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Gait Deviations of the Uninvolved Limb and Their Significance in Unilateral Cerebral Palsy

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Abstract: Little is known about the impact of the impaired limb on the uninvolved side, which might influence the overall functional outcome in individuals with unilateral cerebral palsy (CP). The objective of this work was to perform an assessment considering the kinematics/joint moments and ground reaction forces (GRFs). Eighty-nine individuals with unilateral CP were included and classified according to their functional impairment. Level-specific differences according to the Gross Motor Function Classification System (GMFCS), including pelvic and trunk movements, were analyzed using instrumented 3D gait analysis (IGA). Anterior trunk and pelvic tilt, trunk lean/pelvic obliquity, pelvic internal rotation, hip adduction, and external hip rotation, as well as pronounced flexion (ankle dorsiflexion), at all joint levels were significant kinematic alterations. Concerning joint moments, the most remarkable alterations were hip and ankle flexion, hip abduction, knee varus/valgus, and transversal joint moments at all levels (external rotation moments in particular). The most remarkable differences between GMFCS levels were at proximal segments. The kinematics and joint moments of the sound limb in patients with unilateral CP differ significantly from those of healthy individuals—partially concomitant to those of the involved side or as motor strategies to compensate for transversal malalignment and leg-length discrepancies (LLDs). GRF showed almost identical patterns between GMFCS levels I and II, indicating an unloading of the involved limb. Compensatory motor strategies of the sound limb do not influence functional outcomes.

Keywords: 3D-instrumented gait analysis; unilateral cerebral palsy; GMFCS level-specific compensation mechanisms; sound/uninvolved limb

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Citation: Tsitlakidis, S.; Campos, S.; Mick, P.; Doll, J.; Hagmann, S.; Renkawitz, T.; Götze, M.; Hetto, P. Gait Deviations of the Uninvolved Limb and Their Significance in Unilateral Cerebral Palsy. *Symmetry* **2023**, *15*, 1922. https://doi.org/10.3390/sym15101922

Academic Editor: John H. Graham

Received: 26 August 2023
Revised: 8 October 2023
Accepted: 12 October 2023
Published: 16 October 2023

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1. Introduction

A variety of gait pathologies with different degrees of severity are part of the neuromuscular result and secondary clinical manifestations of cerebral palsy (CP) that often lead to the necessity of orthopedic treatment, among other treatments [1–3]. Here, the extent of the secondary movement disorder (secondary deviation of the involved limb) is dependent on the primary brain lesion [1,4–6]. The secondary deviation itself causes adaption/compensatory movement patterns (tertiary deviation) of the uninvolved limb [7–9].

So far, consensus has been reached for six multiple sagittal joints' gait patterns of the involved limbs of patients with CP [10]. Hence, many classification systems disregard coronal and transversal plane deviations, as well as compensatory adaption/strategy mechanisms of the sound limb (tertiary deviation) in unilaterally affected individuals [7,10]. However, transversal plane malalignment (particularly internal hip rotation of the involved limb) and compensatory deviations (pelvic protraction on the uninvolved side) are of importance for sagittal alignment (foot orientation), as these factors influence joint/muscle leverage (e.g., hip abductor weakness due to mal-rotation), and thus for sufficient propulsion in walking (e.g., altered plantarflexion moment due to mal-rotation) [11–16].

Particularly in unilateral CP, the naturally given asymmetry and consecutive highly complex movement patterns of the disorder on the one hand, and the ability of the sound

limb concerning functional strategies to compensate on the other hand, affect the overall functional impairment, which is commonly classified using the Gross Motor Function Classification System (GMFCS) [8,9,17]. The functional capabilities of the sound limb are highly relevant for the overall propulsion and stability of walking [18,19]. GMFCS level-specific differences considering kinematics and joint moments of the involved limb have recently been described in a preceding work, showing significant differences that might contribute to or at least be the manifestation of the different dimensions of functional impairment [20].

However, the effects and possible tertiary (compensatory) deviations of the uninvolved limb due to gait deviations of the involved limb (secondary deviations) in unilateral CP have received little attention so far [7,8,21]. But it is clear that the gait deviations of the involved limb have an impact on the gait pattern of the sound limb [22]. Furthermore, treatment planning in unilateral CP usually considers and is conducted on the involved side, disregarding the altered gait pattern (tertiary deviation) of the sound limb [7,21]. Thus, capturing all gait deviations is crucial but remains challenging. In this regard, instrumented 3D gait analysis (IGA) is highly significant in this area [4,6,10].

Insights into tertiary gait deviations of the sound limb might lead to a better and more holistic understanding of the pathophysiology of gait deviations in unilateral CP and may have an impact on treatment approaches.

The effects of secondary gait deviations on the sound limb may differ significantly between the different levels of functional impairment (represented by GMFCS levels) and might have an influence on overall functional outcome after treatment.

