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The impact of shoes versus ankle-restricted orthoses on sit-to-stand kinematics and centre of mass trajectories in adults with myelomeningocele

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ABSTRACT

Background: Individuals with myelomeningocele (MMC) present with neurological and orthopaedic deficiencies, requiring orthoses during walking. Orthoses for counteracting dorsiflexion may restrict activities such as rising from a chair.
Research question: How are sit-to-stand (STS) movements performed with ankle joint-restricted ankle-foot orthoses (AFO) and knee-ankle-foot orthoses with a free-articulated knee joint (KAFO-F)?
Methods: Twenty-eight adults with MMC, mean age 25.5 years (standard deviation: 3.5 years), were divided into an AnkleFree group (no orthosis or a foot orthosis) and an AnkleRestrict group (AFOs or KAFO-Fs). Study participants performed the five times STS test (5STS) while their movements were simultaneously captured with a three-dimensional motion system. Centre of mass (CoM) trajectories and joint kinematics were analysed using statistical parametric mapping.
Results: The AnkleRestrict group performed the STS slower than the AnkleFree group, median 8.8 s (min, max: 6.9, 14.61 s) vs 15.0 s (min, max: 7.5, 32.2 s) ($p = 0.002$), displayed reduced ankle dorsiflexion (mean difference: 6°, $p = 0.044$) (74–81 % of the STS cycle), reduced knee extension (mean difference: 14°, $p = 0.002$) (17–41 % of the STS cycle), larger anterior pelvic tilt angle (average difference: 11°, $p = 0.024$) (12–24 % of the STS cycle), and larger trunk flexion angle (on average 4°, $p = 0.029$) (6–15 % of the STS cycle).
Significance: The differences between the AnkleFree and AnkleRestrict groups in performing the STS seem consistent with the participants functional ambulation: community ambulation in the AnkleFree group, and household and nonfunctional ambulation with less hip muscle strength in the majority of the AnkleRestrict group. No differences in the 5STS CoM trajectories or the kinematics were found with respect to the AFO and KAFO-Fs groups. Because orthoses are constructed to enable walking, the environment needs to be adjusted for activities in daily living such as the STS movement.

1. Introduction

Myelomeningocele (MMC) is a congenital neural tube defect associated with brain malformations and hydrocephalus and to motor and sensory pareses at various neurological levels [1]. In people with MMC functional movements such as rising from sitting to standing may be challenging. An individual with MMC with a low lumbar lesion level often requires an ankle-foot orthosis (AFO) for walking to stabilise the ankle joint against tibial advancement due to plantar flexor weakness [2,3]. When hip abduction strength is affected at the mid-lumbar level, a knee-ankle-foot orthosis with a free mechanical knee joint (KAFO-F) is used to align the shank and thigh segments in the frontal and transverse planes [3].

Rising from a chair, a functional task demanding a high degree of coordination, is a common activity of daily living [4], whereby arm assistance during rising influences the sit-to-stand (STS) transfer [5,6]. A test consisting of five repeated STS movements (5STS) has been shown to have good to excellent test-retest reliability and has been recommended as a functional strength measure for people ages 14–70 years in most populations and settings and for people with neurological diseases [7–9]. In addition, STS has been considered a particular transfer skill influenced by multiple physiological and psychological processes [10].

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To detect functional movement compensations during STS transitions, movement patterns have been studied by means of centre of mass (CoM) trajectories using three-dimensional (3D) motion analysis in individuals with knee and hip osteoarthritis [11,12].

In people with MMC, the use of orthoses to counteract dorsiflexion while walking is common [3]. A blocked ankle joint however hinders forward movement of the shank thus it is possible that individuals requiring ankle joint stabilization exhibit altered STS movements compared to people without joint restriction. Current knowledge on the impact of ankle restricted orthoses on sit-to-stand movement patterns, i.e. a common movement in everyday life, is sparse. Therefore, the primary aim of this study was to examine how people with various levels of MMC perform sit-to-stand movements. It was hypothesised that individuals with MMC using orthoses with dorsiflexion-restricted ankle joints would require more time to complete an STS test and display altered movement patterns when rising from a seated position compared to individuals without being hindered from the ankle joints. Secondly, this study has attempted to compare patterns in the STS motion of individuals with MMC wearing an AFO vs those wearing a KAFO-F.

2. Methods

2.1. Participants

A group of 28 individuals with MMC participated in the study between February 2018 and May 2019. Inclusion criteria were the diagnosis of MMC, ambulatory function outdoors or indoors [13], and good to normal knee extensor strength (grade 4 or 5) [14]. The occurrence of neurosurgically shunted hydrocephalus was obtained from medical records (Table 1). Ethical approval for the study was obtained from the Regional Ethical Review Board in Stockholm, Sweden, Dnr 2017/910–31/4, and written informed consent was obtained from all participants.

