adequate hand function as also reported previously [67].

Table 4. Percentage and number of children by reported health profiles, in groups Ort and Non-Ort.

EQ-5D-Y health profile	Ort n=10 %	n	Non-Ort n=12 %	n
11111	18.2	4	18.2	4
12111	4.5	1	9.1	2
21211	4.5	1	4.5	1
21221			9.1	2
11121	4.5	1		
11232	4.5	1		
21122	4.5	1		
13111	4.5	1		
11221			4.5	1
11122			4.5	1
21112			4.5	1

A health profile of 11232 represents 'no problems' in the dimensions 'mobility (walking about') and 'looking after myself', 'some problems' in the dimensions 'doing usual activities' and 'feeling worried, sad or unhappy', and 'a lot of problems' in the dimension 'having pain or discomfort'.

Six children reported 'some problems' with 'mobility' of those four were found in the Non-Ort group, and two in the Ort group, both dependent on orthoses for walking. None of the children using orthoses, however, did report 'a lot of problem' with mobility. As reported by the parents, the lowest physical functioning (PF) score was found in those who were dependent on orthoses for walking.

Bodily pain (BP) were similar in the AMC orthoses groups when reported by the parents. In the EQ-5D-Y dimension 'having pain or discomfort', the reported frequency reported by the children were similar between the Ort and Non-Ort groups. Agreement has been found to be greater between the child and parent in domains of physical function and less in emotional and social domains [102]. Moreover, in which way the children perceive their own walking ability and how they interpret the various questions must be further explored for better understanding of the children's perspectives.

4.7 Orthoses satisfaction

Quebec User Evaluation of Satisfaction with assistive Technology (QUEST 2.0) was used to evaluate satisfaction with the children's orthoses in 18 children. The children answered the questionnaire together with their parents. When giving a total score of the orthotic device subscale, Ort-D showed lower median score than Ort-ND indicating less satisfaction in general. Specifically, Ort-D was less satisfied with orthosis weight than Ort-ND, which was the only item that differed significantly between the groups. In the total score of the service subscale, both groups were very satisfied.

The child was given an opportunity to choose the three most important items of the 12 QUEST satisfaction items. Ort-D chose 'comfort' as the most important followed by 'safety' and 'easy to use'. Ort-ND chose 'easy to use' and 'comfort' as the most important followed by 'effectiveness' (Table 5).

Table 5. Distribution of the most important items in Ort-D and Ort-ND.

QUEST items	Ort-D (n=9) % (numbers of response)	Ort-ND (n=9) % (numbers of response)
1. Dimension	0 (0)	7.4 (2)
2. Weight	3.7 (1)	7.4 (2)
3. Adjustment	7.4 (2)	0 (0)
4. Safety	18.5 (5)	7.4 (2)
5. Durability	3.7 (1)	0 (0)
6. Easy to use	14.8 (4)	22.2 (6)
7. Comfort	22.2 (6)	22.2 (6)
8. Effectiveness	11.1 (3)	14.8 (4)
9. Service/delivery	3.7 (1)	3.7 (1)
10. Repairs/sevicing	3.7 (1)	3.7 (1)
11. Professional service	11.1 (3)	7.4 (2)
12. Follow-up service	0 (0)	3.7 (1)

Staheli summarized important characteristics for orthoses used for walking in children with AMC: they should be lightweight, durable, easily applied and removed, and comfortable [7]. In a study comparing two different orthoses for children with cerebral palsy with use of the Orthotics and Prosthetics User Survey (OPUS), answered by the parents on behalf of the children, important factors with the orthoses were weight, comfort, and ease of use [103]. In the present study, Ort-D chose safety as the second most important item, which confirms the intention of orthotic management to construct orthoses to guarantying security during walking. A further explanation may be the importance of feeling safe in those who are dependent on orthoses for walking, since children with upper limb involvement may have difficulties to protect themselves in case of falling, which has been described [34].

4.8 Methodological considerations and limitations

AMC is a heterogeneous condition [4], thus children both using orthoses and children walking independently without orthoses were included in the studies. Due to the different conditions, the participants in Study I–IV were designated to three orthosis groups. Choosing this approach of grouping the children in this thesis, may be questioned. Children in AMC2 were able to walk using both KAFOs with open knee joints and AFOs. This may have been influenced by the childrens' and parents' opinion. The prescription of the orthoses may also have been based on different standpoints as well as the choice between prescribing shoes only or AFOs. This method, however, was found to be the most relevant way of grouping children, considering the orthoses to influence the children's ambulation and mobility most significantly.

AMC is a rare condition [4] and the number of participants were therefore consequently relatively few. When dividing the participants into small groups the statistical analysis should be considered as a limitation. We therefore chose to exclude one group with only three participants of the statistical analysis in Study II.

The clinical examinations were performed by the same physiotherapist in each of the studies to get as accurate data as possible of joint range of motion and muscle strength.

Avoiding measurement errors during marker placement is important in 3D gait analysis and could be minimized with few and well-trained assessors [104, 105]. In both studies using 3D gait analysis, the markers were placed by the same person.