Hence, the assumption arises that there are GMFCS-level-specific gait deviations and specific characteristics of the uninvolved limb that might indicate and contribute to the different levels of functional capability.

Therefore, the primary objective of this current and consecutive work was a detailed evaluation and description of tertiary gait deviations of the uninvolved limb, particularly between functional subgroups represented by GMFCS levels analyzing kinematic features (including all degrees of freedom), joint moments, and ground reaction forces (GRF) and the extent of asymmetry in individuals with unilateral CP, in order to assess for distinguished subgroup-specific differences.

2. Materials and Methods

The current work was realized as a database study exclusively including patients with unilateral CP and a GMFCS level I or II after approval by the local ethics committee (S-198/2019).

The following inclusion criteria were applied:

- Patients exclusively with unilateral spastic CP;
- Patients functioning in GMFCS level I–II;
- Patients with no previous surgery of the lower limbs;
- Patients with no Botulinumtoxin–A injections within the last six months.

2.1. Study Population

A total number of 89 individuals (40 female, 49 male) matched our inclusion criteria. At the time of instrumented 3D gait analysis (IGA), the mean age was 15.3 ± 9.6 years. Using the GMFCS classification system, all participants were classified according to their functional impairment [17]. Of the 89 included individuals, 63 showed a GMFCS level of I, whereas 26 participants were classified as GMFCS level II. The reference data were derived from a group of typically developing (TD) individuals from our gait laboratory. Twenty-six participants (52 limbs) were included in the TD reference group. The mean age of the TD individuals was 15.1 ± 5.9 years.

2.2. Gait Analysis

IGA was performed from 2006 to 2017. A 120-Hz 9-camera system (Vicon, Oxford Metrics, Oxford, UK) and two piezoelectric force plates (Kistler, Winterthur, Switzerland) read out with a sampling frequency of 1080 Hz (9 times the camera frequency) were used. For motion capturing, according to the Plug-In Gait, a lower body model and protocol reflective markers were applied to bony landmarks [23,24]. In this procedure, the examiner determined the knee axis via a knee-alignment device. In order to capture trunk motion, additional markers were placed on the subjects' shoulder girdle (processus spinosus of the 7th cervical vertebra, left and right acromion, and incisura jugularis) [25]. The participants walked a seven-meter walkway barefoot and at a self-selected speed.

2.3. Data Analysis

Kinematic parameters, joint moments and ground reaction forces (GRF) were processed via commercial software by Vicon (Vicon Nexus 2.12, Oxford Metrics, Oxford, UK) using the Plug-In Gait model averaging at least five strides [23,26]. On the basis of Matlab R2018b (MathWorks, Natick, MA, USA), lab-specific software codes were used in order to conduct visual inspection of stride-to-stride consistency as well as the time normalization of the gait data to the gait cycle (GC in %). The following features were included for further analysis:

- Kinematic parameters:
  - Trunk tilt, trunk obliquity and trunk rotation;
  - Pelvic tilt, pelvic obliquity and pelvic rotation;
  - Hip flexion/extension, hip abduction/adduction and hip rotation;
  - Knee flexion/extension, knee valgus/varus and knee rotation;
  - Ankle flexion/extension, ankle valgus/varus and foot progression.
- Joint moments:
  - Hip flexion/extension, hip abduction/adduction and hip rotation moments;
  - Knee flexion/extension, knee valgus/varus and knee rotation moments;
  - Ankle flexion/extension, valgus/varus and ankle rotation moments.
- Ground reaction forces:
  - Mediolateral (ML) GRF;
  - Anteroposterior (AP) GRF;
  - Vertical (V) GRF.
- Spatiotemporal parameters:
  - Stance phase (StP) duration;
  - Single support (ss) duration;
  - Double support (ds) duration;
  - Swing phase (SwP) duration.

We chose to analyze foot progression (orientation of the foot in relation to the gait direction) rather than ankle rotation, as this parameter is given more clinical importance. The joint moments of each individual were normalized to body weight [26].

The collected features were analyzed by comparing GMFCS levels in order to assess for subgroup-specific characteristics and deviations from the gait of typically developing (TD) individuals.

According to Perry et al., the sub-phases of gait were named as follows: loading response (LR), mid stance (MSt), terminal stance (TSt), preswing (PSw), initial swing (ISw), mid swing (MSw), and terminal swing (TSw) [27].

2.4. Statistical Analysis

Data were analyzed using Matlab R2018b (MathWorks, Natick, MA, USA). For descriptive statistics, mean values and the standard deviations (SDs) were calculated and are displayed graphically. Comparative statistics of subgroup-specific demographic and an-

thropometric characteristics, as well as spatiotemporal parameters, included the two-tailed Student's *t*-test. Using multivariate ANOVA, the interaction effect (involved/uninvolved, GMFCS*gender) was analyzed. Furthermore, using custom scripts in Matlab, comparative continuous statistics (kinematics, joint moments and GRF) using one-dimensional statistical parametric mapping (SPM) were performed with ANOVA-1D followed by Bonferroni's post hoc test for the whole gait cycle. The level of significance was set at $p < 0.05$.