Eight participants formed the AnkleFree group, of which three used only shoes, five used foot orthoses (FOs), and one wore a supramalleolar orthosis unilaterally. The AnkleRestrict group had 20 participants, of which 11 wore ankle-foot orthoses (AFOs) and 9 wore knee-ankle-foot orthoses with free-articulating knee joint (KAFO-Fs) [3,15–17] (Table 1). The soles of all orthoses extended to the toes, encompassing the entire foot. The orthoses were adjusted with heel wedges on the shoes to attain accurate shank to vertical angle alignment when standing [18]. The orthosis types were defined based on the international classification (ISO 2007) [19]. FOs, which do not limit ankle motion, were merged with shoes worn by some participants and defined as free-ankle orthoses (AnkleFree). AFOs and KAFO-Fs [3] were grouped as ankle-restricted orthoses (AnkleRestrict). All orthoses were custom made, constructed and delivered by the same local prosthetic and orthotic provider. All participants who wore orthoses had used them since childhood. Orthosis types and material are shown in Supplements A and B.

Table 1
Patient characteristics with respect to the AnkleFree and AnkleRestrict groups.

	AnkleFree n = 8 (Shoe: 3 FO: 5 SMO:1)	AnkleRestrict n = 20 (AFOs: 11 KAFO-F: 9)	*p*
Sex (m=male, f= female)	m: 3, f: 5	m: 13, f: 7	ns
Age, years mean (SD) (min-max)	25.3 (3.9) (19–37)	25.5 (3.4) (18–32)	ns
Weight, kilogram (kg) mean (SD) (min-max)	70 (15.1) (55–103)	67.3 (15.5) (46–107)	ns
Height, metre (m) mean (SD) (min-max)	1.6 (0.1) (1.5–1.8)	1.6 (0.7) (1.4–1.7)	ns
Body Mass Index (m^2/kg) mean (SD) (min-max)	25 (6) (20–39)	27.4 (16.5, 41.4)	ns
MFC	I: 3, II: 5	II: 12, III: 8	**0.002**
Hip flexion contractures (degrees), median (min, max)	0 (0, 0)	0 (0, 30)	ns
Knee flexion contractures (degrees) median (min, max)	0 (0, 5)	7.5 (0, 30)	**0.016**
Shunted hydrocephalus number of participants	5	17	ns
Functional ambulation number of participants	Ca:7 Ha:1	Ca:2 Ha:15 N-f:3	**< 0.001**

FO, foot orthosis; SMO, supramalleolar orthosis; AFO, ankle-foot orthosis; KAFO-F, knee-ankle-foot orthosis with free knee joint; SD, standard deviation; min, minimum; max, maximum; MFC, muscle function class; Ca, community ambulation; Ha, household ambulation; N-f, nonfunctional ambulation.
Statistical differences are marked in bold.

The participants were designated a muscle function class (MFC) based on manual muscle strength measurement [14]. Individuals with weakness in foot intrinsic muscles and plantarflexors of grade 4–5 were designated a sacral neurological level (MFC I). Those with foot plantarflexion grade 3, knee flexion grade 3, and hip extension and/or hip abduction grade 2–3 were designated a low lumbar level (MFC II). Those with knee flexion grade 3, only traces of hip extension and hip abduction activity, and below-knee muscle weakness had a mid-lumbar level designation (MFC III) (Table 1). All levels had good to normal hip flexion, hip adduction, and knee extension [2]. Hip and knee flexion contractures defined as less than neutral joint position were measured using a goniometer (Table 1). There were no differences between the groups in underwent shunted hydrocephalus (Table 1). The walking function of study participants was classified as community ambulation, household ambulation, and nonfunctional ambulation [13] (Table 1).

2.2. Three-dimensional (3D) motion analysis

3D motion analysis was conducted at the Motion Analysis Laboratory at Karolinska University Hospital, Stockholm, Sweden using 12 cameras (Vicon MX40VR, Oxford, UK) at a sampling rate of 100 Hz. Thirty-four retroreflective markers attached to anatomical landmarks (Plug-In-Gait model ViconVR) were utilised to record joint kinematics and CoM trajectories [20]. Two analogue video cameras from the frontal and sagittal perspectives were used to assess presence of compensatory arm movements and use of support.

2.3. The five times sit-to-stand (5STS) test

Study participants were instructed to rise from a bench without armrests, with a seat height of 44.5 cm, five times as fast as possible while being told to maintain a safe performance [9]. They were instructed to keep their arms folded across their chest if possible. The test started in a seated position and ended in a standing position. A support frame was located ~0.5 m in front of the participants to hold in case of insecurity. An initial test was done for familiarization. Two trials were offered of which the one with the shortest time was chosen for further analysis. The time to perform the test was recorded with a stopwatch, and the fastest trial was used for further analysis.

