Gait & Posture 46 (2016) 104–111

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

An individual approach for optimizing ankle-foot orthoses to improve mobility in children with spastic cerebral palsy walking with excessive knee flexion

Yvette L. Kerkum [a,*], Jaap Harlaar [a], Annemieke I. Buizer [a], Josien C. van den Noort [a], Jules G. Becher [a], Merel-Anne Brehm [a,b]

[a] Department of Rehabilitation Medicine, MOVE Research Institute Amsterdam, VU University Medical Center, Amsterdam, The Netherlands
[b] Department of Rehabilitation, Academic Medical Center, University of Amsterdam, Amsterdam, The Netherlands

ARTICLE INFO

Article history:
Received 27 October 2015
Received in revised form 4 February 2016
Accepted 2 March 2016

Keywords:
Lower limb orthotics
Gait efficiency
Gait biomechanics
Daily walking activity

ABSTRACT

Ankle-Foot Orthoses (AFOs) are commonly prescribed to promote gait in children with cerebral palsy (CP). The AFO prescription process is however largely dependent on clinical experience, resulting in confusing results regarding treatment efficacy. To maximize efficacy, the AFO's mechanical properties should be tuned to the patient's underlying impairments. This study aimed to investigate whether the efficacy of a ventral shell AFO (vAFO) to reduce knee flexion and walking energy cost could be improved by individually optimizing AFO stiffness in children with CP walking with excessive knee flexion. Secondarily, the effect of the optimized vAFO on daily walking activity was investigated. Fifteen children with spastic CP were prescribed with a hinged vAFO with adjustable stiffness. Effects of a rigid, stiff, and flexible setting on knee angle and the net energy cost (EC) [J kg^{-1} m^{-1}] were assessed to individually select the optimal stiffness. After three months, net EC, daily walking activity [strides min^{-1}] and knee angle [deg] while walking with the optimized vAFO were compared to walking with shoes-only. A near significant 9% ($p = 0.077$) decrease in net EC (−0.5 J kg^{-1} m^{-1}) was found for walking with the optimized vAFO compared to shoes-only. Daily activity remained unchanged. Knee flexion in stance was reduced by 2.4° ($p = 0.006$). These results show that children with CP who walk with excessive knee flexion show a small, but significant reduction of knee flexion in stance as a result of wearing individually optimized vAFOs. Data suggest that this also improves gait efficiency for which an individual approach to AFO prescription is emphasized.

1. Introduction

Children with cerebral palsy (CP) have a wide variety of motor impairments (e.g. spasticity and muscle weakness), often resulting in gait deviations, such as excessive knee flexion in stance. The gait pattern of children who walk with excessive knee flexion is prone to deteriorate, as it is associated with the development of knee flexion contractures [1] and elevated walking energy cost levels, reflecting poor gait efficiency [2]. Interventions in these children therefore primarily aim to reduce knee flexion to prevent deterioration, which could improve gait efficiency [3] and walking activity in daily life.

A rigid ventral shell Ankle-Foot Orthosis (vAFO) is a commonly applied intervention in children with CP walking with excessive knee flexion to reduce knee flexion [4] in stance and improve gait efficiency [3,5]. Despite the frequent use of vAFOs in CP, the prescription process of these orthoses is currently largely dependent on clinical experience, and prescription guidelines are scarce [6]. Considering the diversity in underlying impairments within CP, the varying effects of AFOs on gait efficiency as reported in the literature [3,5] might be partly explained by an inadequate match between the patient's impairments and the vAFO's mechanical properties, including its ankle stiffness [7,8].

To maximize treatment outcome, an AFO is designed to improve the most important deviation in gait biomechanics, while adverse effects on other gait features should be minimized. A rigid vAFO for example, primarily aims to counteract excessive knee flexion during stance, which has been associated with gait efficiency improvements [3]. The vAFO's properties however also obstruct ankle range of motion, therewith impeding ankle push-off power and negatively impacting gait efficiency [9,10]. Applying a more compliant, spring-like vAFO may enhance push-off power

* Corresponding author at: Department of Rehabilitation Medicine, VU University Medical Center, PO Box 7057, 1007 MB Amsterdam, The Netherlands.
Tel.: +31 20 4443062; fax: +31 20 4440787.
E-mail address: yvettekerkum@gmail.com (Y.L. Kerkum).

http://dx.doi.org/10.1016/j.gaitpost.2016.03.001
0966-6362/

and subsequent gait efficiency [7,11], while ideally still counteracting excessive knee flexion. The optimal AFO stiffness that will maximally enhance gait efficiency may rely on a trade-off between counteracting knee flexion during stance, and preserving remaining push-off power [12].

As the aforementioned trade-off is expected to be primarily dependent on the patient's specific underlying impairments, an individual optimization of AFO stiffness seems essential to maximize treatment outcome [8]. Such an optimization requires an extensive evaluation of the effects of AFOs on multiple gait-related outcomes [13]. Brehm et al. [14] suggested a core set of outcome measures for studies on lower limb orthoses, covering all levels of the International Classification of Functioning, Disability and Health (ICF) framework. Such a core set is also useful for the process of AFO stiffness optimization, and includes outcomes quantifying the AFO's effect on gait biomechanics, gait efficiency and daily walking activity [14,15]. In this context, we tested the hypothesis that the efficacy of vAFOs to reduce knee flexion and improve gait efficiency in children with CP who walk with knee flexion in stance can be improved by individually tuning the mechanical properties of the vAFO, i.e. optimizing the AFO stiffness to the underlying impairments of the patient. Secondarily, we investigated whether this stiffness-optimized vAFO would also improve daily walking activity in these children.