3. Results

3.1. Demographics, Anthropometric Characteristics and Spatiotemporal Parameters

Table 1 shows the demographic and anthropometric characteristics, as well as the spatiotemporal parameters of the GMFCS levels I and II subgroups. There were demographic/anthropometric characteristics that showed no statistically significant differences between the subgroups with respect to all depicted parameters (Table 1). Specifically, there were no statistically significant differences with regard to the leg lengths of the involved side compared to the uninvolved side for both subgroups (plevelI = 0.647 and plevelII = 0.753). A statistical analysis of spatiotemporal parameters showed statistically significant differences between the uninvolved and involved limbs, for both GMFCS levels, as well as between GMFCS levels (Table 1).

Table 1. Demographic/anthropometric characteristics, spatiotemporal parameters and corresponding statistics of the study population.

	GMFCS Level I	**GMFCS Level II**	***p*-Values Level I vs. II**
demographic/anthropometric characteristics			
n	63	26	
ratio f:m	29:34	11:15	
age (years)	14.0 ± 7.3	18.3 ± 12.9	0.053
BMI mean ± SD (kg/m^2)	19.0 ± 3.9	20.6 ± 5.3	0.104
leg lengths (cm)			
leg length involved mean ± SD	76.5 ± 11.4	79.5 ± 12.9	0.286
leg length uninvolved mean ± SD	77.5 ± 11.5	80.6 ± 12.9	0.260
***p*-value leg length involved vs. uninvolved**	0.647	0.753	
leg-length discrepancy mean ± SD	0.9 ± 0.9	1.1 ± 0.9	0.344
spatiotemporal parameters (%GC)			
StP-duration involved	58.6	59.4	0.201
StP-duration uninvolved	63.2	65.8	<0.001
***p*-value StP involved vs. uninvolved**	<0.001	<0.001	
ss-duration involved	36.8	33.9	<0.001
ss-duration uninvolved	41.3	40.5	0.205
***p*-value ss-duration involved vs. uninvolved**	<0.001	<0.001	
ds-duration involved	21.8	25.5	<0.001
ds-duration uninvolved	21.8	25.3	<0.001
***p*-value ds-duration involved vs. uninvolved**	0.962	0.919	
SwP-duration involved	41.4	40.6	0.201
SwP-duration uninvolved	36.8	34.2	<0.001
***p*-value SwP involved vs. uninvolved**	<0.001	<0.001	

Table 2 represents a numerical summary of the obtained gait features, including the results of interaction effect analyses.

Table 2. Numerical depiction of gait features, including the results of interaction effect analyses in the extent of asymmetry.