2.4. Data analysis

3D motion analysis data were processed using Vicon Nexus software (2.1), and raw motion data were filtered using a Woltring filter. SPM analysis, a method enabling precise point-by-point comparisons between groups that is highly sensitive for accurate registration (similar boundary conditions between movements), was used to examine movement patterns [21,22]. Four sit-to-stand-to-sit movements were considered full cycles (cycles 1–4) and were used for further analysis. Each cycle was time normalized to100 %, and the 4 cycles were averaged. Outcome measures derived from the 3D motion analysis included

CoM trajectories in the sagittal and frontal planes. The kinematic variables of interest included the trunk, pelvis, hip, knee, and ankle angles in the sagittal plane. The left and right sides were averaged and presented bilaterally (hip, knee, and ankle).

2.5. Statistical analysis

Statistical analyses were performed using commercially available software (SPSS version 28.0). The significance level was set at $p < 0.05$. The normality distribution was determined via Shapiro Wilk's test and inspection of Q-Q plots. Descriptive data are presented as mean and standard deviation (SD), median, minimum (min), and maximum (max) values. The Mann Whitney U test was used to compare differences between the AnkleFree and AnkleRestrict groups and between the AFO and KAFO-F groups. A Chi-Square test was used to compare muscle function class, joint contractures, and ambulatory level between the AnkleFree and AnkleRestrict groups. Differences across kinematic waveforms of the STS cycles between groups were evaluated using the statistical parametric mapping (SPM) version of a t-test [21,22]. SPM analyses were performed in MATLAB (R2022a) (The MathWorks, Inc., Natick, Massachusetts, USA).

3. Results

3.1. Participant characteristics

Table 1 shows age, weight, height, body mass index, MFC, presence of shunted hydrocephalus, joint contractures, and level of functional ambulation for the AnkleFree and AnkleRestrict groups. Knee flexion contractures were larger in the AnkleRestrict group than in the AnkleFree group. There were no participants in MFC III in the AnkleFree group. In the AnkleRestrict group, there were no participants in MFC I. Participants with nonfunctional ambulation were found only in the AnkleRestrict group (Table 1).

