Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Neuromedicine and Movement Science

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The effect of orthotic alignment on gait kinematics in inclined and declined walking in children with cerebral palsy

Master's thesis in Human Movement Science
Supervisor: Karin Roeleveld
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Kunnskap for en bedre verden

Abstract

Introduction: Children with cerebral palsy (CP) experience different limitations in gait, in which ankle-foot-orthoses (AFO) are commonly used to improve gait function. Altering the heel-sole differential in an AFO-footwear combination has been found to affect gait kinematics such as ankle and knee angles, as well as temporal-spatial gait parameters such as stride length and walking speed. This method of tuning an AFO is easily done in a clinical setting. However, the clinical setting does not represent all aspects of daily living and community ambulation. Gait kinematics and temporal-spatial gait parameters have been found to be altered during inclined and declined walking, for both non-disabled and children with CP, as well as adults wearing AFOs. Nonetheless, evidence is lacking on how orthotic alignment affects inclined and declined walking.

Aim: The primary aim of this study is to describe the relationship between walking with AFO and gait kinematics in inclined and declined walking. The secondary aim is to investigate if orthotic alignment increasing symmetry differs between inclined and declined walking.

Methods: Seven children with spastic CP were included in this study (mean age 11 years old). They performed a 3D gait analysis walking on level ground, 7° incline and 7° decline, wearing a neutral AFO (AFOn) and an adjusted AFO (AFOa). The adjustment was done by adding a 5 mm heel wedge between the AFO and the shoe. Because of small n, statistical analyses were not performed. Results are described as differences between median values, to find clinical significant effects suitable for future research.

Results: During inclined walking, the affected leg (Aleg) had an increase in knee and hip flexion compared to level walking. Increased walking speed and increased forward trunk lean was also found during inclined walking compared to level walking. During declined walking, the Aleg had an increased ankle range-of-motion (ROM) and decreased hip and sagittal thoracic ROM compared to level walking. The AFOa increased symmetry in the ankle joint between Aleg and non-affected leg (NAleg) during both inclined and declined walking.

Discussion/conclusion: Adjusting the alignment of the AFO altered both kinematics and temporal-spatial gait parameters during inclined and declined walking, however increased symmetry was found with the AFOa for both inclinations. Future research should aim to recruit more participants to evaluate statistical significance, and include several alignment changes to ensure that observed differences are not coincidental.

Sammendrag

Introduksjon: Barn med cerebral parese (CP) opplever ulike begrensninger ved gange, hvor ankel-fot-ortoser (AFO) er et vanlig hjelpemiddel for å forbedre gangfunksjon. Endring av vinkelen mellom leggen og vertikalen kan gjøres ved å øke netto hælhøyde i en AFO-fottøykombinasjon, og er funnet å påvirke gangkinematikk som ankel- og knevinkel, i tillegg til temporal-spatiale gangparametre som steglengde og ganghastighet. Dette er en enkel måte å justere en AFO i en klinisk setting. Den kliniske settingen er imidlertid ikke representativ for alle aspekter ved hverdagslivet og forflytning i nærmiljøet. Gangkinematikk og temporal-spatiale gangparametre endres ved gange i oppover- og nedoverbakke, både for funksjonsfriske og barn med CP, i tillegg til voksne AFO-brukere. Likevel er forskningen rundt ortosealignment og dens påvirkning på gange i oppover- og nedoverbakke mangelfull.

Formål: Å beskrive forholdet mellom gange med AFO og gangkinematikk i gange i oppover- og nedoverbakke. Sekundærmålet med denne studien er å undersøk om ulikt ortosealignment kreves for å forbedre symmetri i oppover- og nedoverbakke.

Metode: Syv barn med spastisk CP deltok i studien (gjennomsnittsalder 11 år). De gjennomførte en 3D ganganalyse, hvor de gikk på flatt gulv og opp og ned en rampe med 7° helning. På rampen gikk de med nøytral AFO (AFOn) og justert AFO (AFOa). Justeringen var tillegget av en 5 mm hælkile mellom AFO og sko. På grunn av liten n ble ikke statistiske analyser gjennomført. Resultat beskrives som forskjell mellom medianverdier, for å finne klinisk signifikante sammenhenger som kan undersøkes nærmere i fremtidige studier.

Resultat: Ved gange oppover, hadde affisert ben (Aleg) økt fleksjon i kne og hofte sammenlignet med flatt underlag. Det ble også funnet økt ganghastighet og økt forovertilt av trunkus sammenlignet med flatt. Ved gange nedover hadde Aleg en økning i ankelens bevegelsesutslag (ROM), og redusert ROM i hofte og thorax i sagittalplanet sammenlignet med flatt underlag. AFOa bedret symmetrien i ankelleddet mellom Aleg og ikke-affisert ben (NAleg), både ved gange i oppover- og nedoverbakke.

Diskusjon/konklusjon: Justering av AFO-alignment endret både gangkinematikk og temporal-spatiale gangparametre i oppover- og nedoverbakke, og i begge tilfellene økte symmetrien med AFOa. Fremtidig forskning bør forsøke å rekruttere flere deltakere for vurdering av statistisk signifikans, og inkludere flere alignmentendringer for å sikre at observerte endringer ikke er tilfeldige.

Acknowledgements

First and foremost, I would like to express my deepest gratitude to my supervisor Karin Roeleveld for going above and beyond to guide me through the writing of this thesis. Without your unwavering support and understanding, I would not have been able to do this. I would also like to give a special thank you to Ane Øvrenæss for all the hours spent helping me with data processing.

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Additional thank you to everyone at Øya gait laboratory for your help and patience in training, which took more than a few hours.

Vera Kristine Heggenhougen, Stine Øverengen Trollebø and Roar Munkeby Fenne, my fellow students, thank you for making every day in the gait laboratory enjoyable. Vera, you have also given me so much support during this whole period. Stine, I greatly appreciate all the preparation you did, which eased the data collection period. Roar, you spent more hours than anyone could expect, helping us with our data collection. Thank you.

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Last, but not least, a special thank you to all the participants and their families for the time and effort they put into the data collection, making this project come true.

Abbreviations

CP - Cerebral Palsy

GMFCS - Gross Motor Function Classification Scale

AFO - Ankle-foot Orthosis

AFOn - AFO with neutral alignment

AFOa - AFO with adjusted alignment

ROM - Range of motion

IC - Initial contact

Aleg - Affected leg

NAleg - Non-affected leg

SVA - Shank-to-vertical angle

Table of Contents

1.0 Introduction

Cerebral palsy (CP) has a prevalence of over 2 per 1000 live births, being the largest diagnostic group in pediatric (re)habilitation clinics. Every case of CP has some form of motor impairment, and spasticity is the most common cause (Odding et al., 2006). In addition, primary abnormalities of the central nervous system such as loss of selective motor control and abnormal muscle tone, result in an inability to walk and run with normal movement patterns. This may in turn lead to secondary musculotendinous contractures, where the ankle and foot are more affected than more proximal joints (Novacheck, 2008, p. 487-488). Motor function is associated with everyday activities (Østensjø et al., 2004), and is commonly graded using the Gross Motor Function Classification System (GMFCS; Palisano et al. 1997), which ranges from I-V, where V is the most debilitating grade. In level I, children can walk without restrictions, and in level II without assistive devices but with limitations during outdoor walking (Palisano et al., 1997). Level I-IV can grossly be divided into either hemiplegia or diplegia (Nordmark et al., 2001), and presents with different gait patterns and gait deviations (Rodda & Graham, 2001).