Gait Features	GMFCS Level I				GMFCS Level II				Within-Subject Factor Un- vs. Involved	Asymmetry (Diff. Uninvolved-Involved)		Between-Subject Factor Asymmetry (GMFCS*Gender)
	Uninvolved		Involved		Uninvolved		Involved			Mean	SD	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD				
Kinematics (°)												
ankle flexion												
initial contact	0.0	4.2	−11.6	8.6	−1.9	6.4	−13.4	8.7	<0.001	−11.5	8.6	0.368
StP max	15.7	3.9	9.2	9.8	16.3	9.4	5.2	11.5	<0.001	−7.8	9.6	0.356
SwP max	5.5	4.6	−7.1	9.2	7.8	10.1	−9.3	10.5	<0.001	−13.9	10.3	0.658
ankle valgus												
StP mean	0.2	1.9	1.1	3.2	−0.2	1.9	1.4	3.4	0.006	1.5	5.1	0.383
SwP max	6.1	4.1	6.5	5.2	6.1	5.3	6.9	5.9	0.428	0.5	5.8	0.430
foot progression												
StP mean	−3.6	8.3	−1.8	10.3	−0.4	13.6	−6.3	21.3	0.824	−0.4	18.1	0.375
knee flexion												
initial contact	11.8	6.4	14.9	8.3	13.7	9.8	17.9	8.5	0.003	3.4	10.5	0.715
StP min	5.9	5.2	5.3	9.3	7.9	9.2	9.6	11.3	0.955	0.1	10.7	0.139
SwP max	59.5	6.8	55.6	8.1	56.2	7.9	49.3	9.8	<0.001	−4.7	11.7	0.611
knee valgus												
StP mean	−1.0	4.1	−1.9	3.6	−3.0	4.4	−2.8	4.1	0.179	−0.6	3.9	0.339
SwP max	9.1	8.3	9.8	8.3	6.3	8.0	7.7	7.9	0.316	1.0	8.9	0.276
knee rotation												
StP mean	3.9	6.9	4.6	7.1	1.1	6.9	−0.4	6.3	0.979	0.0	8.8	0.706
hip flexion												
initial contact	38.4	5.4	33.6	7.5	40.7	10.0	34.9	9.5	<0.001	−5.1	8.6	0.030
StP min	−8.3	6.3	−5.8	7.3	−3.1	8.9	2.6	8.9	<0.001	3.4	6.5	0.186
SwP max	39.7	5.8	37.3	6.9	42.4	9.9	39.4	9.4	0.006	−2.6	8.5	0.135
hip add/abd												
initial contact	1.2	4.3	1.5	4.6	1.4	5.3	0.7	4.4	1.000	0.0	6.0	0.646
StP mean	4.4	3.9	2.9	4.2	2.8	4.0	2.9	6.5	0.197	−1.0	7.5	0.031
hip rotation												
StP mean	−1.0	10.4	5.7	13.1	−3.5	10.9	2.8	18.6	<0.001	6.5	16.2	0.966
pelvic tilt												
StP mean	12.2	4.7	12.8	5.1	14.9	6.8	14.9	6.7	0.009	0.4	1.5	0.599
pelvic obliquity												
StP max	6.3	3.7	3.1	3.2	5.2	4.0	2.8	3.8	<0.001	−2.9	6.3	0.009
StP mean	2.8	3.2	−0.7	3.0	1.7	3.4	−0.7	4.0	<0.001	−3.2	6.3	0.020
toe off			−5.3	3.9			−3.6	3.9	<0.001	−4.0	6.2	0.022
pelvic rotation												
StP min	−0.5	5.3	−4.8	5.1	−1.3	7.0	−4.2	8.2	<0.001	−11.0	11.8	0.985
StP mean	6.6	5.0	−11.6	5.4	7.3	8.1	−11.9	9.6	<0.001	−11.4	12.0	0.903
SwP max	11.0	5.7	−0.7	5.5	10.2	9.6	−0.3	7.7	<0.001	−11.3	12.1	0.815
trunk tilt												
StP mean	−2.6	3.5	−2.6	3.9	−0.7	5.1	−0.8	5.4	0.994	0.0	1.4	0.361
trunk obliquity												
StP mean	1.1	1.6	0.4	1.7	1.0	2.7	2.0	3.2	0.732	−0.1	4.0	0.741
SwP min	−1.9	2.1	−2.2	1.7	−4.4	3.9	−2.6	3.2	0.491	0.3	4.2	0.844
trunk rotation												
StP mean	4.0	5.7	−0.7	5.4	4.0	8.5	−0.7	7.4	0.001	−4.7	12.4	0.960
StP max	7.9	5.9	2.6	5.8	7.5	9.1	2.7	7.3	<0.001	−5.1	12.6	0.943
SwP min	−1.9	5.9	−7.7	5.6	−1.5	7.8	−6.7	8.7	<0.001	−5.6	12.4	0.999
Joint moments (Nm/kg)												
ankle flexion												
StP mean	0.601	0.116	0.675	0.159	0.583	0.146	0.553	0.169	0.016	0.042	0.161	0.699
StP max	1.372	0.270	1.140	0.258	1.178	0.297	0.927	0.291	<0.001	−0.232	0.259	0.345
ankle valgus												
StP mean	0.005	0.041	0.010	0.048	0.002	0.032	0.028	0.052	0.048	0.011	0.053	0.191
StP max	0.085	0.066	0.066	0.060	0.075	0.056	0.088	0.060	0.257	−0.009	0.074	0.023
ankle/foot rotation												
StP min	−0.055	0.031	−0.038	0.034	−0.071	0.044	−0.060	0.036	0.001	0.015	0.041	0.443
StP mean	0.035	0.027	0.033	0.032	0.010	0.041	0.006	0.042	0.570	−0.003	0.049	0.920
StP max	0.139	0.084	0.093	0.047	0.097	0.072	0.060	0.041	<0.001	−0.042	0.090	0.366