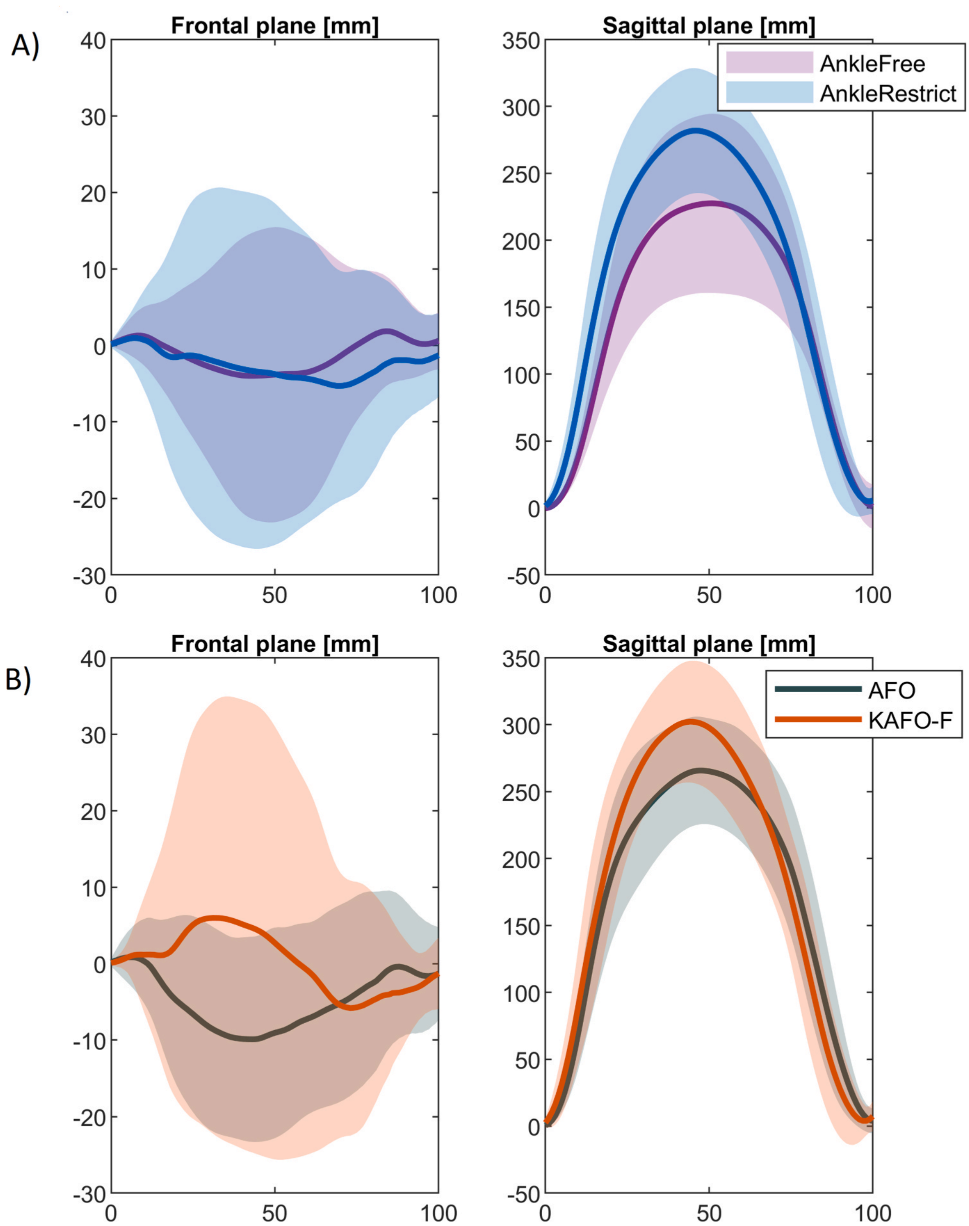

Fig. 1. Group average of centre of mass trajectories of four complete sit-to-stand cycles during the five times sit-to-stand test in the frontal (contralateral shift) and the sagittal (forward displacement) planes in A) the AnkleFree and AnkleRestrict groups and B) in the AFO and KAFO-F groups.

3.2. External support and arm position

Seven of 20 participants in the AnkleRestrict and none in the AnkleFree group performed the 5STS test using external support (p=0.024). In the AnkleRestrict versus AnkleFree group, 6 vs 6 participants performed the test with folded arms across the chest as requested, 6 vs 2 extended their arms anteriorly while rising, and one participant in AnkleRestrict performed the test with hands pressed on thighs.

3.3. Time to complete the 5STS test

Two trials were conducted by 12/20 (60 %) in the AnkleRestrict and by 6/8 (75 %) in the AnkleFree group. The median time required to complete the 5STS test was 8.8 s (min, max: 6.9, 14.61 s) in the AnkleFree group and 15.0 s (min, max: 7.5, 32.2 s) in the AnkleRestrict group (p = 0.002). The median time to complete the 5STS test was 14.6 s (min, max 7,5, 32.2 s) in the AFO group, and 16.7 s (min, max: 11.4, 25.2 s) in the KAFO-F group (p = 0.370). In the AnkleRestrict group, those using no (nr=13) vs those using external support (n = 7) required shorter time to complete the 5STS test, median 13.6 (7.5, 18.7) and 18.2 (12.9, 32,2) (p = 0.030) respectively.

3.4. Sit-to-stand (STS) movements

AnkleFree vs AnkleRestrict No differences in CoM trajectories were observed in the frontal or the sagittal plane between the AnkleFree and

