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The influence of wearing an ultrasound device on gait in children with cerebral palsy and typically developing children

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ABSTRACT

Background: Ultrasonography with motion analysis enables dynamic imaging of medial gastrocnemius (MG) muscles and tendons during gait. This revealed pathological muscle-tendon dynamics in children with spastic cerebral palsy (CP) compared to typically developing (TD) children. However, wearing an ultrasound probe on the lower leg could interfere with gait and bias muscle length changes observed with ultrasound.
Research question: Does wearing an ultrasound probe on the MG influence gait in children with CP and TD children?
Methods: Eighteen children with spastic CP and 16 age-matched TD children walked at comfortable walking speed on an instrumented treadmill. One baseline gait condition (BASE) and two conditions with an ultrasound probe and custom-made probe holder were measured: on the mid-muscle fascicles (FAS) and on the muscle-tendon junction (MTJ). The effect of condition and group on spatiotemporal parameters, hip, knee and ankle kinematics, ankle moment, ankle power, and modeled MG muscle-tendon unit (MTU) length was assessed using two-way repeated measures ANOVA's. Statistical non-parametric mapping was applied for time-series. Post-hoc paired-samples t-tests were conducted, and the root mean square difference was calculated for significant parts.
Results: Children took wider steps during FAS (CP, TD) and MTJ (TD) compared to BASE, and during FAS compared to MTJ (CP). Hip extension was lower (2.7°) during terminal stance for MTJ compared to FAS for TD only. There was less swing knee flexion (FAS 4.9°; MTJ 4.0°) and ankle plantarflexion around toe-off (FAS 3.0°; MTJ 2.4°) for both ultrasound placements, with no group effect. Power absorption during loading response was slightly increased for both ultrasound placements (0.12 W/kg), with no group effect. MTU shortened less in swing for both ultrasound placements (FAS 3.6 mm; MTJ 3.7 mm), with no group effect.
Significance: Wearing an ultrasound probe causes minimal lower-limb gait alterations and MTU length changes that are mostly similar in CP and TD.

1. Introduction

Dynamic 2D B-mode ultrasonography (US) can be used to observe medial gastrocnemius (MG) length changes during gait [1,2]. This revealed an important decoupling mechanism between the contractile and elastic tissues of the MG muscle-tendon unit (MTU), which influences gait efficiency [3]. Additionally, it revealed pathological tendon and muscle dynamics during gait in children with spastic cerebral palsy (CP), that may underlie their gait pattern alterations [4–7].

However, several methodological issues are associated with dynamic ultrasound imaging during gait that may compromise the study results. For example, probe tilt, due to the probe weight, and muscle compression can affect measured length changes [8]. These issues could be largely avoided with a custom probe holder [9]. However, probe holders are bulky, which could interfere with gait especially in children and this

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could bias muscle length changes observed with US. Furthermore, adaptation capabilities have shown to differ in CP compared to typically developing (TD) children [10,11]. Therefore children with CP might be affected differently by wearing the probe. Many dynamic US studies focus on comparing CP to TD reference data [4–7], emphasizing the relevance of assessing both CP and TD. Therefore, we investigated whether the presence of an US probe and probe holder on the MG influences the gait pattern and modeled MG MTU length in children with CP and TD children. We expected increased step width and decreased knee flexion in mid-swing due to the location and weight of the probe. Coinciding with the decreased knee flexion, decreased shortening of the MG MTU in swing is expected.

2. Methods

Eighteen children with spastic CP and 16 age-matched TD children (Table 1) participated in this study after providing informed consent. The study was approved by the local medical ethics committee (registration number: NL65846.029.18). Participants walked at comfortable walking speed on an instrumented split-belt treadmill (GRAIL, Motek ForceLink BV, The Netherlands), while wearing gymnastic shoes and a safety harness. 3D kinematics were collected at a sampling frequency of 100 Hz with a 10-camera system (Vicon Motion Systems, Oxford, UK) using the human body model marker set [12,13]. Following six minutes of habituation to determine comfortable walking speed [14], a one-minute baseline condition (BASE) of the children's typical gait pattern was measured.