Table 2. *Cont.*

Gait Features		GMFCS Level I				GMFCS Level II				Within-Subject Factor Un- vs. Involved	Asymmetry (Diff. Uninvolved-Involved)		Between-Subject Factor Asymmetry (GMFCS*Gender)
		Uninvolved		Involved		Uninvolved		Involved			Mean	SD	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD				
knee flexion													
	StP min	−0.289	0.123	−0.348	0.177	−0.321	0.143	−0.292	0.191	0.125	−0.032	0.195	0.527
	StP mean	0.044	0.108	−0.073	0.174	0.075	0.183	0.050	0.230	<0.001	−0.088	0.220	0.025
	StP max	0.464	0.278	0.234	0.190	0.527	0.293	0.341	0.273	<0.001	−0.212	0.314	0.799
knee valgus													
	StP mean	0.166	0.083	0.149	0.082	0.106	0.102	0.098	0.116	0.244	−0.014	0.114	0.481
	StP max	0.381	0.174	0.344	0.124	0.269	0.132	0.267	0.126	0.142	−0.026	0.165	0.274
knee rotation													
	StP min	−0.047	0.029	−0.021	0.021	−0.060	0.030	−0.040	0.026	<0.001	0.023	0.034	0.708
	StP max	0.113	0.049	0.086	0.035	0.082	0.042	0.050	0.033	<0.001	−0.028	0.045	0.500
hip flex/ex													
	StP max	0.883	0.275	0.722	0.281	0.827	0.311	0.708	0.305	<0.001	−0.144	0.336	0.756
	StP min	−0.684	0.209	−0.553	0.196	−0.599	0.214	−0.435	0.164	<0.001	0.138	0.213	0.837
	SwP max	0.588	0.187	0.493	0.175	0.533	0.151	0.452	0.146	<0.001	−0.089	0.154	0.596
hip add/abd													
	StP min	−0.204	0.166	−0.109	0.157	−0.128	0.116	−0.133	0.110	0.002	0.064	0.187	0.941
	StP max	0.702	0.166	0.703	0.179	0.680	0.183	0.615	0.201	0.470	−0.019	0.242	0.004
	StP mean	0.401	0.105	0.385	0.120	0.381	0.140	0.330	0.129	0.119	−0.025	0.153	0.054
hip rotation													
	StP min	−0.147	0.057	−0.077	0.052	−0.134	0.062	−0.083	0.053	<0.001	0.063	0.072	0.012
	StP max	0.088	0.038	0.070	0.039	0.078	0.045	0.058	0.044	0.001	−0.018	0.051	0.237
	StP mean	−0.008	0.020	0.007	0.036	−0.017	0.033	−0.014	0.039	0.010	0.011	0.041	0.001
GRF (N/kg) mediolateral													
	StP min	−0.400	0.221	−0.288	0.199	−0.292	0.231	−0.283	0.207	0.005	0.083	0.261	0.052
	StP mean	0.257	0.135	0.281	0.140	0.323	0.153	0.361	0.184	<0.001	0.028	0.062	0.219
anteroposterior													
	StP min	−1.730	0.570	−1.819	0.479	−1.680	0.725	−1.551	0.682	0.704	−0.027	0.656	0.109
	StP max	2.075	0.425	1.575	0.448	1.562	0.568	1.247	0.551	<0.001	−0.448	0.508	0.542
vertical													
	StP mean	8.212	0.277	7.849	0.324	8.058	0.501	7.478	0.535	<0.001	−0.424	0.505	0.408
	StP max	11.877	1.352	11.329	1.081	11.582	1.943	11.195	1.644	0.002	−0.503	1.432	0.426

The kinematic measures and joint moments of the uninvolved side over the course of time (averaged GC in %) are shown in Figure 1 (Figure 2 shows complementary data of the involved limb [20]) and Figure 3 (Figure 4 shows complementary data of the involved limb [20]). The additionally evaluated GRF for both the uninvolved and involved limbs are shown in Figure 5.

3.2. Kinematic Features and Joint Moments

Trunk kinematics showed pronounced anterior tilt mainly in the GMFCS level II subgroup during almost the whole GC, whereas level I participants showed a slight anterior tilt only during TSw/LR (Figure 1a). There were no statistically significant differences between levels I and II participants, but there were statistically significant differences for both subgroups compared to the TD (Figure 1a). In the coronal plane, mainly the GMFCS levels I and II participants showed a slight ipsilateral lean during MSt/TSt and a contralateral lean during the whole Sw (Figure 1a). Significant differences were found between levels I and II during Sw and between levels I and II compared to the TD during MSt/TSt and almost the whole Sw (Figure 1a). A slightly increased internal trunk rotation during St with no significant differences was found for both subgroups (Figure 1a). Differences were significant during the LR and MSt/TSt and early PSw compared to the TD (Figure 1a).

