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Wearing an ultrasound probe during walking does not influence lower limb joint kinematics in adolescents with cerebral palsy and typically developing peers

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ABSTRACT

Background: Enhancing traditional three-dimensional gait analysis with a portable ultrasound device at the lower-limb muscle-tendon level enables direct measurement of muscle and tendon lengths during walking. However, it is important to consider that the size of the ultrasound probe and its attachment on the lower limb may potentially influence gait pattern.
Research question: What is the effect of wearing an ultrasound probe at the lower limb in adolescents with cerebral palsy and typically developing peers?
Methods: Eleven individuals with cerebral palsy and nine age-matched typically developing peers walking barefoot at their self-selected speed were analyzed. Data collection occurred under three conditions: the reference condition (GAIT), and two conditions involving placement of the ultrasound probe over the distal medial gastrocnemius-Achilles tendon junction (MTJ) and over the medial gastrocnemius mid-belly to capture fascicles (FAS). Data processing included calculating differences between conditions using root mean square error (RMSE) for joint kinematics and comparing them to the overall mean difference. Additionally, Spearman correlations were calculated to examine the relationship between kinematic RMSEs and walking speed.
Results: No significant differences in stance phase duration or walking speed were observed among the three conditions. Average RMSEs were below 5° for all parameters and condition comparisons in both groups. In both the TD and CP groups, RMSE values during the swing phase were higher than those during the stance phase for all joints. No significant correlations were found between height or body mass and swing phase RMSEs. In the CP group, there was a significant correlation between joint kinematics RMSEs and differences in walking speed at the hip, knee and ankle joints when comparing the MTJ condition with the GAIT condition.
Significance: This study confirms joint kinematics alterations are smaller than 5° due to wearing to the leg an ultrasound probe during walking.

1. Introduction

The combination of three-dimensional (3D) gait analysis with a portable ultrasound device (3DGAUS) allows a direct assessment of muscle and tendon lengths during walking [1–3]. Adding these lengths, assessed in-vivo, to the traditional information from gait analysis opens new horizons for clinical assessment as well as for personalized musculoskeletal models [4–6]. Previous studies have mostly applied 3DGAUS on the triceps surae muscles due to their critical role in stability and propulsion during gait and their easy accessibility for imaging [7,8]. More recently, medial gastrocnemius (MG) muscle belly and MG fascicles length changes have been reported in individuals with cerebral palsy (CP) [9–12]. Reliability studies on 3DGAUS have mostly focused on the imaging side, by analysing the quality of tracking muscle-tendon features and reporting satisfactory results [1,13]. Yet, there is still a paucity of information regarding the influence of wearing an ultrasound probe to the leg during walking, especially in participants with neuromuscular diseases [14].

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Data acquisition applying 3DGAUS technique relies on some requirements on the usage of the ultrasound probe: this should be rigidly attached to a probe holder, located at the anatomical part under investigation, and tilted and coupled to the skin for assuring a clear image visibility of the relevant muscle and tendon features. Up to our knowledge, the ultrasound probes used for 3DGAUS are still wired and around 5–10 cm long. In addition, the combination of probe and probe holder increase the mass for the leg segment of around 10 % in adults and 15 % in children [15]. Therefore, the ultrasound probe size induces suspects on their effect on gait pattern, especially for lower limb joint kinematics. Also, this might be even more relevant for smaller participants or in individuals with impaired gait patterns such as individuals with CP. Mooijekind et at. [14] showed a knee flexion 5° lower in swing phase and 3° lower ankle plantar flexion around toe-off when an ultrasound probe was attached to the MG compared to walking without an ultrasound probe attached. This study was conducted on a treadmill and with a commercially available probe holder. Since overground walking at self-selected speed reflects typical daily activities, the previous results need further verification in such condition. Additionally, to generalize the previous findings, a generic custom-made probe holder is required.

Therefore, the aim of the current study was to analyse the effect of wearing an ultrasound probe on the MG at two different positions compared to walking without an ultrasound probe attached in adolescents with cerebral palsy and typically developing (TD) peers. We hypothesized that the errors would be smaller than 5° [14,16] and that the knee flexion in swing would be the variable most affected when the ultrasound probe was attached. In addition, considering the relevance of walking speed in kinematic and spatio-temporal parameters [17], its influence for the differences between conditions will be assessed.