Subsequently, a 59 mm linear US probe (Telemed SmartUS, Lithuania) was attached to the non-preferred (TD) or most-affected (CP) lower leg using a custom probe holder. The probe holder was designed to minimally compress the muscle and optimally align the probe to the fascicles [16], allowing movements in 5 degrees-of-freedom, and was equipped with four clustered infrared-reflective markers to enable 3D motion tracking (Probefix Dynamic T, USONO, The Netherlands; Fig. 1). The complete probe-holder combination including plastic probe holder (219 g) and probe (111 g) weighs a total of 330 g. Two one-minute trials were collected in random order; one with mid-muscle probe position to image fascicles (FAS) and one on the MG muscle-tendon junction (MTJ). Children were instructed to walk normally. After quality control, eight representative strides per condition were randomly selected for further processing.

3D marker data were processed with Vicon Nexus (v2.3, Oxford, UK). The spatiotemporal parameters step length, step width and stride time were computed using the Gait Off-line Analysis Tool (GOAT v4.2, Motek Medical, The Netherlands). Since MG length is mostly affected by flexion-extension, only sagittal plane hip, knee and ankle kinematics, and ankle kinetics over time-normalized gait cycles were computed using GOAT.

MG MTU length was calculated with musculoskeletal modeling software (OpenSim 4.2, [17]). First, a generic gait model (GAIT2392)

Table 1
Participant characteristics.

	CP (n = 18)	TD (n = 16)
Age (years)	11.1 ± 3.3	10.6 ± 4.2
Weight (kg)	39.0 ± 14.6	42.9 ± 17.5
Height (m)	1.45 ± 0.18	1.51 ± 0.21
Distribution (uni/bi)	8/10	NA
GMFCS (I/II)	9/9	NA
SPAT score MG (0–3)	1:4, 2:1, 3:3, CL:10	NA
Comfortable walking speed (m/s)	0.72 ± 0.14	1.01 ± 0.13

Abbreviations; TD—typically developing children. CP—children with spastic cerebral palsy. GMFCS—Gross Motor Function Classification System. Uni—unilateral. Bi—bilateral. SPAT—clinical SPAsticity Test [15]. MG—medial gastrocnemius muscle. CL—Clonus; no score for the SPAT can be assigned. NA—not applicable.

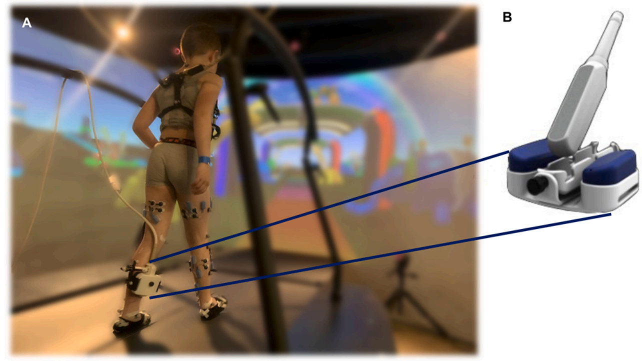

Fig. 1. (A) Ultrasound probe placement on the gastrocnemius muscle-tendon junction. (B) Probefix Dynamic T, USONO, The Netherlands.

was scaled to the participant using marker data of a standing calibration trial. Second, the inverse kinematic tool was used to track the marker data of the walking trials with the scaled model [17]. MG MTU length was extracted with the muscle analysis tool.

A two-way repeated measures ANOVA was conducted to study the effect of group (CP/TD) and condition (BASE/MTJ/FAS) on the spatiotemporal parameters. For kinematics, kinetics, and MTU lengths, a two-way repeated measures ANOVA using statistical non-parametric mapping (SnPM) with 1000 permutations [18] was applied [19]. As this test requires equal group sizes, we conducted it ten times, each time comparing all 16 TD children to 16 randomly selected participants with CP. An effect was considered significant if > 50% of the tests were significant. Post-hoc paired t-tests with Bonferroni correction (SnPM with 10,000 permutations for kinematics/kinetics) were applied. This was done for TD and CP separately in case of an interaction effect, and otherwise, for the BASE/MTJ/FAS main effect over both groups combined. The average root mean square difference (RMSd) was calculated as effect size for all significantly different phases in the gait cycle.

3. Results

Kinetics of four children with CP were excluded from analysis due to poor data quality. All other data could be included.

Step width showed an interaction effect ($p < 0.05$) and was overall increased by wearing the probe (CP: $p = 0.001$; TD: $p = 0.015$). Children with CP walked with significantly wider steps during the FAS condition (18.9 ± 4.49 cm) compared to BASE (16.89 ± 4.36 cm, $p = 0.004$) and MTJ (17.5 ± 4.53 cm, $p = 0.006$). TD children took significantly wider steps during the MTJ condition (16.9 ± 3.17 cm) compared to BASE (15.4 ± 3.17 cm, $p = 0.007$). Step length ($p = 0.135$) and stride time ($p = 0.155$) were not affected by the probe.