Ankle-foot-orthoses (AFO) are orthotic devices used to improve gait in the presence of gait deviations (Aboutorabi et al., 2017). The biomechanical goal of an AFO is to control the motion and alignment of the foot and the ankle joint in order to reduce gait abnormalities in the ankle, knee and hip (NHS Quality Improvement Scotland, 2009, p. 41-42). AFOs have been found to increase dorsiflexion, knee and hip flexion at initial contact (IC) as well as increase walking speed (Lintanf et al., 2018; Nikamp et al., 2017), reducing common gait deviations seen in hemiplegic and diplegic gait (Rodda & Graham, 2001).

The shank-to-vertical angle (SVA), the angle between the tibia and the vertical in the sagittal plane, has an effect on the progression of the stance limb, as an inclination of the tibia allows the femur to also be inclined and the hip joint can progress forward without hyperextension of the knee (NHS Quality Improvement Scotland, 2009, p. 42). The SVA can be altered through a change of the heel-sole differential, and adding a five millimeter heel wedge has been found to increase the SVA in an AFO-footwear combination by 2° in adults (Meadows et al., 2008, p. 307). Such tuning of the AFO-footwear combination may often be necessary to optimize gait, and can easily be done in a clinical setting. Increasing the SVA by adding heel wedges has been found to alter kinematics of gait, resulting in increased dorsiflexion (Kerkum et al., 2015), knee flexion (Jagadamma et al., 2010; Kerkum et al., 2015), hip flexion (Kerkum et al.,

2015) and reduced knee hyperextension (Jagadamma et al., 2010). Temporal-spatial gait parameters have also been found to be affected by an addition of a heel wedge, such as increased stride length and walking speed (Jagadamma et al., 2010).

Gait kinematics during inclined and declined walking is different from level walking with increased dorsiflexion, knee and hip flexion during IC upslope and reduced hip flexion at IC downslope compared to level walking. The strategies used during inclined walking are necessary to raise the limb for toe clearance and heel strike, as well as lifting the body up the incline. During declined walking, changes are seen to achieve a controlled descent of the body. (Lay et al., 2006). Lay et al. (2006) presents an idea that the kinematic changes seen during inclined and declined walking are associated with muscle length changes. If that is true, one could expect different changes in children with spastic CP walking on sloped surfaces. However, previous studies have found the same kinematic changes in children with CP during inclined walking, as well as increased range of motion (ROM) in the ankle, knee and hip (Ma et al., 2019; Mélo et al., 2017; Stott et al., 2014; Topçuoğlu et al., 2018). During declined walking, the opposite has been found, that is increased plantarflexion, reduced knee and hip flexion in addition to decreased ROM in the ankle and hip, and increased ROM in the knee (Topçuoğlu et al., 2018). It has also been reported that stride length is decreased for inclined walking compared to level walking (Ma et al., 2019; Mélo et al., 2017; Topçuoğlu et al., 2018) and declined walking (Stott et al., 2014; Topçuoğlu et al., 2018) compared to level walking. There is no consensus on whether walking speed is altered during sloped walking. However, the similar patterns of change in gait kinematics does not imply that there are no gait abnormalities for children with CP during sloped walking. Compared to healthy children, children with CP adapt more plantarflexion and less knee flexion during declined walking (Topçuoğlu et al., 2018) and increased knee flexion and forward lean of the trunk during inclined walking (Stott et al., 2014). None of these studies have included the use of AFOs. Four studies investigating inclined and/or declined walking and the use of AFO has been identified, with study participants wearing AFOs due to limb-salvage (Haight et al., 2015), ankle osteoarthritis (Huang et al., 2006), stroke (Lewallen et al., 2010) and lower motor neuron pathology (Bautista, 2019). They have reported decreased ankle ROM (Haight et al., 2015; Huang et al., 2006), increased stride or step width (Bautista, 2019; Haight et al., 2015) and decreased walking speed (Bautista, 2019; Lewallen et al., 2010). However, other aspects of gait such as joint angles have either not been investigated or have not been found to differ between inclined and/or declined walking and level walking. Moreover, alignment of the AFO has not been investigated in this respect.

This study is a pilot study that aims to get more insight into how joint kinematics during inclined and declined walking differ from level walking kinematics while wearing an AFO, and methodological considerations that have to be taken into account when investigating this subject in future research. Provided information on how AFOs should be tuned to improve gait in all aspects of daily living, clinical orthotists can provide a broader evidence-based practice. The primary aim of this study is to describe the relationship between walking with AFO and gait kinematics in inclined and declined walking, with the hypothesis being that an AFO with increased SVA will enhance the kinematic patterns seen with a neutral AFO during inclined and declined walking. The secondary aim is to investigate if the orthotic alignment that enhances symmetry differs between inclined and declined walking, with the hypothesis being that different orthotic alignment is needed to enhance symmetry in inclined and declined walking.

2.0 Methods

2.1 Participants

Inclusion of participants were based on the following criteria:

- Aged between 7 to 17 years old at data collection
- Hemiplegic CP
- GMFCS I-III
- Able to walk without walking aids
- Having received an AFO
- Able to understand and follow verbal instruction

Participants meeting the inclusion criteria were recruited through Trøndelag Ortopediske Verksted. In total, 11 were eligible for participation, whereas two declined and one was not able to participate because of surgery.

2.2 Ethical considerations

Written and oral information about the project was provided to both participants and legal guardians, with the written information being available in three versions depending on the age of the participant. Before starting data collection, written consent was collected. Participants were informed that they could withdraw from the project at any time, without giving a reason. They received a gift card for their participation. The project was approved by the regional ethics committee (REK 2019/28777), and the university institute's privacy impact assessment. Data was stored on the NTNU server as well as HUNT cloud.

2.3 Data collection

A three hour test protocol was carried out in the NTNU gait laboratory at Campus Øya, with support from core facility NextMove. Only measurements relevant for this thesis are described here.

Following calibration of the system and anthropometric measurements, an instrumented 3D gait analysis with ten Vicon Vantage cameras (Vicon Motion Systems Ltd., Oxford, UK) was performed with spherical reflective markers positioned after the Vicon Plug-in-Gait lower body model. Three additional markers were placed at the spinous process of the seventh cervical vertebrae and both of the acromioclavicular joints. The gait analysis was carried out with the participants walking at self-selected speed under five conditions in the following order:

1. Level surface, shoes only
2. Level surface, AFOn
3. 7° inclined ramp, AFOn
4. 7° inclined ramp, AFOa
5. Level surface, AFOa

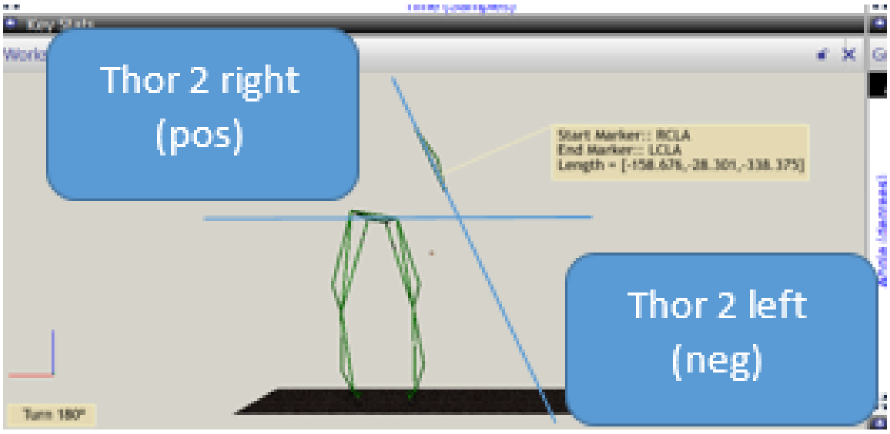
Only the latter four will be focused on in this study. The neutral AFO (AFOn) was adjusted by adding a 5 mm heel wedge between the shoe and the AFO for the adjusted AFO (AFOa). At the start of each condition, a static trial was completed.