2. Methods

2.1. Participants

Eleven individuals with CP (17.2 ± 4.2 years, 1.66 ± 0.084 m, 57.9 ± 12.3 kg, Gross Motor Function Classification System: level I = 8, level III = 3) and 9 TD peers (18.2 ± 4.4 years, 1.71 ± 0.11 m, 66.1 ± 11.8 kg) were included in this study. The study was approved by the Research Ethics Committee of Central Finland Hospital District (Dnro 8 U/2017 amended 2021) and a written informed consent was acquired from participants and legal guardians of those under 18 years of age.

2.2. Data collection

One operator placed 20 reflective markers on the body according to the lower-limb Plug-in-Gait model [18]. Participants were asked to walk barefoot along an 8-meter walkway at self-selected speed. After a few minutes of habituation, a minimum of six trials were collected. This baseline condition will be referred to as GAIT. Afterwards, additional markers were placed on the head of the fibula, tibial tuberosity and medial malleolus [19]. A 60 mm linear ultrasound probe with flat connection to cord (Telemed, SmartUS, Lithuania) was rigidly attached. Predefined US acquisition parameters (focus 17 mm, depth 65 mm, dynamic range 48 dB, power 0 dB, gain 60 %, frequency 8 MHz, 50 frame per seconds) were used and adjusted when needed to maximise the visibility of MTJ and MG fascicles. The US probe was rigidly attached to a custom made probe holder instrumented with four reflective markers and secured to the leg using an elastic band, tight enough to provide a stable coupling with the leg but still limiting soft tissue deformation [1] (Figure S1 in supplementary material). For the CP group, the most affected limb was measured, whereas for the TD participants a random limb was chosen. Two different conditions were recorded with the ultrasound probe fixed to the participant's leg. In the first condition (MTJ), the mid-point of the ultrasound probe was positioned at the distal MG muscle-tendon junction, along the pulling direction of the AT. In the second condition (FAS), the mid-point of the ultrasound probe was positioned at 50 % of the MG muscle length and adjusted transversely to optimize visualization of the MG fascicles, ensuring it was located at the thickest part of the muscle. As for GAIT condition, participants were asked to walk along an 8-meter walkway at self-selected speed and a minimum of six trials were collected for each of the two conditions. The cable connecting the probe to the ultrasound device was stabilized at the participant's hip level using a nylon strap.

A 12-camera, marker-based motion capture system (Vicon Motion Systems Ltd., UK, 200 Hz) synchronized with the portable ultrasound device was used to record marker trajectories. During dynamic trials, one operator carried the ultrasound device approximately 1.5 m behind the participant.

Table 1
Stance phase duration and walking speed (mean ± standard deviation) for each condition in the CP and TD group.

	CP			TD		
	FAS	MTJ	GAIT	FAS	MTJ	GAIT
Stance phase duration (%)	60.2 ± 4.3	60.8 ± 4.4	60.3 ± 4.6	59.3 ± 0.7	58.6 ± 0.9	59.5 ± 1.1
Walking speed (m/s)	1.12 ± 0.34	1.12 ± 0.31	1.17 ± 0.33	1.36 ± 0.09	1.42 ± 0.15	1.38 ± 0.09

Abbreviations; CP: participants with cerebral palsy, TD: typically developing peers, FAS: gait analysis with probe attached on muscle fascicle; MTJ: gait analysis with probe attached on muscle tendon junction; GAIT: gait analysis without probe attached.

2.3. Data processing and statistical analysis

Data were processed using Vicon Nexus (Vicon, Oxford Metrics Ltd, Oxford, UK). Kinematic data were filtered using the Woltring method (mean squared error 10). Since MG length is mostly affected by flexion-extension, only sagittal hip knee and ankle joint angles were calculated. All waveforms were time-normalised to the duration of the gait cycle (GC) from heel strike (0 %) to heel strike (100 %) of the ipsilateral leg.

Only the leg with the ultrasound probe attached to was considered for this analysis. Differences between conditions were calculated for each joint angles and each group separately. An acceptable error of 5° was considered for kinematics [14,16].