Hip, knee, ankle kinematics, and ankle power were affected by wearing the probe ($p < 0.05$; Fig. 2; Fig. 3; Fig. 4). Hip flexion showed a significant interaction effect ($p < 0.05$) with reduced hip extension during terminal stance during MTJ compared to FAS in TD (RMSd 2.7°, $p = 0.002$), but not CP. Both groups showed less knee flexion in swing with both probe placements compared to BASE (FAS/BASE 4.9°, $p < 0.001$; MTJ/BASE 4.0°, $p < 0.001$). Especially in the FAS condition, a large portion of the swing phase showed less knee flexion (60–93% gait cycle). Furthermore, knee flexion in a small part of swing was lower during FAS compared to the MTJ condition (4.1°, $p = 0.003$; 75–89% gait cycle). Wearing the probe also significantly reduced ankle plantarflexion around toe-off (FAS/BASE 3.0°, $p < 0.001$; FAS/MTJ 3.3° and 2.4° for the two significant regions, $p < 0.001$). Additionally, slightly more power absorption was found with the probe in loading response (FAS/BASE 0.12 W/kg, $p = 0.007$; MTJ/BASE 0.12 W/kg, $p = 0.006$).

The alterations in the gait pattern coincided with less shortening of the MG MTU in swing when the probe was worn for both TD and CP (FAS/BASE 3.6 mm, $p < 0.001$; MTJ/BASE 3.7 mm, $p < 0.001$, Fig. 2).