Three OR6-7 2000 force plates (© Advanced Mechanical Technology, Inc.; Watertown, MA, USA) were available for level surface walking, and two Vicon Bonita cameras captured video at 100 Hz in frontal and sagittal plane. Trials were completed when the participant had at least three force plate hits for each side. For conditions 3 and 4, each participant had to walk up and down the ramp three times. The participants were allowed to take breaks when needed. The reflective markers were also checked between conditions and after breaks.

2.4 Data analysis

2.4.1 Kinematics and temporal-spatial parameters

Kinematic data was processed in Nexus software (Oxford Metrics, Oxford, UK), by labelling markers, detecting events and defining gait cycles. The data was filtered with a woltring filter. Joint and segment angles were calculated from the Vicon Plug-in-Gait lower and upper body models, figure 1 showing the definition of the frontal thoracic angle.



Start Marker:: RCLA
End Marker:: LCLA
Length = [-158.676,-28.301,-138.375]

Figure 1. Segment angle computation for the frontal thoracic angle.

From the exported c3d-files from Nexus, the data was further processed in Matlab (R2019a, MathWorks, Inc., Natick, MA, USA). The script calculated joint and segment angles throughout the gait cycle for each trial of each participant. The angle for each participant at IC was extracted for each condition and trial, and for both affected and non-affected leg. For thorax segmental angles, both frontal and sagittal plane angles were extracted. Sagittal plane ROM was calculated and extracted for the ankle and knee joint. The mean angle and ROM was calculated for each participant, which was used to calculate the mean for all participants. The temporal-spatial parameters walking speed (m/s), step width (m) and step length (m) were also calculated.

2.4.3 Statistics

Data were plotted into boxplots in Matlab (R2019a, MathWorks, Inc., Natick, MA, USA), and will be presented in such manner. As the data is paired, conclusions can be made from box plots, where differences between conditions will be considered clinically significant if the median of one box lies outside the interquartile range of the comparative box (Ngo, 2018). The central tendency, i.e. median, is shown by a line that divides the boxes in a box plot.

Because of outliers, median values were used to compare central tendencies. Comparisons regarding the relationship between walking with AFO and gait kinematics in inclined and declined walking were made between:

- AFOn level walking vs AFOn inclined walking for Aleg
- AFOn level walking vs AFOn inclined walking for NAleg
- AFOn level walking vs AFOn declined walking for Aleg
- AFOn level walking vs AFOn declined walking for NAleg
- AFOn inclined walking vs AFOa inclined walking for Aleg
- AFOn inclined walking vs AFOa declined walking for NAleg
- AFOn declined walking vs AFOa declined walking for Aleg
- AFOn declined walking vs AFOa declined walking for NAleg

To evaluate symmetry between Aleg and NAleg in inclined and declined walking for the two alignment conditions, the following comparisons were made if there was found a clinically significant difference between AFOa and AFOn in either Aleg or NAleg:

- Difference in median value between AFOn inclined walking Aleg and NAleg vs difference in median value between AFOa inclined walking Aleg and NAleg

- Difference in median value between AFOn declined walking Aleg and NAleg vs difference in median value between AFOa declined walking Aleg and NAleg

3.0 Results

Eight children and adolescents were recruited, where all had received an AFO from Trøndelag Ortopediske Verksted. One participant did not carry out the 3D gait analysis due to technical difficulties, and was not included in the data set. It was not possible to perform the protocol at a later date due to the outbreak of covid-19. For one participant, walking up and down with AFOa was excluded from the data set due to poor data quality. Of the seven participants, four wore the original ToeOFF® 2.0 (Allard, Helsingborg, Sweden), one wore a customized ToeOFF®, and two wore customized thermoplastic AFOs with hinges. The age ranged from 7-17 years old, with a mean of 11 years old. The mean height was 144 cm and mean weight was 36 kg. Table 1 shows the participant characteristics, where age is presented in age groups to protect anonymity.

Table 1

Participant characteristics.

ID	**Age group (years old)**	**Height (cm)**	**Weight (kg)**
D1	7-11	117	18
D2	7-11	132	30
D3	12-17	169	57
D4	12-17	159	50
D6	7-11	142	34
D7	12-17	156	34
D8	7-11	136	29

All participants wore AFOs unilaterally, the leg wearing AFO being referred to as Aleg. While wearing shoes only, the median ankle angle at IC of the Aleg was -7° dorsiflexion, and 7° dorsiflexion for NAleg. The median ankle angle at IC of the NAleg did not notably differ between AFO conditions. When wearing the AFOn the median ankle angle at IC of the Aleg increased with 11° to 4° dorsiflexion, and with the AFOa the median ankle angle at IC of the Aleg increased to 5°, thereby both AFO conditions largely decreased the asymmetry in ankle angle at IC between Aleg and NAleg.

3.1 Inclined walking

3.1.1 Kinematics

Ankle angle at IC: For NAleg the median ankle angle at IC was 7° dorsiflexion for level walking and 9° for inclined walking in the AFOn condition. The Aleg had a 4° median ankle angle at IC during level walking and 1° during inclined walking with the AFOn. With the AFOa the median ankle angle of the Aleg increased by 600% to 7° dorsiflexion during inclined walking (Figure 2), reducing asymmetry between Aleg and NAleg.

Ankle ROM: Figure 3 shows that the median ankle ROM of the NAleg was 33° during level walking with the AFOn and 39° during inclined walking with both the AFOn and AFOa. For the Aleg, the AFOn gave a median ankle ROM of 23° during level walking and 24° median ankle ROM during inclined walking.

Knee angle at IC: The NAleg had an increase of 13° (163% increase) in median knee flexion at IC during inclined walking compared to level walking, from 8° in level walking to 21° in inclined walking for AFOn (Figure 4). The median knee angle at IC increased with 4° (27% increase) for Aleg during inclined walking with the AFOn compared to level walking, from 15° to 19°. The AFOa did not have an effect on median knee angle at IC for either Aleg or NAleg.

Knee ROM: Figure 5 shows that there was a 9° (15%) decrease in median knee ROM in NAleg during inclined walking compared to level walking with the AFOn (50° vs 59°). No other changes of central tendency were seen in median knee ROM.

Hip ROM: The hip ROM for both Aleg and NAleg showed a slight increase (7°/15% and 8°/18%) in median ROM for inclined walking compared to level walking, but no difference between AFOn and AFOa (Figure 6).

Sagittal thoracic ROM: The participants walked on average with increased forward lean throughout the gait cycle when walking up compared to level walking. The median sagittal ROM of the thorax did not differ between level and inclined walking for the Aleg, neither for AFOn or AFOa. For the NAleg, there was a 0.5° (9%) decrease in median sagittal thoracic ROM during inclined walking compared to level walking for the AFOn (Figure 7).

Frontal thoracic ROM: There was no changes in central tendency between level and inclined walking, for neither AFOn nor AFOa for the frontal thoracic ROM in either leg (Figure 8).

3.1.2 Temporal-spatial gait parameters

Step length: The Aleg had a slight tendency for longer step length during inclined walking (0.6 m) compared to level walking (0.5 m) with the AFOn (Figure 9). The NAleg did not show any difference between level and inclined walking. There was no difference for the AFOa.

Step width: Step width for the Aleg did not show any difference between level and inclined walking for either AFO condition. For the NAleg, the AFOa during inclined walking increased the step width from 0.12 to 0.14 m (17% increase) compared to the AFOn (Figure 10), which increased asymmetry between Aleg and NAleg.

Walking speed: Walking speed increased by 0.1 m/s (10%) for inclined walking compared to level walking for the Aleg and NAleg (Figure 11). The AFOa did not have an effect on walking speed for either leg.