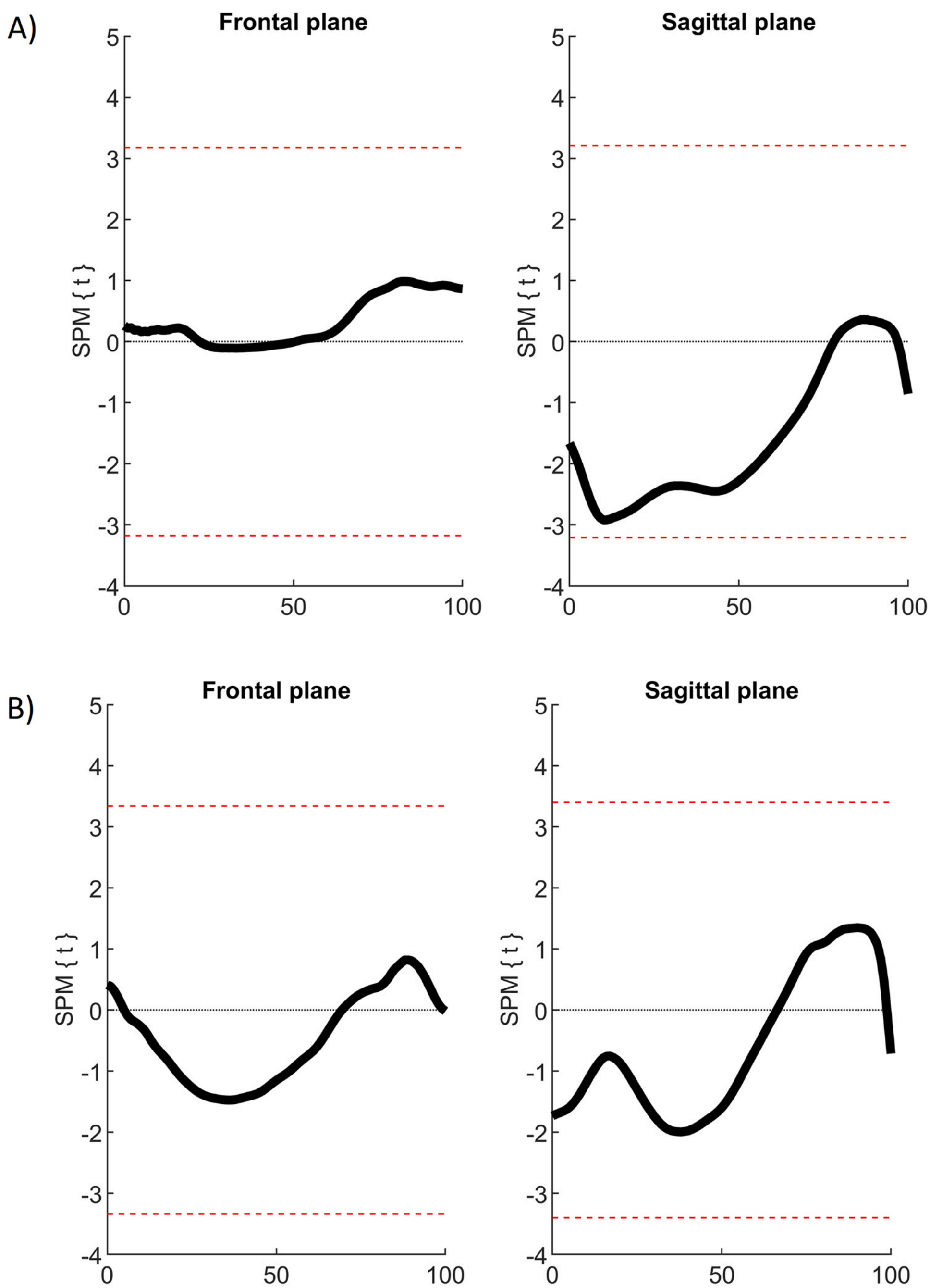

Fig. 2. Statistical parametric mapping curves of the centre of mass in the frontal and sagittal planes in A) the AnkleFree and AnkleRestrict groups and in B) the AFO and KAFO-F groups. The dotted red line represents the critical statistical threshold. The bold black line indicates the t-value for each timepoint. Statistical differences are observed when the black line crosses the critical threshold.

AnkleRestrict groups during the 5STS test (Fig. 1A and Fig. 2A). In the kinematic analysis of the sagittal plane, the AnkleRestrict group compared to the AnkleFree group, displayed reduced ankle dorsiflexion (mean difference: 6°, p = 0.044) during 74–81 % of the complete STS cycle, and reduced knee extension during the stand-up phase (mean difference: 14°, p = 0.002) during 17–41 % of the STS cycle (Fig. 3A). The average anterior pelvic tilt angle and the average trunk flexion angle were larger in the AnkleRestrict group compared to the AnkleFree group: 11° (p = 0.024) during 12–24 % of the STS cycle and 4° (p = 0.029) during 6–15 % of the STS cycle, respectively (Fig. 3A, Fig. 4A). All cycles for CoM and kinematics separately are shown in supplements C and D.

3.5. Sit-to-stand movements: AFO vs KAFO-F

No differences were observed in CoM trajectories during the 5STS test between the AFO and KAFO-F groups in the frontal and sagittal planes (Fig. 1B, Fig. 2B) or in the sagittal plane kinematics (Figs. 3B and 4B). All cycles for CoM and kinematics separately are shown in supplements E and F.

4. Discussion

This study was conducted based on observations during clinical examinations that orthoses with dorsiflexion-restricted ankle joints hindered the ability of individuals with MMC to rise from sitting to standing. In accordance with our hypothesis, the group using only shoes and FOs (AnkleFree) required less time to perform the 5STS test than the group with restricted ankle joints (AnkleRestrict). Even though both groups had fully innervated knee extensors, most participants who used ankle-restricted orthoses presented with lower muscle strength in knee flexors, hip extensors, and hip abductors than those using shoes and FOs, which may have affected the time required to complete the STS test.