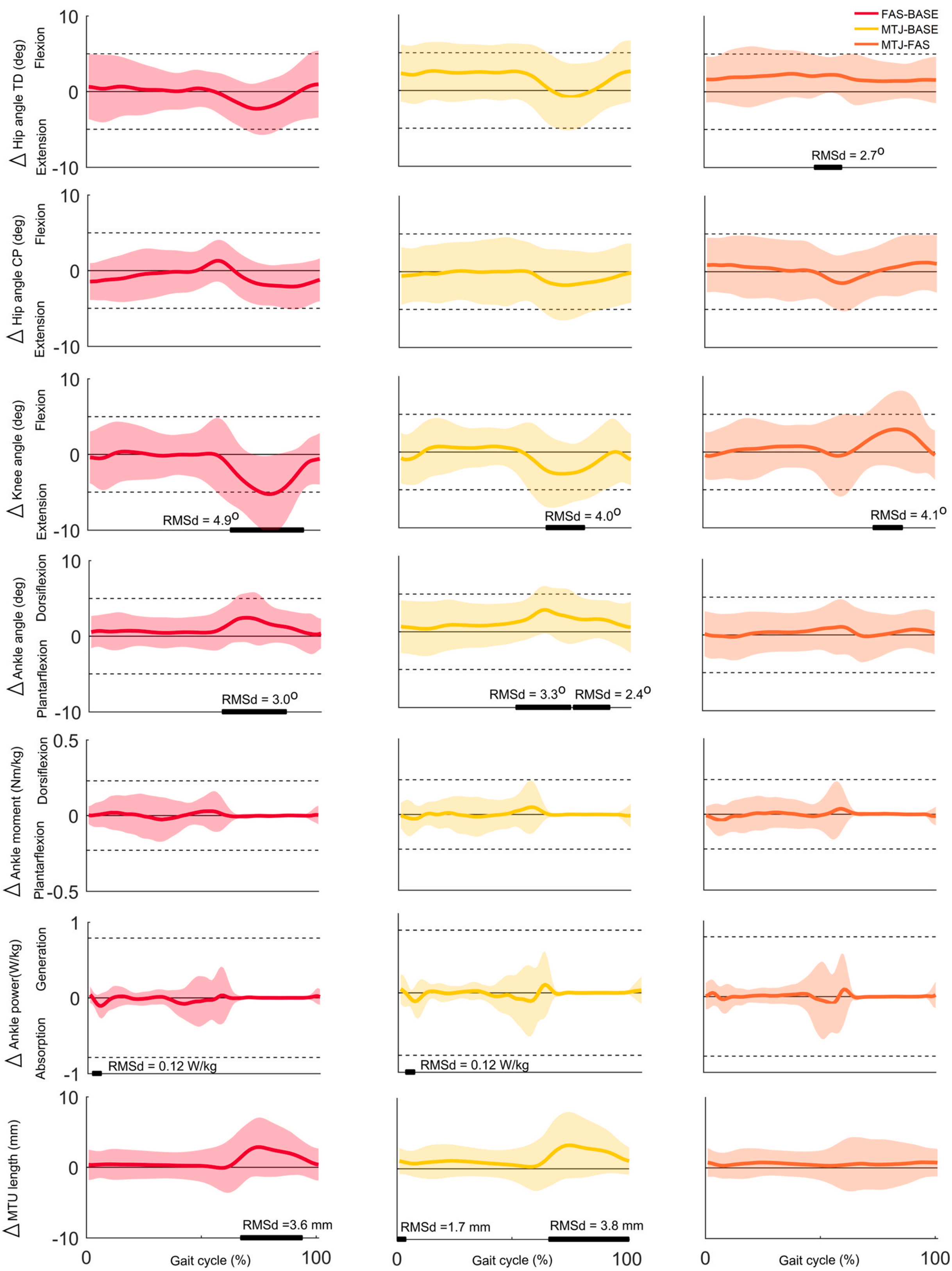

Fig. 2. Average difference with standard deviation between gait conditions, with post-hoc SnPM results. Significant ($p < 0.05$) parts of the curves are indicated with black bars with the corresponding average RMSd values. The dashed lines represent the acceptable error of 5° for kinematics [20], and the standard error of measurement for kinetics [21]. The differences are presented for TD and CP separately in case of significant interactions, and otherwise, combined for TD and CP. Abbreviations; TD—typically developing children. CP—children with spastic cerebral palsy. RMSd—Root Mean Square Difference. MTU—muscle-tendon unit. FAS—gait condition of fascicle tracking. BASE—baseline gait condition. MTJ—gait condition of muscle-tendon junction tracking.