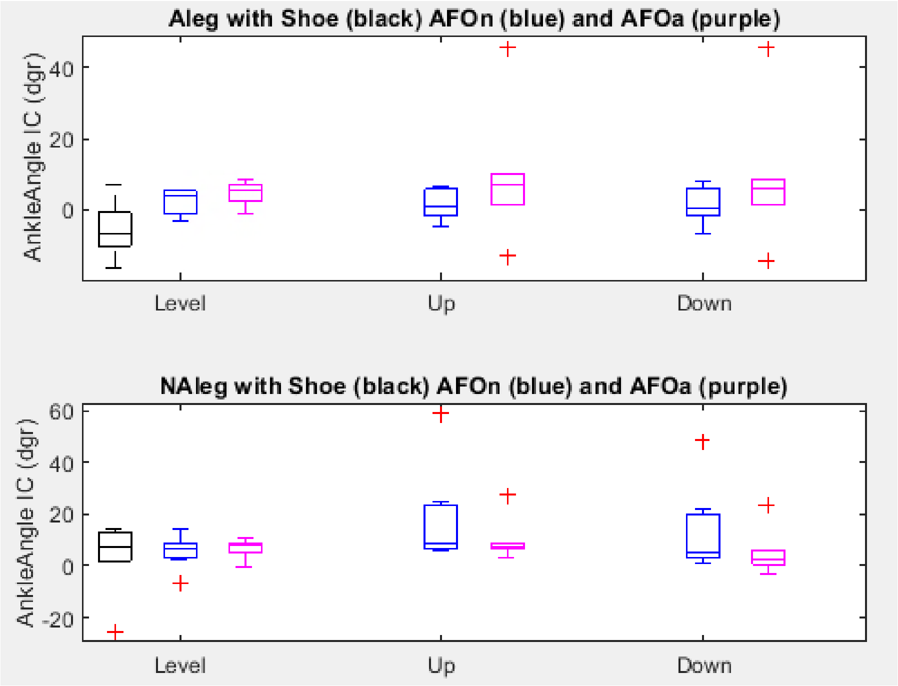


Figure 2. Box plots of ankle angle at initial contact (IC) in degrees for affected leg (Aleg, upper plot) and non-affected leg (NAleg, lower plot) during level, inclined (up) and declined (down) walking. The box shows the distance between the quartiles, where the median is marked as a line. Extreme values are shown as whiskers and/or outliers (+).

AFOn: Neutrally aligned ankle-foot-orthoses.

AFOa: Ankle-foot-orthoses with 5 mm increased heel-sole differential.

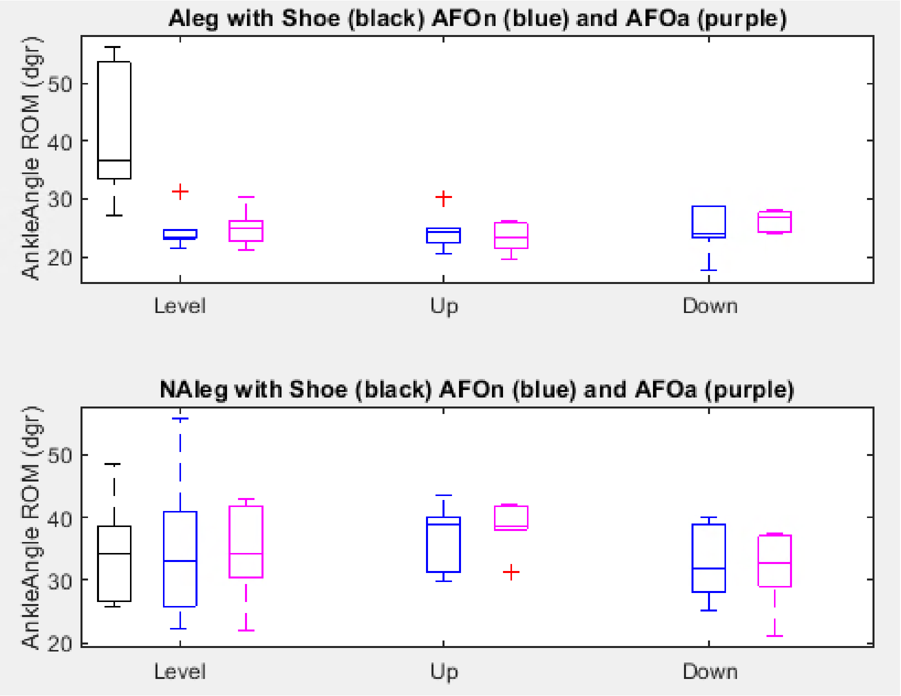


Figure 3. Box plots of ankle range of motion in degrees for affected leg (upper plot) and non-affected leg (lower plot) during level, inclined (up) and declined (down) walking. The box shows the distance between the quartiles, where the median is marked as a line. Extreme values are shown as whiskers and/or outliers (+).

AFOn: Neutrally aligned ankle-foot-orthoses.

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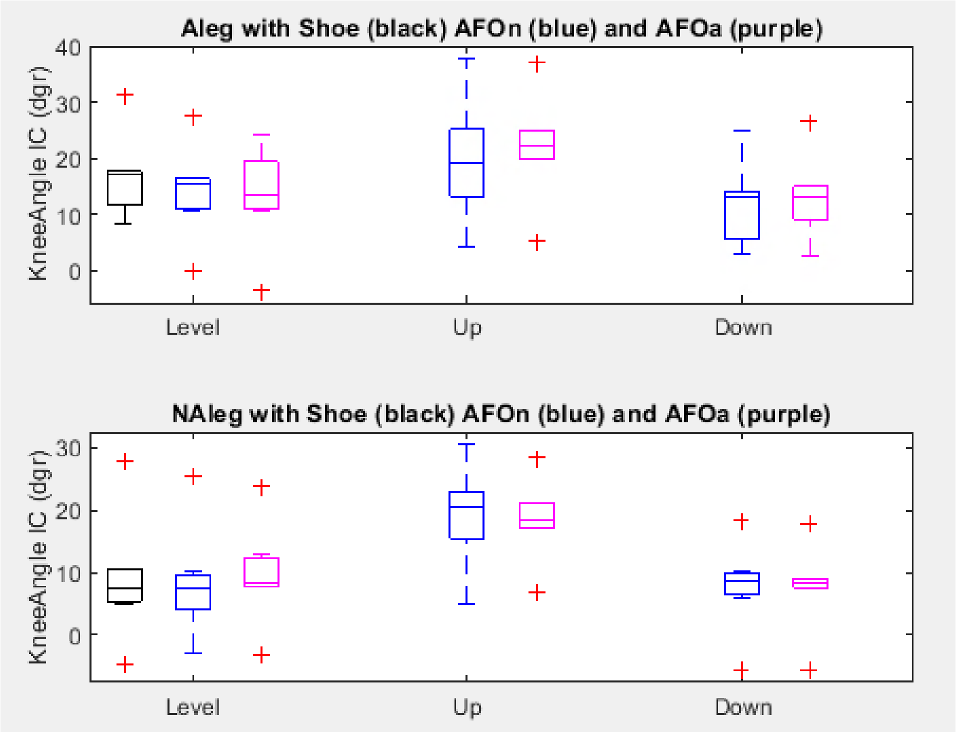

Figure 4. Box plots of knee angle at initial contact (IC) in degrees for affected leg (upper plot) and non-affected leg (lower plot) during level, inclined (up) and declined (down) walking. The box shows the distance between the quartiles, where the median is marked as a line. Extreme values are shown as whiskers and/or outliers (+).

AFOn: Neutrally aligned ankle-foot-orthoses.