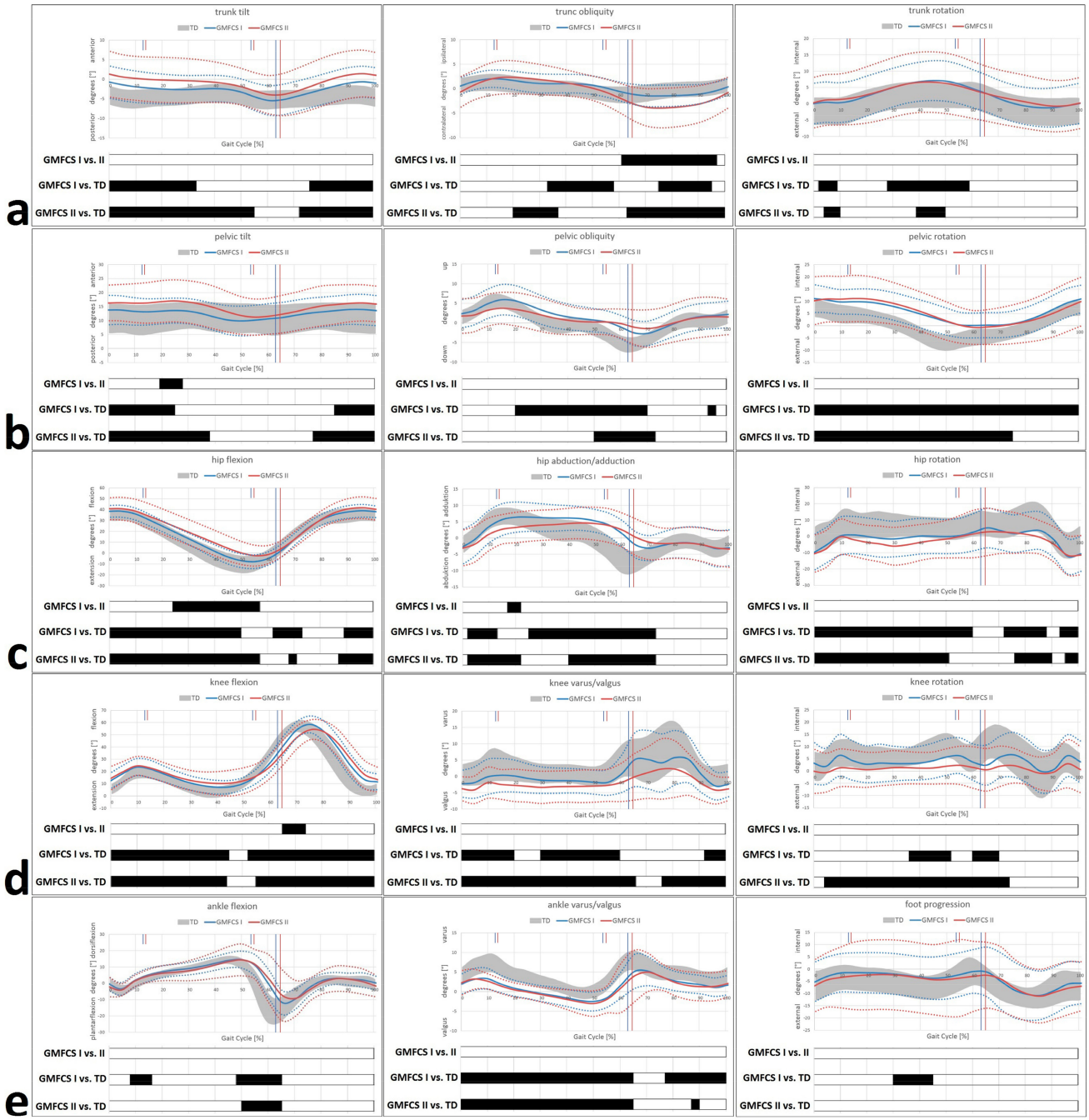


Figure 1. GMFCS-level-specific kinematics of the sound limb. Trunk kinematics (**a**); pelvic kinematics (**b**); hip kinematics (**c**); knee kinematics (**d**); ankle/foot kinematics (**e**). TD group (age-matched typically developing individuals) of the gait laboratory database. Vertical lines represent "opposite foot off", "opposite foot contact", and "foot off", in order to indicate double support phases and to divide the stance and swing phase. Solid lines represent the mean of the sound limb, whereas dotted lines indicate a range of ± 1 standard deviation (SD). Black bars represent the results of SPM and indicate significant differences throughout the gait cycle.