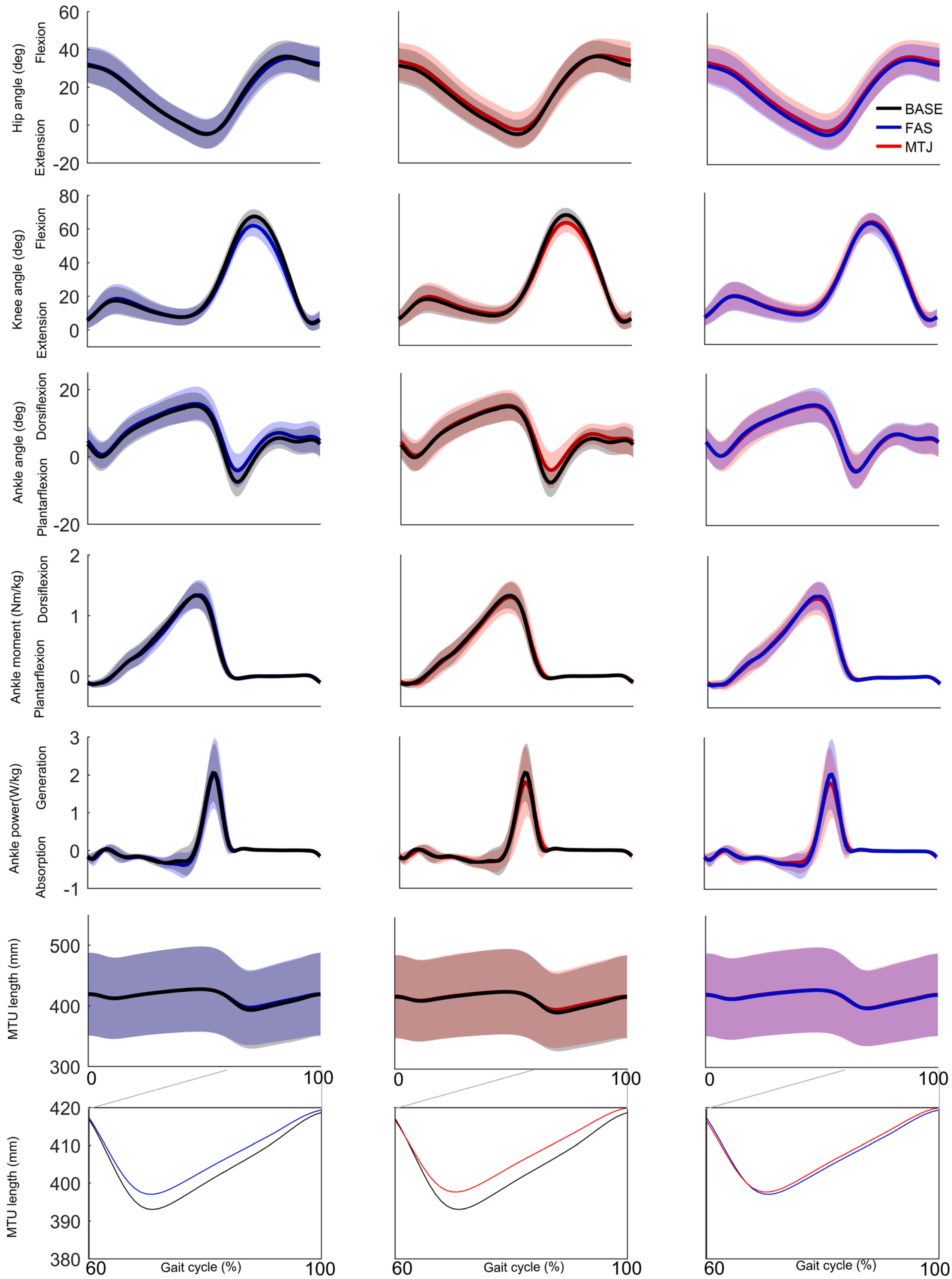

Fig. 3. Average kinematic, kinetic and MTU length curves with standard deviations for TD children. The last row shows zoomed in figures of MTU length without standard deviations. Abbreviations; TD—typically developing children. MTU—muscle-tendon unit. FAS—gait condition of fascicle tracking. BASE—baseline gait condition. MTJ—gait condition of muscle-tendon junction tracking.