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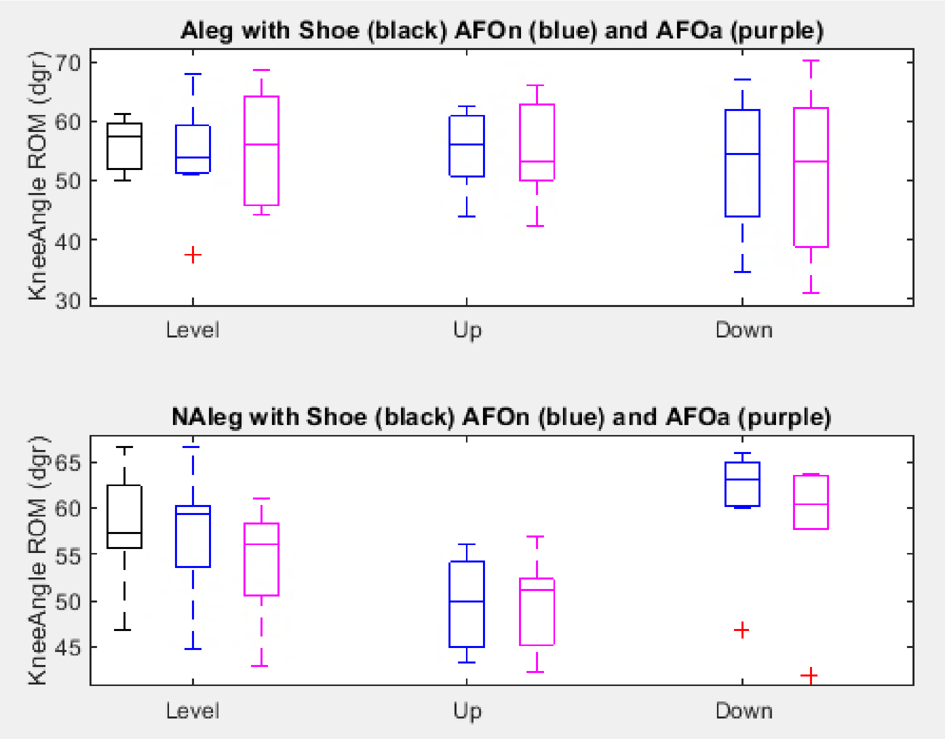

Figure 5. Box plots of knee range of motion in degrees for affected leg (upper plot) and non-affected leg (lower plot) during level, inclined (up) and declined (down) walking. The box shows the distance between the quartiles, where the median is marked as a line. Extreme values are shown as whiskers and/or outliers (+).

AFOn: Neutrally aligned ankle-foot-orthoses.

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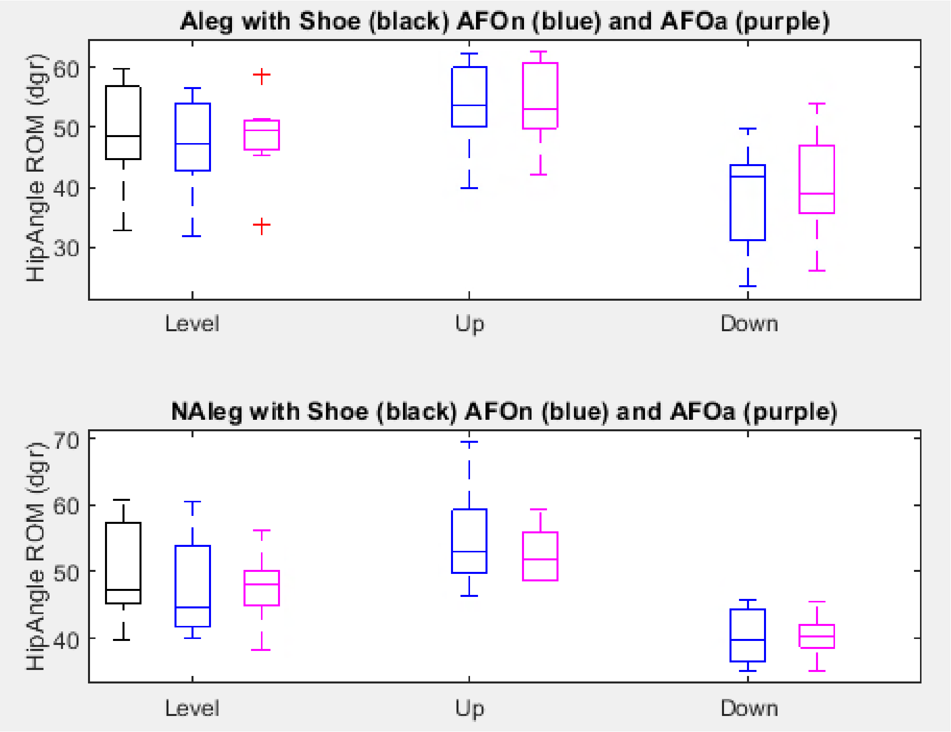

Figure 6. Box plots of hip range of motion in degrees for affected leg (upper plot) and non-affected leg (lower plot) during level, inclined (up) and declined (down) walking. The box shows the distance between the quartiles, where the median is marked as a line. Extreme values are shown as whiskers and/or outliers (+).

AFOn: Neutrally aligned ankle-foot-orthoses.

AFOa: Ankle-foot-orthoses with 5 mm increased heel-sole differential.

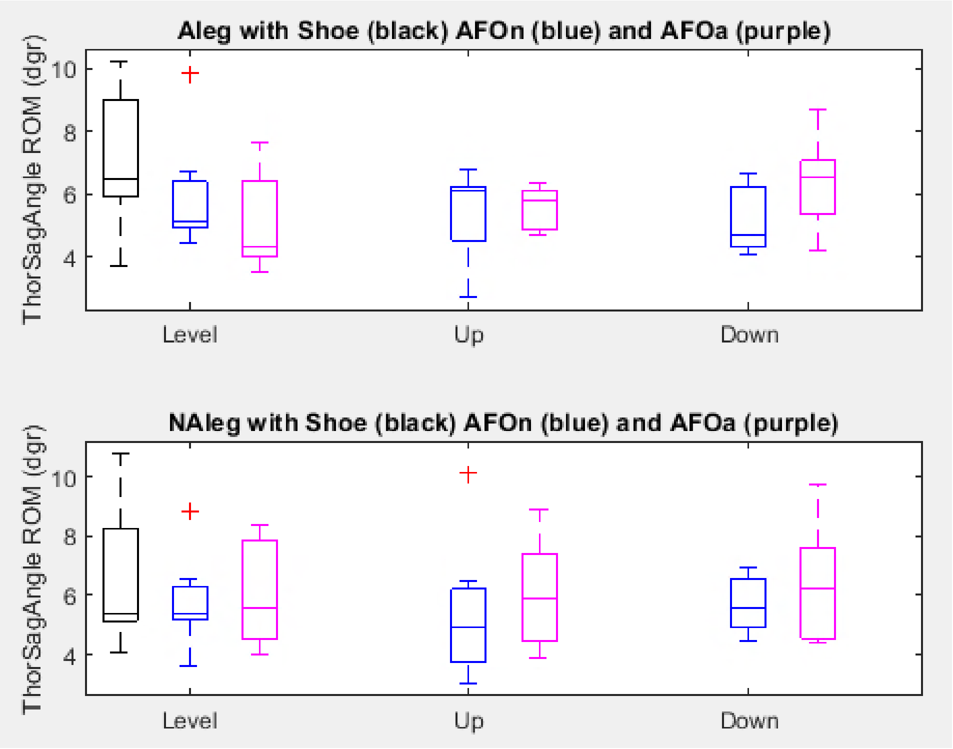

Figure 7. Box plots of sagittal thoracic range of motion in degrees for affected leg (upper plot) and non-affected leg (lower plot) during level, inclined (up) and declined (down) walking. The box shows the distance between the quartiles, where the median is marked as a line. Extreme values are shown as whiskers and/or outliers (+).