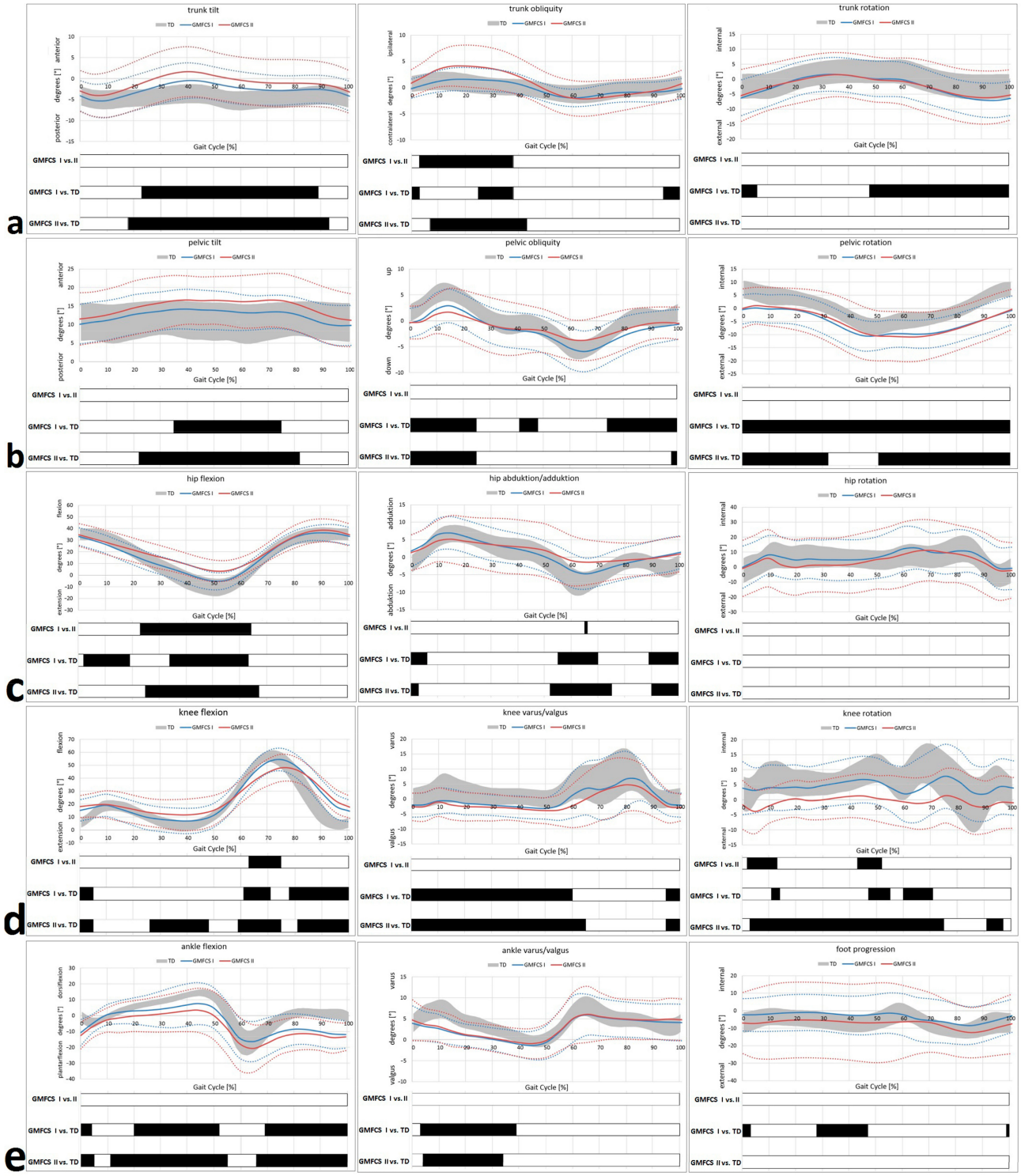


Figure 2. Complementary GMFCS-level-specific kinematics of the involved limb. Trunk kinematics (**a**); pelvic kinematics (**b**); hip kinematics (**c**); knee kinematics (**d**); ankle/foot kinematics (**e**). TD group (age-matched typically developing individuals) of the gait laboratory database. Solid lines represent the mean of the involved limb, whereas dotted lines indicate a range of ± 1 standard deviation (SD). Black bars represent the results of SPM and indicate significant differences throughout the gait cycle. Adapted from [20].