We also hypothesised that people using orthoses with dorsiflexion-restricted ankle joints would display altered movement patterns when rising from a seated position compared to those using shoes or FOs. Visual inspection of the ankle kinematics revealed that there were distinct differences in ankle movement patterns between the AnkleFree and AnkleRestrict groups. The AnkleRestrict group exhibited a limited range of motion, while the AnkleFree group demonstrated substantial ankle movement. This was confirmed statistically, where the AnkleRestrict group presented with reduced dorsiflexion at the end of the standing-up phase compared to the AnkleFree group. However, in restricted ankle joints, the range of motion may differ for different biomechanical orthosis constructions, which could not be controlled in this study. Furthermore, knee extension at the beginning to the middle of the standing-up phase was reduced in the AnkleRestrict group compared to the AnkleFree group. This restriction could be attributed to the presence of knee and hip contractures and as a consequence of weakness in the hip extensor muscles in the former group. Moreover, the increased pelvis forward tilt in the AnkleRestrict group compared to the AnkleFree group at the beginning of the standing-up phase could be

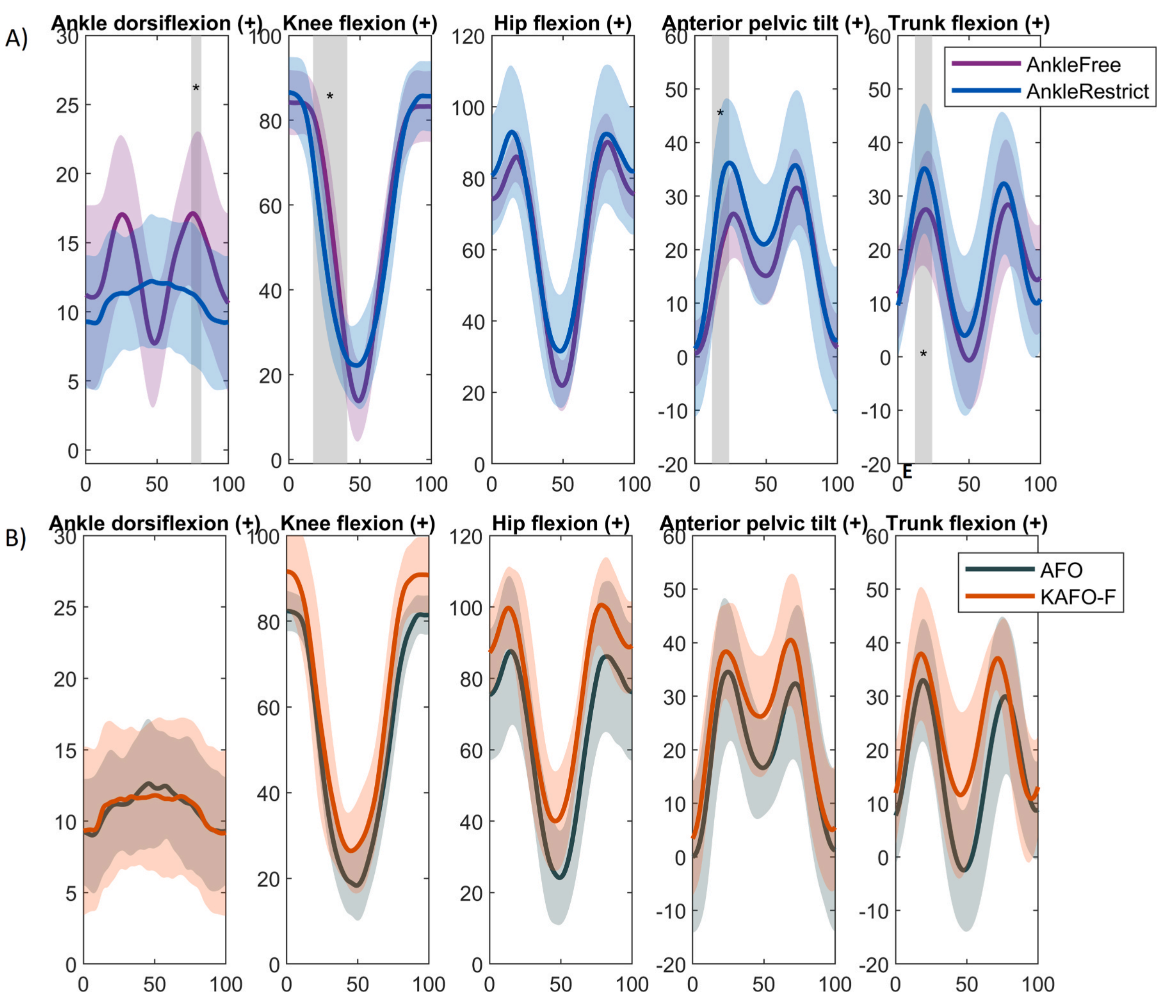

Fig. 3. Group average of kinematics of the sagittal plane in the ankle, knee, hip, pelvis, and trunk of four complete sit-to-stand cycles during the five times sit-to-stand test in A) the AnkleFree and AnkleRestrict groups and in B) the AFO and KAFO-F groups. The statistical differences are marked with a shaded grey area with a star. (+) indicates the movement direction.