AFOn: Neutrally aligned ankle-foot-orthoses.

AFOa: Ankle-foot-orthoses with 5 mm increased heel-sole differential.

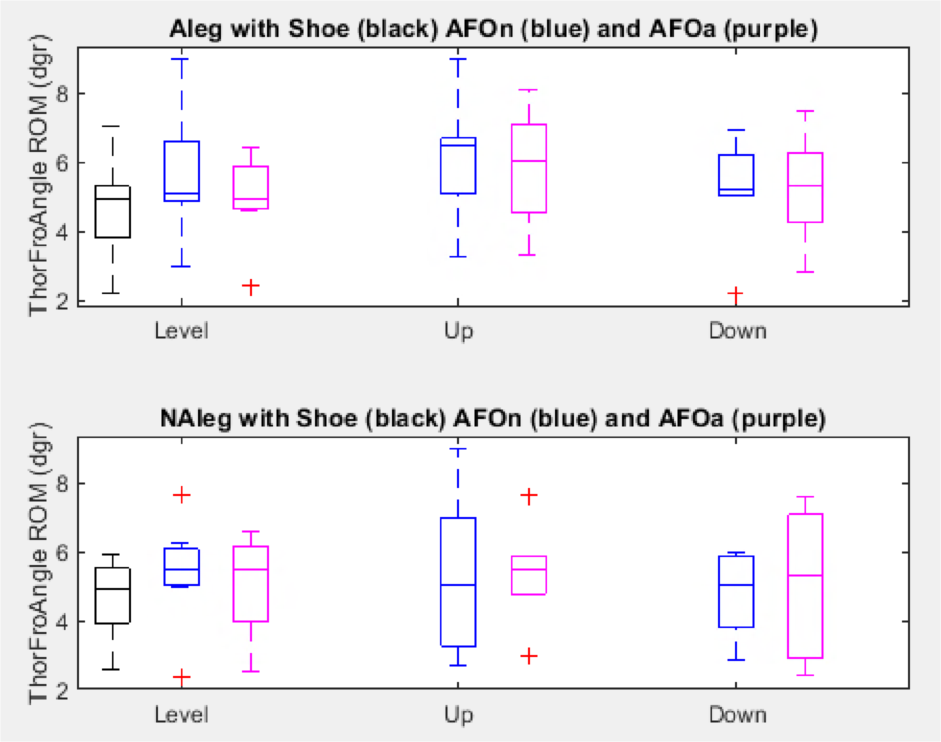

Figure 8. Box plots of frontal thoracic range of motion in degrees for affected leg (upper plot) and non-affected leg (lower plot) during level, inclined (up) and declined (down) walking. The box shows the distance between the quartiles, where the median is marked as a line. Extreme values are shown as whiskers and/or outliers (+).

AFOn: Neutrally aligned ankle-foot-orthoses.

AFOa: Ankle-foot-orthoses with 5 mm increased heel-sole differential.

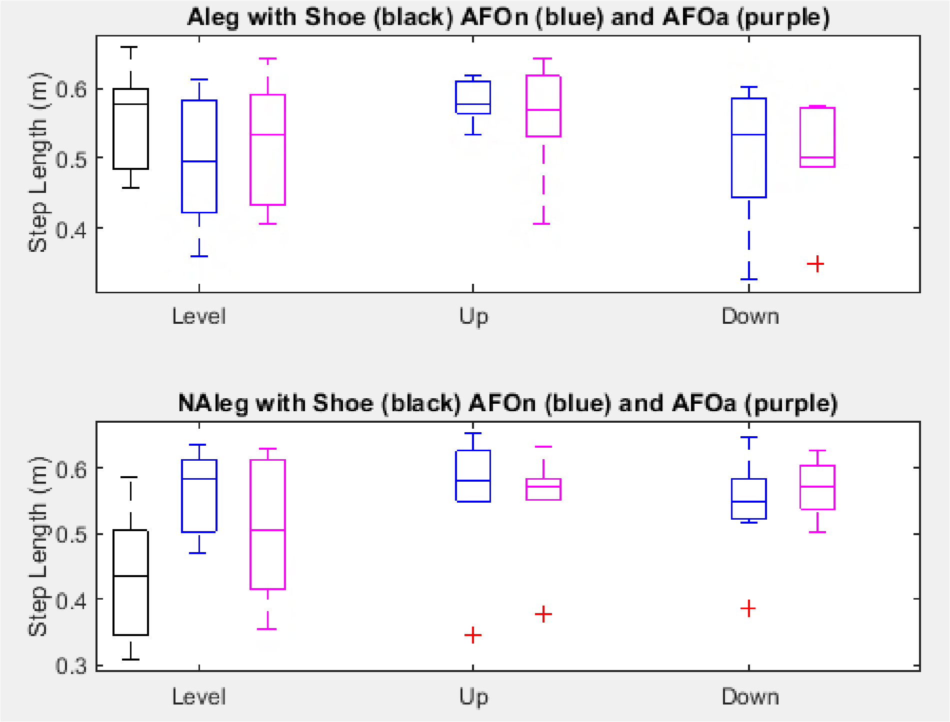

Figure 9. Box plots of step length in metres for affected leg (upper plot) and non-affected leg (lower plot) during level, inclined (up) and declined (down) walking. The box shows the distance between the quartiles, where the median is marked as a line. Extreme values are shown as whiskers and/or outliers (+).

AFOn: Neutrally aligned ankle-foot-orthoses.

AFOa: Ankle-foot-orthoses with 5 mm increased heel-sole differential.

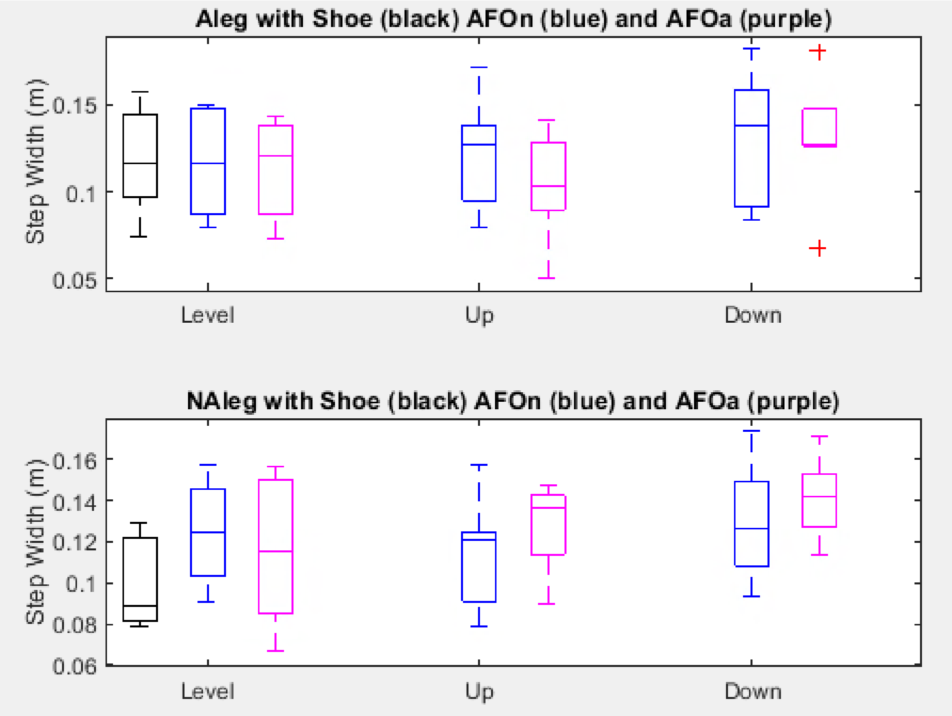

Figure 10. Box plots of step width in metres for affected leg (upper plot) and non-affected leg (lower plot) during level, inclined (up) and declined (down) walking. The box shows the distance between the quartiles, where the median is marked as a line. Extreme values are shown as whiskers and/or outliers (+).