Furthermore, differences between conditions were analyzed using root mean square error (RMSE) and Pearson's correlation coefficients. This was done comparing all three conditions (FAS, MTJ, GAIT) with each other for the whole gait cycle duration, stance phase and swing phase. For the whole gait cycle duration RMSE and correlation coefficients were calculated over 101 data points (n). For each participant across all three conditions, a mean toe-off (i.e. the end of stance phase and the start of swing phase) was calculated. This allowed us to have the same data points between different conditions. The individual RMSE between different conditions were calculated for joint kinematics to compare the overall mean difference over the entire gait cycle, stance phase or swing phase and corresponding n-points:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(CON_1 - CON_2)^2}{n}} \quad (1)$$

where CON_1 refers to gait condition without probe and CON_2 to with ultrasound probe. For a better overview for each condition comparison, the sum of RMSE was calculated.

Mooijekind et at. [14] stated that in particular for small children the attached ultrasound cable

being placed close to the knee joint might present a problem. To get a first insight, we calculated the Spearman correlations between height and RMSEs as well as body mass and RMSEs in swing phase for TDs. Only TDs were included in this analysis, since there would be other concomitants in CP participants, such as already decreased knee flexion due

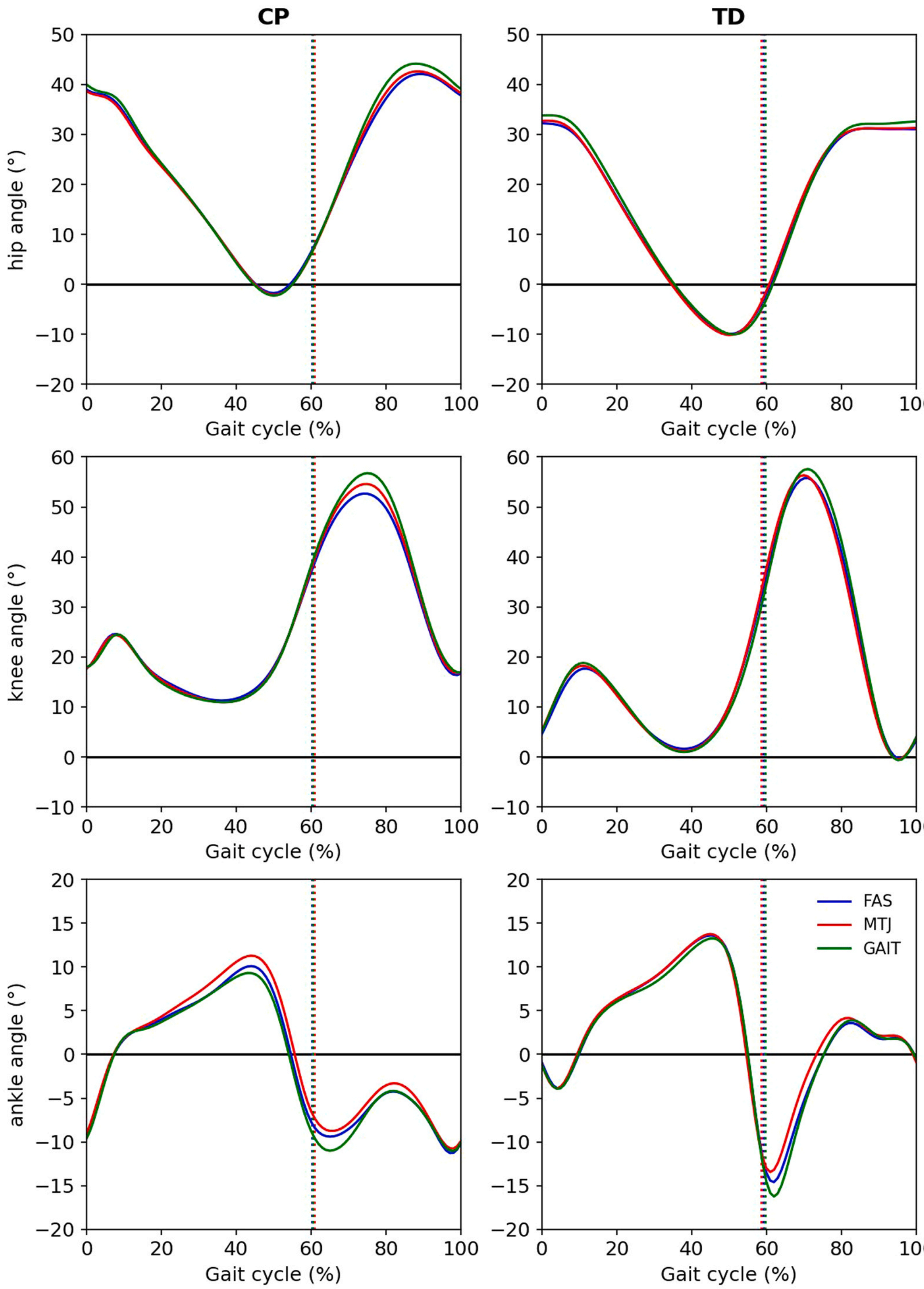

Fig. 1. Mean joint kinematics for hip (first row), knee (second row) and ankle (third row) for participants with cerebral palsy (first column) and typically developing peers (second column). Each condition, FAS, MTJ and GAIT, is reported in blue, red and green respectively. Vertical dotted lines separate stance (from 0 % initial contact) from swing phase (from approximately 60–100 %).

to the underlying neurological disease.

Finally, stance phase duration (%) and walking speed were compared between the three conditions, FAS, MTJ and GAIT, within each group separately by means of a repeated measures ANOVA ($\alpha = 0.05$). Since walking speed might differ between conditions, Spearman correlations between kinematic RMSEs and walking speed were calculated.

3. Results

No significant differences in stance phase duration or walking speed were found among the three conditions ($p > 0.05$, Table 1).

The joint kinematics for the conditions FAS, MTJ and GAIT are shown in Fig. 1 for CP and TD groups, whilst the differences between FAS and GAIT, MTJ and GAIT, and MTJ and FAS for joint kinematics are shown in Fig. 2. The mean difference did not exceed 5° for lower limb joint kinematics in either group.