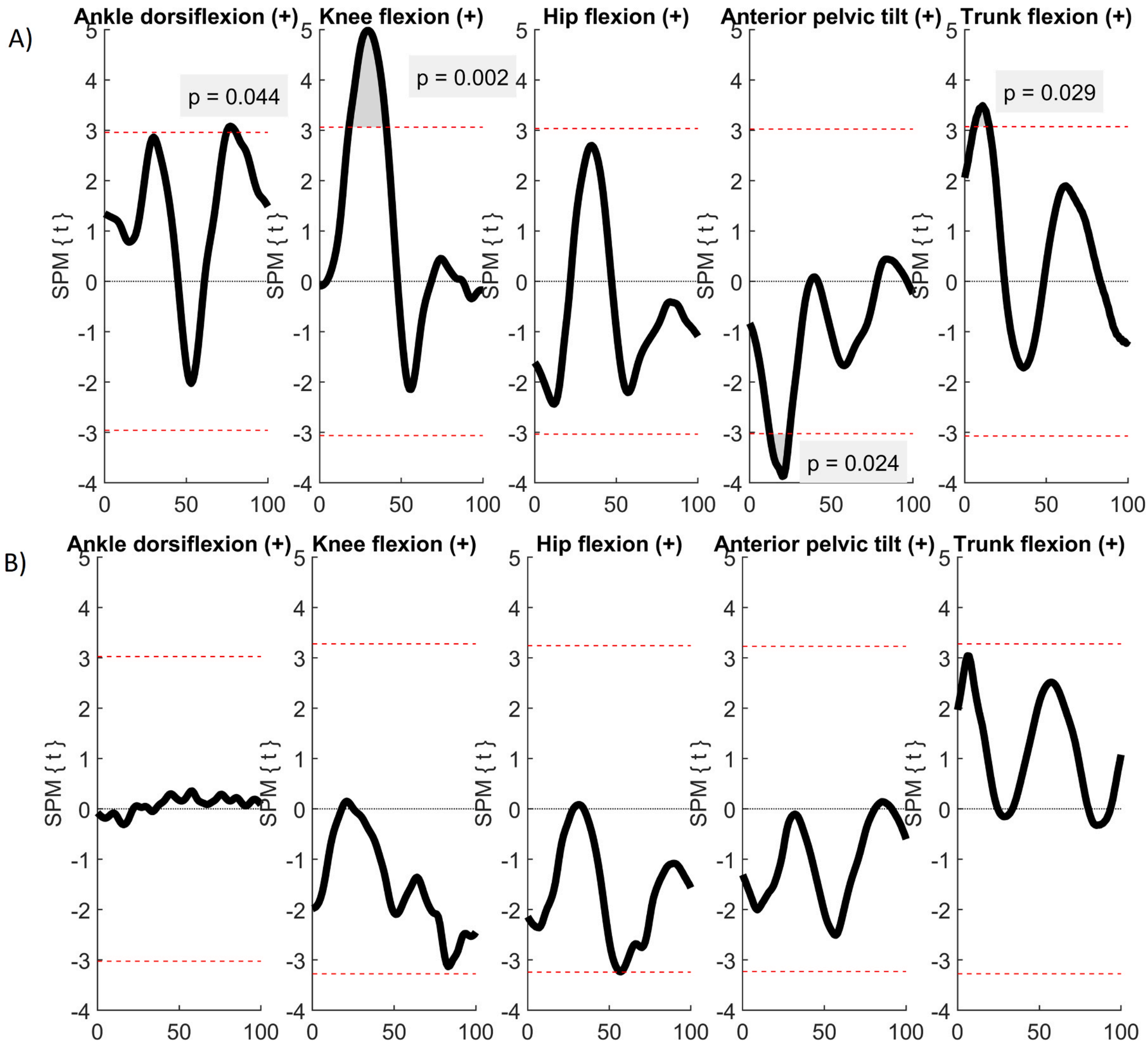

Fig. 4. Statistical parametric mapping curves of the kinematics of the sagittal plane in the ankle, knee, hip, pelvis, and trunk of four complete sit-to-stand cycles during the five times sit-to-stand test in A) the AnkleFree and AnkleRestrict groups and in B) the AFO and KAFO-F groups. The dotted red line represents the critical statistical threshold. The bold black line indicates the t-value for each timepoint. Statistical differences are observed when the black line crosses the critical threshold.

explained by less hip extensor strength in combination with a more erect trunk to counteract hip flexion when initiating the rising movement. This finding corresponds to available muscle strength in the MFC groups, whereby the participants in the AnkleRestrict group were classified as both MFC II and III, presenting with more weakness in hip extension and/or hip abduction compared to the participants in the AnkleFree group consisting of the MFC I and II groups.