AFOn: Neutrally aligned ankle-foot-orthoses.

AFOa: Ankle-foot-orthoses with 5 mm increased heel-sole differential.

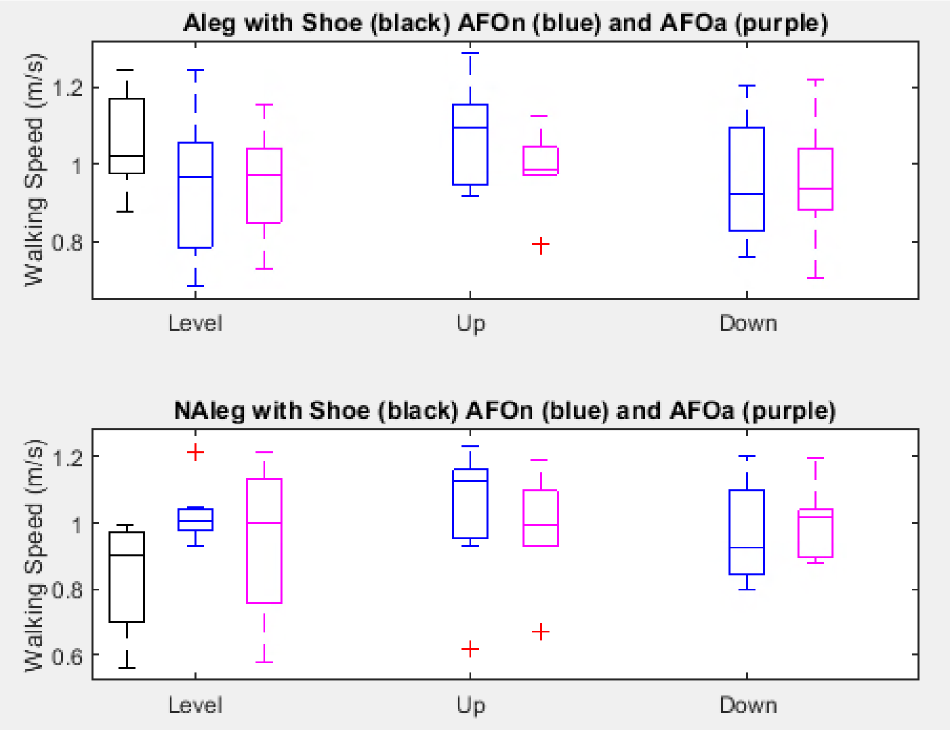

Figure 11. Box plots of walking speed in metres per second for affected leg (upper plot) and non-affected leg (lower plot) during level, inclined (up) and declined (down) walking. The box shows the distance between the quartiles, where the median is marked as a line. Extreme values are shown as whiskers and/or outliers (+).

AFOn: Neutrally aligned ankle-foot-orthoses.

AFOa: Ankle-foot-orthoses with 5 mm increased heel-sole differential.

3.2 Declined walking

3.2.1 Kinematics

Ankle angle at IC: During declined walking, the Aleg did not show a difference for the AFOn compared to level walking in regards to the median ankle angle at IC. However, with AFOa dorsiflexion increased at IC during declined walking compared to level walking with AFOn (6° vs 4°). The NAleg only showed a difference between AFOn and AFOa during declined walking, where the dorsiflexion decreased by 3° (40%) at IC with the AFOa compared to the AFOn (2° vs 5°), which increased symmetry between Aleg and NAleg. (Figure 2).

Ankle ROM: The median ankle ROM of the Aleg increased from 23° during level walking with the AFOn to 27° during declined walking with AFOa (Figure 3). No differences were seen for the NAleg.

Knee angle at IC: Figure 4 shows no difference in knee angle at IC between level and declined walking for either leg.

Knee ROM: Median knee ROM increased by 4° (7%) for the NAleg with AFOn (63°) during declined walking compared to level walking AFOn (59°) (Figure 5). No differences were seen in the Aleg.

Hip ROM: Hip ROM decreased for both legs with AFOn and AFOa during declined walking compared to level walking (Figure 6). The median hip ROM for Aleg was 47° during level walking with AFOn, and 42° during declined walking with AFOn (11% decrease) and 39° with AFOa (17% decrease compared to level walking). For NAleg the median ROM was 45° during level walking with AFOn, and 40° (11% decrease) with both AFOn and AFOa during declined walking.

Sagittal thoracic ROM: For the thoracic sagittal ROM, there was no difference between AFOn during level and decline walking. With the AFOa, the ROM in the NAleg increased by 0.9° (17%) during declined walking compared to level walking with AFOn. The Aleg also had increased sagittal thoracic ROM with the AFOa, from 5.1° during level walking with the AFOn to 6.5° (27% increase) during declined walking with the AFOa. For the Aleg, the AFOa also increased the sagittal thoracic ROM by 1.8° (38% increase) compared to the AFOn during declined walking, increasing symmetry between Aleg and NAleg (Figure 7).

Frontal thoracic ROM: Figure 8 shows that the thoracic frontal ROM did not differ between the conditions.

3.2.2 Temporal-spatial gait parameters

Step length: Step length did not differ between level and declined walking (Figure 9).

Step width: There was no difference in step width between level and declined walking, but with the AFOn the step width decreased by 0.01 m (8%) compared to AFOa during declined walking for the NAleg (Figure 10).

Walking speed: Figure 11 shows that the walking speed was 0.1 m/s lower (10% reduction) for declined walking with the AFOn compared to level walking with the AFOn.

4.0 Discussion

The primary aim of this study was to describe the relationship between walking with AFO and gait kinematics in inclined and declined walking. The secondary aim was to investigate if the orthotic alignment that enhances symmetry differs between inclined and declined walking. In this chapter, the main results will be discussed in light of previous work.

4.1 Inclined walking

The NAleg was more dorsiflexed throughout the gait cycle during inclined walking compared to level walking, which is a compensatory strategy during inclined walking to achieve toe clearance and heel strike (Lay et al., 2006). Ma et al. (2019) and Topçuoğlu et al. (2018) also found increased dorsiflexion during inclined walking compared to level walking. This was however not seen in Aleg in this study, which may be because of the AFO, where the ankle is set in an angle close to maximum dorsiflexion. The knee and hip joints are also important to raise the limb during inclined walking, by an increased flexion angle at IC compared to level walking (Lay et al., 2006). This concur with the findings of increased knee flexion at IC in both Aleg and NAleg in this study. Previous studies on children with CP have also found increased knee flexion at IC (Ma et al., 2019; Stott et al., 2014; Topçuoğlu et al., 2018) and hip flexion at IC (Mélo et al., 2017; Stott et al., 2014; Topçuoğlu et al., 2018). In the NAleg there was also a decrease in knee ROM during inclined walking compared to level walking, which has been found to be unchanged in healthy adults (Lay et al., 2006). Topçuoğlu et al. (2018) did not find a significant change in knee ROM during inclined walking compared to level walking, but typically developing children showed an increased knee ROM compared to children with CP. Further, we found a decreased sagittal thoracic ROM, which Kang & Dingwell (2008) reports as an indication of increased instability. At the same time, we also found increased forward trunk lean throughout the gait cycle. Tilting the trunk forward is necessary to propel the body forward, and by moving the center of mass in front of the area of support assists the lower limbs in generating forward momentum (Leroux et al., 2002). Topçuoğlu et al. (2018) did not find a difference in thoracic sagittal ROM between level and inclined walking in children with CP, but found increased trunk tilt compared to typically developing children. This may be a way of utilizing the effect the center of mass has on forward progression.