Similarly, average RMSEs (Table 2) were below 5° for all parameters

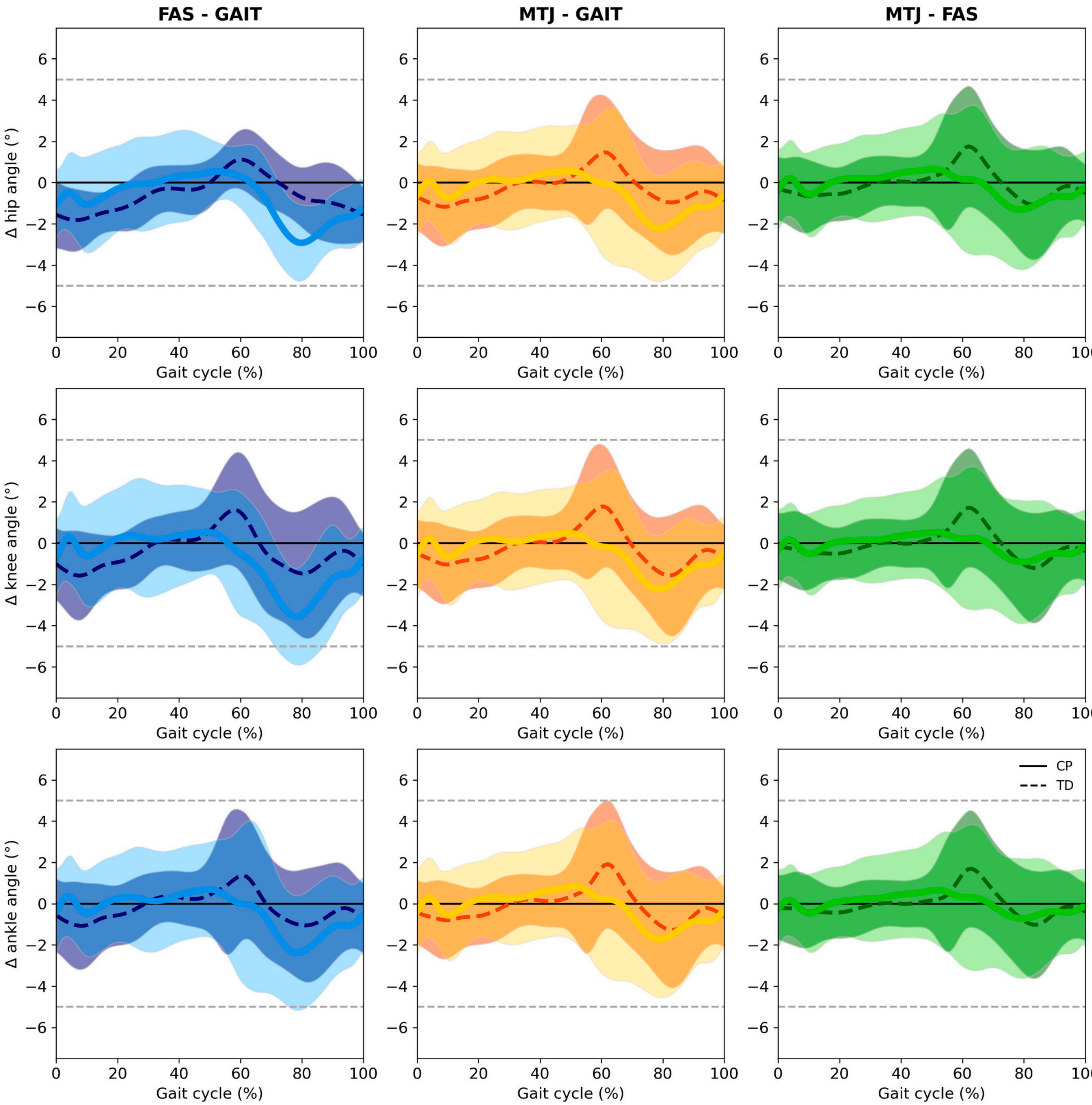

Fig. 2. Mean and standard deviation of the differences between gait conditions are presented. Each column reports the comparisons between gait conditions, whilst each row represents a specific joint (hip, knee and ankle, respectively). Solid lines indicate data for participants with cerebral palsy, while dashed lines represent data for typical developing peers. In each column, the colours distinguish between participants with cerebral palsy (solid lines) and typical developing peers (dashed lines).

and condition comparisons in both groups, with the highest value found for the knee angle during swing phase (3.6 ± 1.6°). In both groups, TD and CP, swing phase RMSE values were higher compared to stance phase values for all joints. The sum of ankle, knee and hip angle RMSE showed lower values for MTJ than FAS in both groups. Except for CP participants comparing FAS to GAIT for ankle angles in swing phase, the correlation coefficients were above 0.9 for all comparisons (Table 3).

No significant correlations were found between height and swing phase RMSEs, and between body mass and swing phase RMSEs. The correlations found were between −0.251 (MTJ-GAIT hip angle) and 0.418 (FAS-GAIT ankle angle) for height, and between −0.333 (MTJ-GAIT sum of ankle, knee and hip) and 0.317 (FAS-GAIT ankle angle) for body mass. The joint kinematics RMSEs were correlated with the differences in walking speed among conditions (Table 4). For CP group, this correlation was significant at the hip, knee and ankle joints when the MTJ condition was compared with the GAIT condition. For TD group, this correlation was significant at the ankle joint for the MTJ condition compared with the GAIT and FAS condition.

4. Discussion

The present study aimed to explore the influence of wearing an

Table 2
Average root mean square error ± standard deviation between three conditions for hip, knee and ankle joint kinematics over the whole gait cycle, stance and swing phase for both groups.