In the AnkleRestrict group, seven participants required arm support during rising, the former group also showing increased time utilization compared to the AnkleFree group.

Previous research has shown that arm support during STS transfer expands the body's support base in healthy subjects, enhancing postural stability [5]. In this study, four participants in the AnkleRestrict group needed support during the entire rising phase, whereas three used the handrail only once they reached a standing position. Although the variance in STS performance could be due at least in part to muscle strength, it could also be influenced by disturbances in sensation and balance [9]. The use of an arm support, therefore, could have partially been due to associated neurological factors that are present in individuals with MMC that go beyond the effects of muscle paresis [2]. However, even if it was recommended to perform the 5STS without hand support to not confound the outcome [6], this was not feasible in all the participants and reflected their everyday reality.

In the present study, all participants were instructed to place their arms folded across their chests if possible. In the AnkleFree group, most maintained their arms positioned on their chest during the entire 5STS test, and two extended their arms anteriorly while rising. Among the participants in the AnkleRestrict group who did not require external support during the test, 12 participants were able to perform the test with arms folded across the chest throughout the test, as requested. In contrast, eight participants extended their arms anteriorly during the rising phase, which was presumed to be a compensation for lack of hip muscle strength in combination with restricted ankle dorsiflexion of the orthoses.

In a recent study, the STS test demonstrated an excellent relationship with the status of functional ambulation in children with MMC, indicating that better hip extensor control is also related to a higher level of functional ambulation [23]. This agrees with the findings of the present study, wherein all participants in the AnkleFree group were community ambulators, in contrast to the AnkleResist group, who all used AFOs or KAFO-Fs and the majority of whom were either household or nonfunctional ambulators. Concerning the use of AFOs vs KAFO-Fs, there were no differences between the groups in time required to perform the 5STS, nor were there differences in the lower limb kinematics or CoM trajectories. The purpose of an AFO is primarily to stabilise the ankle in the sagittal plane to compensate for weak plantarflexors occurring at a low neurological level. Due to the construction of the AFO and KAFO-F with a restricted ankle joint, rising from sitting to standing may be challenging for many people with MMC. This was confirmed in Fig. 2b in which almost identical ankle kinematics were observed in the AFO and KAFO-F groups. Additionally, at mid-lumbar neurological levels, the KAFO-F is intended to stabilise the shank and thigh segments in the frontal and transverse planes to withstand external forces due to weak hip abduction, avoiding malalignment in the knee, hip, and trunk during walking. Even if not statistically significant, the AFO group displayed even more contralateral shift of the CoM than the KAFO-F group, whereas forward displacement of the CoM was smaller in the AFO group than in the KAFO-F group, as shown in Fig. 2b. Furthermore, as expected, there was no difference in ankle kinematics between the AFO and KAFO-F groups as both orthosis ankle joints were dorsiflexion-restricted. Although not statistically confirmed, the extension movements in the knee, hip, and trunk were larger, and the pelvis was less forward tilted in the AFO group than in the KAFO-F group, as could be observed in Fig. 3B. These differences could be because most participants in the KAFO-F group were in the MFC III class. Thus, despite the KAFO-F including a thigh section, it did not seem to have a more negative impact than the AFO on the motion of rising to standing in this study. Nevertheless, to achieve the best possible ambulatory function and prevent joint deformities, the appropriate orthosis for each participant must be chosen.

This study holds limitations that need to be acknowledged. First, the different means of using external support and arm positions during the 5STS test may have impacted movement patterns and the time required to complete the test. Second, the diverse construction of the orthosis ankle joints is a factor that may have influenced the results of the 3D analysis. Nevertheless, this study adds to the understanding of the effort required to perform STS, the CoM trajectory and joint strategies during STS for people with MMC using dorsiflexion-restricted orthoses. The study's findings also highlight the importance of adjusting the environment with adequate external support for the common activity of daily living that rising from sitting to standing represents.

5. Conclusions

When comparing the time required to complete the 5STS test for the groups with and without ankle joint-restricted orthoses in adults with MMC, shorter time was found in the AnkleFree than in AnkleRestrict group. In addition, the AnkleRestrict group required external support or compensatory arm movements more frequently than the AnkleFree group to rise from sitting to standing. Compared to the AnkleFree group, kinematic differences in multiple segments were observed in the sagittal plane during rising to standing in the AnkleRestrict group, while no group differences in CoM trajectories were observed. Because orthoses are constructed to achieve the best possible walking function, the environment should be adjusted to facilitate the common everyday activity of rising from sitting to standing.

CRediT authorship contribution statement

Marie Eriksson: Conceptualization, Investigation, Methodology, Resources, Writing – review & editing. **Morten Bilde Simonsen:** Formal analysis, Writing – review & editing. **Josefine Eriksson Naili:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Åsa Bartonek:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

None.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2024.06.025.

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