Walking is a bilateral activity including two limbs, however, when gait analysis data is presented, one side is usually chosen. In Study I, the most involved side with respect to less muscle strength and/or greater contracture was selected. In Study III, the side with the lowest Gait Deviation Index was chosen for presentation. In both studies there were no statistical difference between the left and right side.

Measuring oxygen consumption when evaluating physical effort and gait efficiency is a valid and reliable method in children with disabilities [81]. The net nondimensional scheme was chosen for normalization of the oxygen data. The net energy cost has been found to be less reproducible than gross values, which can be improved by a standardized study protocol [106, 107, 108].

When measuring energy effort and functional exercise capacity, a walking test of longer duration could probably have discriminated more between the groups. The tests were performed during 5 minutes (O_2-walking test) and 6 minutes (6MWT) respectively. A longer test, on the other hand, may have reduced the study group since endurance has been found to be limited in children with AMC [64].

In the parents' perception of their children's health (CHQ-PF50), reference values from a Swedish healthy control group published in 2001 were used [85]. Today, nearly 15 years later, healthy control children may perceive health differently. An important work for the future will therefore be to update control reference values when reporting HRQoL in children with disabilities.

When reporting the children's perception of their health (EQ-5D-Y), there is a lack of a Swedish control group as reference values [67]. The statistical analysis could therefore be performed only between the AMC groups. Establishing Swedish norm values would provide opportunity to increase our knowledge of the health status in children with disabilities, in particular when reporting by the children themselves.

When investigating HRQoL in children, proxy-reported questionnaires are often used. Recommendations have been made to obtain information from both parents and children [102]. In Study IV, when investigating HRQoL, our intention was to be able to capture the child's opinion. The optimum had been to use the child version of Child Health Questionnaire (CHQ-CF87) [84], although long questionnaires should be avoided in young children [109]. Since the CHQ-CF87 consists of 87 items, we considered it too time-consuming for use in children. We instead chose the EQ-5D-Y which has been found to capture health status in children with functional disabilities [67].

QUEST 2.0 has not yet been validated for use in children, however, the previous version of QUEST has been used in two studies in which the parents answered on behalf of the children [110, 111]. In Study IV, an initially performed pilot study with eight children who all had experience with orthosis use, resulted in some modifications how to explain the QUEST items to the parents, and in particular to the children. QUEST 2.0 measures satisfaction with assistive technology which is a broad area, including orthoses and prostheses but also wheelchairs, walking aids and aids for personal care [92]. An instrument measuring only satisfaction with orthoses and prosthesis would have been suitable and in recent years a Swedish version of the Orthotic and Prosthetic User Survey (OPUS) has been developed [112]. An instrument to be answered by the children themselves, remains to be developed.

4.9 Conclusion

Gait pattern, energy effort, functional exercise capacity, health-related quality of life and satisfaction with orthoses were studied in a group of children with AMC.

Gait patterns with habitual orthoses or shoes, were evaluated with 3D gait analysis. The children were divided into three groups according to orthoses use. The kinematic data illustrated differences among the groups in trunk and knee kinematics, and in walking speed. In the children requiring locked knee joints, the greatest trunk movements and least knee flexion were observed. The step length was similar among the groups, which may be attributable to good hip extensor strength in all participants. Energy effort and functional exercise capacity were compared to a control group of TD children. The children with AMC walked with their habitual orthoses, ranging from KAFOs with locked knee joints to AFOs, and to shoes. When walking at a self-selected speed, energy effort was higher in children walking with KAFOs with open knee joints or AFOs, and in children walking with only shoes than in TD children. The children walking with open KAFOs or AFOs had significantly higher net nondimensional cost than TD children, which indicates a less efficient gait in this group. Children walking with locked KAFOs had the lowest nondimesionalized walking speed of all groups. During the functional exercise capacity test in the 6MWT, all AMC groups walked a shorter distance than the TD children.

Gait pattern, joint moments, and joint mechanical work were evaluated with 3D gait analysis and compared to a control group of TD children. Children with AMC walking with orthoses showed greater trunk movements in the frontal and transverse planes than AMC children walking with shoes and TD children. The generating work around the joints demonstrates the children reliance on hip and trunk muscles to provide propulsion, especially in those walking with orthoses.

HRQoL was investigated with two questionnaires. As reported by the parents, children with AMC had lower physical HRQoL than a Swedish reference group of children, indicating that muscle weakness, orthoses use and deviation in gait pattern may have an impact on physical health. As reported by the children, EQ-5D-Y did not indicate any difference between children using orthoses or not using orthoses. Perceived overall satisfaction with their orthoses asreported with QUEST 2.0 was high, but importance of specific items were chosen slightly differently.

Children with AMC have the potential to achieve functional ambulation through customized orthopaedic treatment and adequate orthotic solutions but gait pattern and energy effort will vary depending on the child’s clinical conditions and need for joint stabilization.

In the future, walking for children with AMC should be further explored in order to establish criteria for use when prescribing orthoses.

A questionnaire specifically developed for children to capture their opinions about their orthoses should also be developed.

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