RMSE	CP			TD		
	FAS-GAIT	**MTJ-GAIT**	**MTJ-FAS**	**FAS-GAIT**	**MTJ-GAIT**	**MTJ-FAS**
Hip angle						
Gait cycle	2.1 ± 0.7	2.1 ± 0.7	1.4 ± 0.6	1.6 ± 0.6	1.6 ± 0.7	0.9 ± 0.4
Stance phase	1.9 ± 0.8	1.9 ± 0.9	1.1 ± 0.5	1.5 ± 0.6	1.4 ± 0.6	0.7 ± 0.4
Swing phase	2.4 ± 1.0	2.2 ± 0.8	1.6 ± 0.9	1.6 ± 0.8	1.8 ± 0.8	1.0 ± 0.6
Knee angle						
Gait cycle	3.2 ± 0.9	2.6 ± 0.9	1.8 ± 0.7	2.7 ± 1.0	2.6 ± 0.8	1.7 ± 0.9
Stance phase	2.4 ± 1.2	2.1 ± 0.8	1.5 ± 0.7	2.1 ± 0.8	1.8 ± 0.7	1.1 ± 0.7
Swing phase	3.6 ± 1.6	2.8 ± 1.6	2.1 ± 1.0	3.3 ± 1.5	3.3 ± 0.9	2.2 ± 1.1
Ankle angle						
Gait cycle	2.3 ± 1.2	2.2 ± 1.2	1.9 ± 1.5	1.8 ± 0.7	2.0 ± 0.6	1.6 ± 0.6
Stance phase	2.1 ± 1.1	2.2 ± 1.2	1.7 ± 1.4	1.7 ± 0.8	1.4 ± 0.6	1.0 ± 0.5
Swing phase	2.4 ± 1.6	2.1 ± 1.7	2.0 ± 1.7	1.9 ± 0.8	2.5 ± 1.2	2.1 ± 0.9
Sum						
Gait cycle	7.6 ± 2.3	7.0 ± 2.4	5.1 ± 2.4	6.1 ± 1.6	6.2 ± 1.6	4.2 ± 1.6
Stance phase	6.3 ± 2.7	6.2 ± 2.3	4.4 ± 2.4	5.3 ± 1.4	4.6 ± 1.3	2.9 ± 1.4
Swing phase	8.4 ± 3.0	7.1 ± 3.4	5.6 ± 2.8	6.7 ± 2.3	7.6 ± 2.2	5.3 ± 2.2

Abbreviations; RMSE: root mean square error, CP: participants with cerebral palsy, TD: typically developing peers, FAS: gait analysis with probe attached on muscle fascicle; MTJ: gait analysis with probe attached on muscle tendon junction; GAIT: gait analysis without probe attached.

Table 3
Average correlation coefficients ± standard deviation for hip, knee and ankle joint kinematics between two conditions over the whole gait cycle, stance and swing phase for both groups.

Correlation coefficient	CP			TD		
	FAS-GAIT	**MTJ-GAIT**	**MTJ-FAS**	**FAS-GAIT**	**MTJ-GAIT**	**MTJ-FAS**
Hip angle						
Gait cycle	0.995 ± 0.005	0.997 ± 0.002	0.998 ± 0.002	0.998 ± 0.001	0.997 ± 0.002	0.999 ± 0.001
Stance phase	0.998 ± 0.001	0.998 ± 0.002	0.999 ± 0.001	0.999 ± 0.001	0.999 ± 0.001	0.999 ± 0.001
Swing phase	0.995 ± 0.005	0.997 ± 0.002	0.999 ± 0.002	0.998 ± 0.001	0.997 ± 0.003	0.999 ± 0.001
Knee angle						
Gait cycle	0.985 ± 0.026	0.992 ± 0.007	0.993 ± 0.012	0.993 ± 0.005	0.992 ± 0.005	0.997 ± 0.005
Stance phase	0.937 ± 0.140	0.973 ± 0.033	0.967 ± 0.077	0.982 ± 0.013	0.983 ± 0.015	0.992 ± 0.013
Swing phase	0.990 ± 0.010	0.990 ± 0.010	0.993 ± 0.007	0.994 ± 0.005	0.992 ± 0.005	0.997 ± 0.005
Ankle angle						
Gait cycle	0.971 ± 0.029	0.967 ± 0.037	0.975 ± 0.044	0.978 ± 0.016	0.976 ± 0.018	0.987 ± 0.012
Stance phase	0.962 ± 0.038	0.957 ± 0.045	0.966 ± 0.071	0.968 ± 0.028	0.978 ± 0.024	0.990 ± 0.014
Swing phase	0.886 ± 0.158	0.924 ± 0.070	0.939 ± 0.065	0.981 ± 0.015	0.975 ± 0.025	0.986 ± 0.013

Abbreviations; CP: participants with cerebral palsy, TD: typically developing peers, FAS: gait analysis with probe attached on muscle fascicle; MTJ: gait analysis with probe attached on muscle tendon junction; GAIT: gait analysis without probe attached.

ultrasound probe to the leg during overground walking by using a custom-made probe holder. Overall, the effect of the probe on kinematics is limited, but we still have identified critical aspects to take into consideration before performing 3DGAUS.