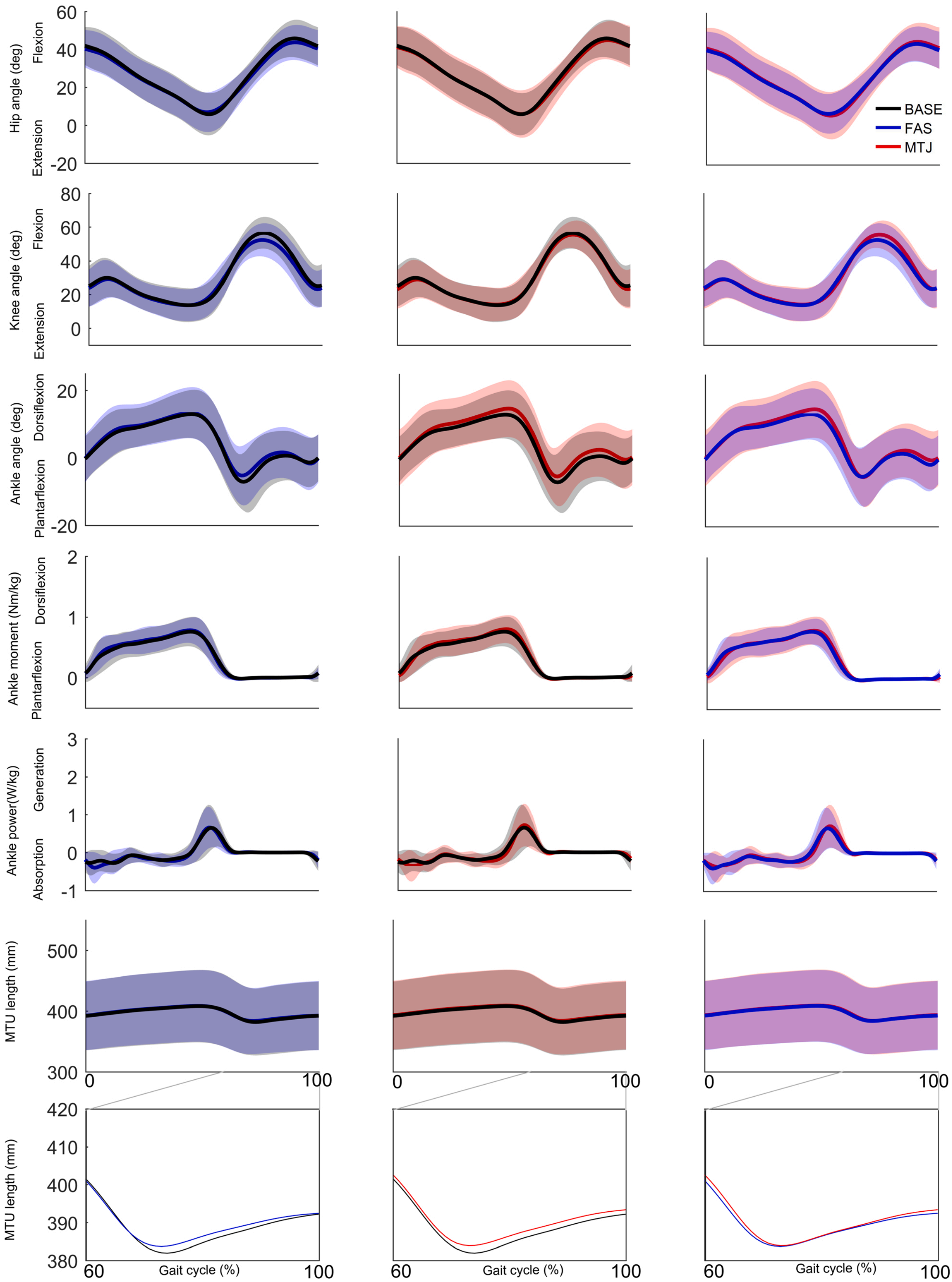

Fig. 4. Average kinematic, kinetic and MTU length curves with standard deviations for children with CP. The last row shows zoomed in figures of MTU length without standard deviations. Abbreviations; CP—children with spastic cerebral palsy. MTU—muscle-tendon unit. FAS—gait condition of fascicle tracking. BASE—baseline gait condition. MTJ—gait condition of muscle-tendon junction tracking.

Additionally, MG MTU length was slightly less shortened (1.7 mm, $p = 0.007$) in loading response during the MTJ condition compared to BASE.

4. Discussion

As hypothesized, wearing an US probe with probe holder leads to slightly increased step width and sagittal plane lower-limb gait alterations. Specifically, reduced plantarflexion around toe-off, reduced knee flexion in initial and mid-swing, and increased ankle power absorption in loading response were observed when wearing an US probe. These kinematic alterations coincided with decreased shortening of MG MTU in swing. The effects of the probe on kinematics can be considered relatively small, since they are similar to the measurement error (<5°) inherent to clinical 3D gait analysis, and smaller than the clinically acceptable error (5°) [20].

Even though the gait alterations are small and, with the exception of minor differences in hip flexion and step width, similar between CP and TD, they occurred systematically and should therefore be considered when interpreting dynamic US imaging results. Reduced knee flexion in swing was probably caused by the US cable being placed close to the knee joint. This is particularly a problem in small children. The reduced ankle plantarflexion around toe-off and ankle power during loading response were possibly due to the added weight of the probe or due to more cautious gait to prevent the probe from slipping off the leg. The low placement over the MTJ made it difficult to avoid probe contact with the opposite leg, which may also explain the increased step width.

MG MTU length was slightly less shortened during swing when the probe was placed on the leg. Compared to age-matched TD children, children with spastic CP generally walk with increased plantarflexion and show reduced MG MTU length during swing [22]. Studies applying dynamic US imaging during gait also identified less muscle belly, tendon and fascicle lengthening during swing in CP compared to TD [4–7]. Our findings on the MTU indicate that shortening could have been underestimated in these dynamic US studies. However, as we did not find an interaction effect, the underestimation is likely to have occurred equally in both groups thus minimally affecting the conclusions drawn.

There are some limitations to this study. Our sample size is small and therefore it could be that we lacked power to find significant interaction effects. Additionally, our results pertain to the probe plus probe holder used in this study. Other dynamic US studies [1,4–7,23] used other types of probe holders with different weights and sizes, which may give different results. Furthermore, this study is performed during treadmill walking, which can result in small changes in kinematics [10] and larger changes in kinetics compared to overground walking [24]. Therefore, treadmill walking itself might also affect muscle dynamics to some extent.

Although effects of the probe are minor, alterations to the measurement equipment could further reduce the effects. For example, a lighter probe or probe holder can be used. Moreover, a more flexible cable may overcome the impediments during swing. In conclusion, minimal and similar gait alterations and MTU length changes due to the probe were found in TD children and children with CP.

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Conflict of interest statement

The authors declare that they have no conflict of interest.

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