2. Methods

2.1. Study design

We performed a pre-post experimental study (AFO-CP study [13]; Dutch National Trial Register No. NTR3418), consisting of two repeated measurements; at baseline (T0), walking with shoes only, and at 12–20 weeks follow-up (T2), walking with the optimized vAFO. Additional measurements were performed to provide data for the optimal AFO stiffness selection (T1). T1 consisted of a period of 3 months (starting directly after T0), in which children wore three different AFO stiffness levels (i.e. rigid, stiff and flexible, applied in random order) for four weeks each.

Institutional review board approvals were obtained prior to the start of the study and all measurements were performed in accordance to the Declaration of Helsinki. Parents of all participants and participants above 12 years old provided written informed consent.

2.2. Participants

Children diagnosed with spastic CP who were indicated for a new AFO were recruited from the rehabilitation department of a university medical center, and two affiliated rehabilitation centers. Children could be included in the study when they were 6–14 years old, classified with a Gross Motor Function Classification System [16] level I, II or III, and presented a barefoot gait pattern that was characterized by excessive knee flexion in stance (i.e. $>10^{\circ}$ knee flexion at midstance). Children were excluded if they had hip and/or knee flexion contractures of $>10^{\circ}$, as these have been shown to impede the effect of vAFOs [4].

2.3. Intervention

For shoes-only measurements, participants wore their own shoes. Children were prescribed with a vAFO with a full-length stiff footplate, which were worn in sneakers with flat flexible soles. The vAFOs were made out of pre-preg carbon fibers and manufactured with an integrated hinge (Neuro Swing®, Fior&Gentz, Germany). Different springs can be inserted into this hinge, allowing the AFO's mechanical properties to be varied, such as the AFO stiffness [12]. For each participant, the hinge was randomly set into three stiffness configurations (i.e. rigid, stiff and flexible), and the effects of each configuration on gait were evaluated (see Appendix A for the detailed protocol). After this, the optimal AFO stiffness was selected (T1) according to a predefined decision scheme (Appendix A), which was based on ranking the vAFO's effect on knee extension (KE) and, in addition, on gait efficiency (i.e. walking energy cost). Outcome was assessed after three months of wearing the optimized vAFO.

2.4. Outcomes

The primary outcome in our study was walking energy cost. Secondary outcomes included daily walking activity, knee angle and ankle power. Additionally, compliance to the optimized vAFO was measured. Extensive descriptions of these outcomes are described elsewhere [13].

Walking energy cost was assessed with a 6-min rest test, followed by a 6-min walk test at comfortable speed on a 40-m indoor oval track. During the rest tests and the walk test, breath-by-breath oxygen uptake (VO_2) and carbon dioxide production (VCO_2) values were recorded using a portable gas analysis system (Metamax 3B, Cortex Biophysik, Germany). Participants were instructed not to talk or laugh during the assessments.

Daily walking activity was assessed using the ankle-worn biaxial StepWatch™ Activity Monitor 3.0 (SAM) (Orthocare Innovations, USA), which registers accelerations of one leg in the frontal–sagittal plane. Children were asked to wear the SAM for seven consecutive days (five weekdays, two weekend days) during waking hours [17].

Gait biomechanics were assessed by 3D-gait analysis that was performed in a gait laboratory. Participants were instructed to walk on a 10 m-walkway with integrated force platform (OR6-5-1000, AMTI, USA) at comfortable speed. Technical marker clusters of three markers were rigidly attached to the body segments and anatomically calibrated by probing bony landmarks [18]. Segment movements were tracked using an optoelectronic motion capture system (Optotrak 3020, Northern Digital, Canada) and synchronized with the force plate data. Measurements were repeated until three successful steps of both legs were recorded (i.e. within the borders of the force plate).

Time of wearing the optimized vAFO [hours day^{-1}] was measured during the seven days that the SAM was worn, using a temperature-based monitor (the @monitor, Academic Medical Center, The Netherlands), which was mounted in the shell of the vAFO. This device has been shown to reliably assess the use of footwear and assistive devices [19].

2.5. Data processing

To calculate walking energy cost, breath-by-breath VO_2 and VCO_2 values from minute three to six of the rest and the walk test were used to determine the mean steady-state energy consumption values (ECSrest and ECSwalk). The mean walking speed [m min^{-1}] was measured over the same time frame of the walk test. Accordingly, the net energy cost (EC) [J kg^{-1} m^{-1}] was calculated as (*ECSwalk − ECSrest)/walking speed*. Net EC values were normalized to calculate the net non-dimensional energy cost [20], and the net non-dimensional energy cost as a percentage of speed-matched control cost (SMC-EC) [%].

Regarding the SAM, data were excluded from the analysis if (i) >3 h of data were missing within the time interval of being awake, and (ii) a day had less than eight hours of registration time. A minimum of three correctly recorded days was required to calculate the average daily stride rate. Daily stride rate was subdivided into stride rate levels, according to existing thresholds [21]: 0 strides min^{-1} (SR0), 1–15 strides min^{-1} (SR1-15), 16–30 strides min^{-1} (SR16-30), 31–60 strides min^{-1} (SR31-60), and >60 strides min^{-1} ($SR > 60$).