The aim of this study was to understand the effect on joint kinematics when a subject wears an ultrasound probe. The results confirmed our hypothesis since RMSEs were smaller than 5°, thus within the clinically acceptable error [16]. Overall, slightly lower RMSE values were found in TD than CP participants. This occurred mostly in individuals with CP with GMFCS III, thereby implying that applying 3DGAUS in severely altered gait pattern might increase joint kinematic alterations. Yet, considering the limited number of participants in this study, this point needs to be further assessed. As hypothesized, we found the knee angle in the swing being the most critical parameter in all the comparisons (Table 2). In particular, the highest RMSE values occurred when FAS and GAIT condition were compared in participants with CP. This finding is in agreement with the one reported on a treadmill-based study [14], thereby suggesting that the attached ultrasound cable, when placed close to the knee joint, influences the gait the most. In addition, the differences in joint angles as well as the reported RMSEs seem lower in our study than the previous results [14]. A possible reason might be the participants' characteristics. Participants in the study by Moojekind et al. were younger and shorter than in our study, where adolescents and young adults were recruited. This appears coherent with the results showing the highest RMSE at FAS condition, where the probe is located more proximally, closer to the knee joint, while for MTJ condition the probe is located more distally. This might suggest a correlation between height and RMSEs at the swing phase, although our results did not show any significant correlations. The available data for height in the current study is not sufficiently spread to answer this question.

This study also investigated the influence of walking speed on RMSEs for different acquisition conditions. The results showed that walking speeds were related to RMSE values, especially when considering the MTJ condition. This seems to be in agreement with previous findings showing an increased step width in MTJ condition [14], thereby slightly influencing walking speed and, in turn, joint kinematics. Therefore, kinematics results derived by MTJ condition should be carefully considered if larger differences in walking speed occur.

This study focused on adolescents and young adults, which may limit the generalizability of the findings regarding the effects of wearing probe and probe holder on joint kinematics. Future studies should include participants of varying ages, heights and body masses to better understand these effects and enhance the generalizability of conclusions. It should be noted that the size of the ultrasound probe may make data collection difficult in very young children, such as those under 5 years of age, thus limiting the extent of generalization of these results in young individuals.

The present study confirms small gait alterations due to wearing an ultrasound probe on the leg during walking in a group of adolescents with CP and TD peers. In addition, considering the differences in walking (overground vs treadmill) and for the probe holder (custom-made vs commercially available) [14], such findings generalize the applicability of 3DGAUS also for overground walking and for custom-made probe holders, although other type of probes would require ad-hoc analysis. Future improvements in the ultrasound probe technology, such a wireless and smaller sensor, would be the ideal direction to further reduce the influence of wearing probe during dynamic

Table 4
Correlation coefficient (p-value) between joint kinematic RMSEs and walking speed over the whole gait cycle, for both groups. Correlation with p-values < 0.05 are denoted.*

Correlation coefficient (p-value)	CP			TD		
	FAS-GAIT	MTJ-GAIT	MTJ-FAS	FAS-GAIT	MTJ-GAIT	MTJ-FAS
Hip angle	-0.500 (0.117)	-0.718 (0.013) *	0.364 (0.272)	-0.283 (0.460)	0.400 (0.286)	0.350 (0.356)
Knee angle	-0.727 (0.011) *	-0.709 (0.015) *	0.364 (0.272)	-0.217 (0.576)	0.183 (0.637)	0.633 (0.067)
Ankle angle	-0.254 (0.450)	-0.682 (0.021) *	0.0637 (0.853)	0.383 (0.308)	0.783 (0.013) *	0.883 (0.002) *

Abbreviations; CP: participants with cerebral palsy, TD: typically developing peers, FAS: gait analysis with probe attached on muscle fascicle; MTJ: gait analysis with probe attached on muscle tendon junction; GAIT: gait analysis without probe attached.

task and further promote similar studies.

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CRediT authorship contribution statement

Francesco Cenni: Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Nathalie Alexander:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Writing – review & editing, Visualization**.** **Iida Laatikainen-Raussi:** Investigation, Resources, Writing – review & editing. **Maria Sukanen:** Investigation, Resources, Writing – review & editing. **Taija Finni:** Conceptualization, Resources, Writing – review & editing, Supervision, Project administration**.**

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2024.05.017.

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