Of the temporal-spatial gait parameters, only walking speed differed from level walking. An increased walking speed was seen for both Aleg and NAleg. Ma et al. (2019) and Topçuoğlu et al. (2018) has found decreased walking speed during inclined walking compared to level walking, as well as lower walking speed for children with CP compared to typically developing children. Topçuoğlu et al. (2018) observed increased forefoot contact during IC for inclined walking, which in light of Lay et al. (2006) may be inconsistent with an effective gait strategy to propel the body forwards during inclined walking. With the AFO, IC was seen with a primary heel strike, which may allow for increased walking speed in this study.

4.2 Declined walking

No clinically significant differences were found in joint positions at IC between declined and level walking. For the Aleg, an increased ankle ROM was found, which does not correspond with the findings of Topçuoğlu et al. (2018). Again, this might be connected to the position of the foot at IC, where an AFO holds the ankle in a position that facilitates heel strike. In addition, most of the participants wore the ToeOFF® 2.0 (Allard, USA) or KiddieGAIT® (Allard, USA) AFOs, which have lateral carbon springs that allow for some plantarflexion. The combination of correct foot position at IC and the ability of plantarflexion may explain the discrepancy between our findings and the findings of Topçuoğlu et al. (2018). Our results show an increased knee ROM in NAleg during declined walking compared to level walking, which concur with Topçuoğlu et al. (2018), but who also reported significantly lower knee ROM in children with CP compared to typically developed children. The reduction in hip ROM seen in both Aleg and NAleg also concurs with Topçuoğlu et al. (2018), who found significantly decreased hip ROM for both children with CP and typically developing children during declined walking, where children with CP further had significantly lower hip ROM than typically developing children. For the Aleg we also found a decreased sagittal thoracic ROM during declined walking compared to level walking. Topçuoğlu et al. (2018) did not report a similar finding, but an increased ROM for children with CP compared to typically developing children. McIntosh et al. (2006) showed that with decreased in ROM in one joint, other joints must have an increased ROM to orient the centre of mass of the trunk, which might explain the opposite results in this study and Topçuoğlu et al. (2018) concerning ROM in the ankle and sagittal thorax.

As for inclined walking, walking speed was the only temporal-spatial gait parameter that showed a possible clinically significant difference between declined walking and level walking. We found a decreased walking speed during declined walking, which is inconsistent with the reportings of Stott et al. (2014), but concur with Mélo et al. (2017). During down-slope walking, a controlled descent of the body is required through joint extensors absorbing energy while lengthening (Lay et al., 2006). Stott et al. (2014) reported an increase in knee flexion during declined walking for children with CP, which they debate might reflect underlying weakness in eccentric quadriceps control, which in our study may be compensated for by the AFO, which in turn might impact the walking speed. Lower limb strength does not seem to be the explanation in our findings, as an increased walking speed was found during inclined walking, where the demands on strength are similar.

4.3 Alignment

Adjusting the alignment of the AFO with the addition of a five mm heel wedge between the AFO and the shoe resulted in an increased dorsiflexion at IC for the Aleg during inclined walking compared to the AFOn during inclined walking. This increased the symmetry between Aleg and NAleg, as NAleg was more dorsiflexed throughout the gait cycle, as well as at IC compared to level walking. In accordance with Lay et al. (2006) the increase in dorsiflexion may therefore imply that the AFOn might not meet the requirements of inclined walking and the need for toe clearance. The AFOa also increased step width for NAleg during inclined walking compared to AFOn during inclined walking, which decreased symmetry. Bautista (2019) found that AFO wearers took wider steps during inclined walking compared to healthy controls, and that the healthy controls took significantly smaller steps during inclined walking compared to level walking. Therefore, the AFOn seems the most appropriate regarding step width during inclined walking in this study.

During declined walking, AFOa decreased dorsiflexion at IC for NAleg compared to AFOn, which increased symmetry between Aleg and NAleg. Leroux et al. (2002) showed a decreased dorsiflexion angle at IC during declined walking compared to level walking in healthy subjects, which contributes to the assumption that the AFOa normalizes dorsiflexion at IC during declined walking. The AFOa increased the sagittal thoracic ROM compared to AFOn during declined walking for the Aleg. This increased symmetry between Aleg and NAleg. However, the movements were very small, although larger than reported in healthy adults (Leroux et al., 2002).

4.4 Methodological considerations and future research

There are several limitations to this study that have to be acknowledged. Firstly, the amount of participants were low, making the results more subject to outliers. A larger number of participants could also have opened for between group analyses, e.g. hemiplegic and diplegic. Previous studies have included twelve (Haight et al., 2015) and thirteen (Huang et al., 2006;

Lewallen et al., 2010) participants with disability, where they have been able to find statistical differences between conditions and/or a control group. Future research on this subject should therefore aim to have at least twelve participants. Adding a control group to the present study would also have been interesting, as to compare the observed kinematic and temporal-spatial changes to typically developing children.

Secondly, the participants completed a lengthy test protocol, although this study only was part of the total protocol. The gait analysis was performed last, because of practical reasons, and several children were starting to get tired at the end of testing. This limited the number of trials, which if were larger could have made a better foundation for calculating mean for each participant. In addition, a shorter test protocol might have opened for adjusting the AFO alignment a second time, for example by adding a ten mm heel wedge. An extra alignment change could have provided more information about the effect of alignment on inclined and declined gait. It could also be of interest to analyze the effect of the heel wedge at mid stance, where the effect on knee flexion may be greater than at IC (Jagadamma et al., 2010). Furthermore, including conditions with shoes only for inclined and declined walking could also provide more useful information, as Näslund et al. (2003) found a perceived effect of AFOs during play and everyday activities.

Thirdly, this study did not allow for any adaptation period of the alignment adjustment. Jagadamma et al. (2010) found changes in both knee kinematics and stride length between initial tuning and after three months, which warrants future research on this field should include an adaptation period. However, in the clinical setting, the effect of tuning orthotic alignment is evaluated immediately, and may be revised at a later consultation. Investigating the immediate effect of alignment change is therefore of clinical importance.

Furthermore, the gait analysis was based on reflective markers placed on the skin and on the AFO to capture joint motion. An orthotic ankle joint does not mimic the motion of an anatomical ankle, and may thereby introduce an error in measurement. However, the knee and ankle motion was based on several markers positioned on the skin, so the main findings are likely not affected by this. In addition, anthropometric measurements were taken both with and without the AFO, so as to limit the possible error.

Lastly, the evaluation of symmetry was done through comparison of each gait parameter by itself, as well as disregarding the cause of movement, which has been proposed by Sadeghi et al. (2000) to be more informative. Moreover, it could also give greater insight into the effect of orthotic alignment. Further research should therefore take this into consideration, as well as quantifying symmetry by using validated methods of measuring symmetry.

4.6 Conclusion

The adjusted AFO did not clinically significant enhance kinematic patterns seen with a neutral aligned AFO during inclined and declined walking, but the AFOa seemed to increase symmetry in the ankle at IC both during inclined and declined walking, as well as sagittal thoracic range of motion during declined walking. The AFOn was found to have a clinically significant effect on step length, increasing symmetry during inclined walking. Future research should aim to recruit more participants to perform statistical analyses, and include several alignment changes as well as walking with shoes only during inclined and declined walking to ensure that the findings are not coincidental.

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