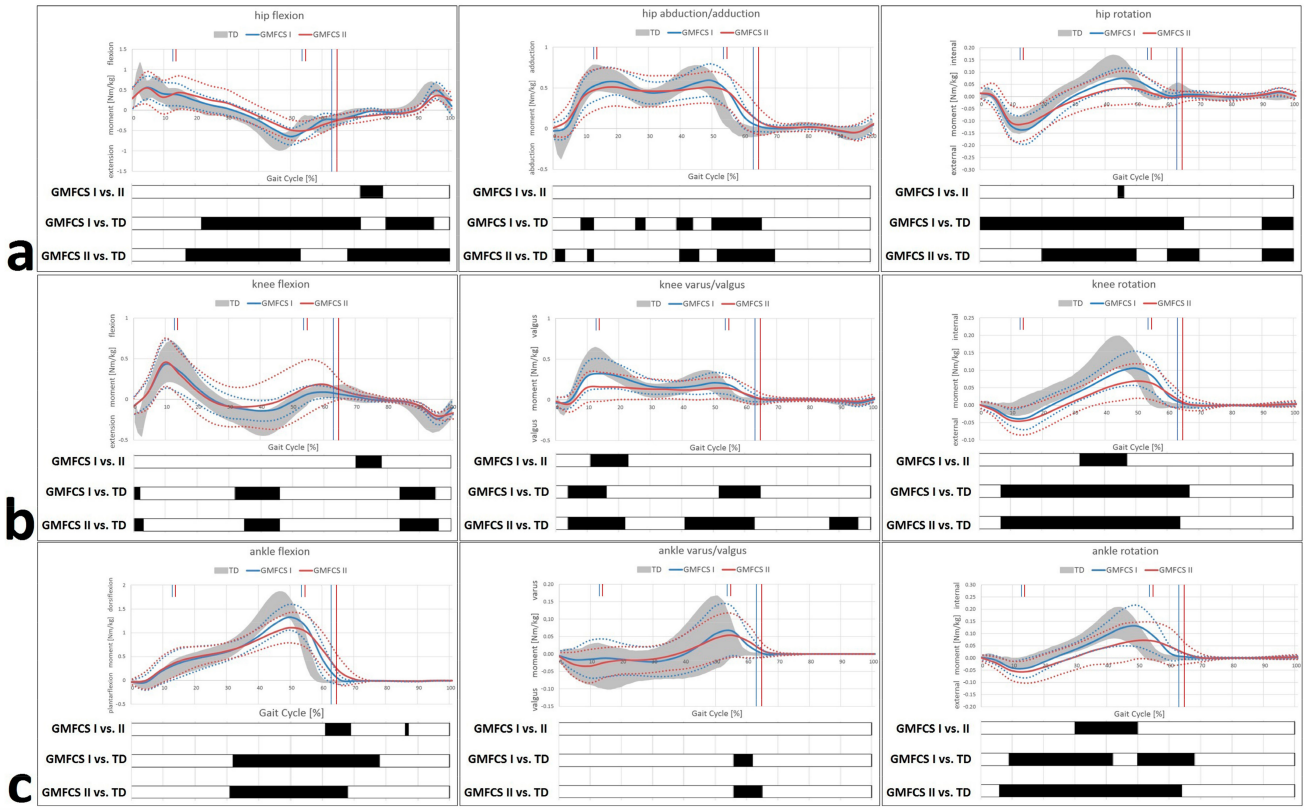


Figure 3. GMFCS-level-specific joint moments of the sound limb. Hip moments (**a**); knee moments (**b**); ankle moments (**c**). TD group (age-matched typically developing individuals) of the gait laboratory database. Vertical lines represent "opposite foot off", "opposite foot contact", and "foot off", in order to indicate double support phases and to divide the stance and swing phase. Solid lines represent the mean of the sound limb, whereas dotted lines indicate a range of ±1 standard deviation (SD). Black bars represent the results of SPM and indicate significant differences throughout the gait cycle.

Anterior pelvic tilt was seen mainly in level II participants during TSw/LR to MSt with significant differences between levels I and II compared to the TD. Statistically significant differences between levels I and II were evident only for a very short period during the GC (Figure 1b). With respect to pelvic obliquity, both subgroups showed slight obliquity from MSt to ISw (Figure 1b). Statistically significant differences were only found compared to the TD (Figure 1b). In the transversal plane, excessive internal rotation of the uninvolved side, and thus pelvic asymmetry, was evident for both subgroups during almost the whole GC with significant differences only compared to the TD (Figure 1b).

At the hip level, increased hip flexion and increased hip-flexion moments were found for both subgroups (Figures 1c and 3a). Hip flexion and moments were pronounced in level II. Significant differences were seen compared to the TD nearly during the whole GC and from MSt to TSt/early PSw between levels I and II with regard to hip flexion (Figures 1c and 3a). Altered hip adduction/abduction—pronounced hip adduction during TSt/PSw to ISw in particular—was found for both subgroups mainly during St (Figure 1c). Hip joint moments in the coronal plane were most noticeably altered from late TSt to ISw (increased adduction moments, Figure 3a). Statistical differences were found mainly during St for levels I and II compared to the TD (Figure 3a). There were no differences or just negligible differences between levels I and II in the coronal plane (Figures 1c and 3a). In the transversal plane, external rotation of the hip with increased external rotation moments/reduced internal rotation moments was found for both levels I and II throughout almost the whole GC (Figures 1c and 3a). There were no statistically significant differences

in the transversal plane between levels I and II but there were such differences compared to the TD (Figures 1c and 3a).

Knee-specific measures revealed increased knee flexion with increased knee-flexion moments for levels I and II during TSt and TSw (Figures 1d and 3b). Differences between levels I and II were negligible, whereas significant differences compared to the TD were evident both throughout the whole GC for sagittal knee kinematics and at IC and during TSt and TSw for joint moments (Figures 1d and 3b). In the coronal plane, individuals with GMFCS levels I and II showed slightly increased knee valgus, especially during St, without statistically significant differences between levels I and II (Figure 1d). Regarding the coronal joint moments, both subgroups showed reduced varus moments, particularly during LR/MSt (Figure 3b). Significant differences were seen between levels I and II during MSt and for levels I and II compared to the TD during MSt and TSt/Psw (Figure 3b) external knee rotation—particularly for level II participants—with reduced internal knee rotation moments was evident during St (Figures 1d and 3b). Differences were found to be significant during the majority of St (Figures 1d and 3b).

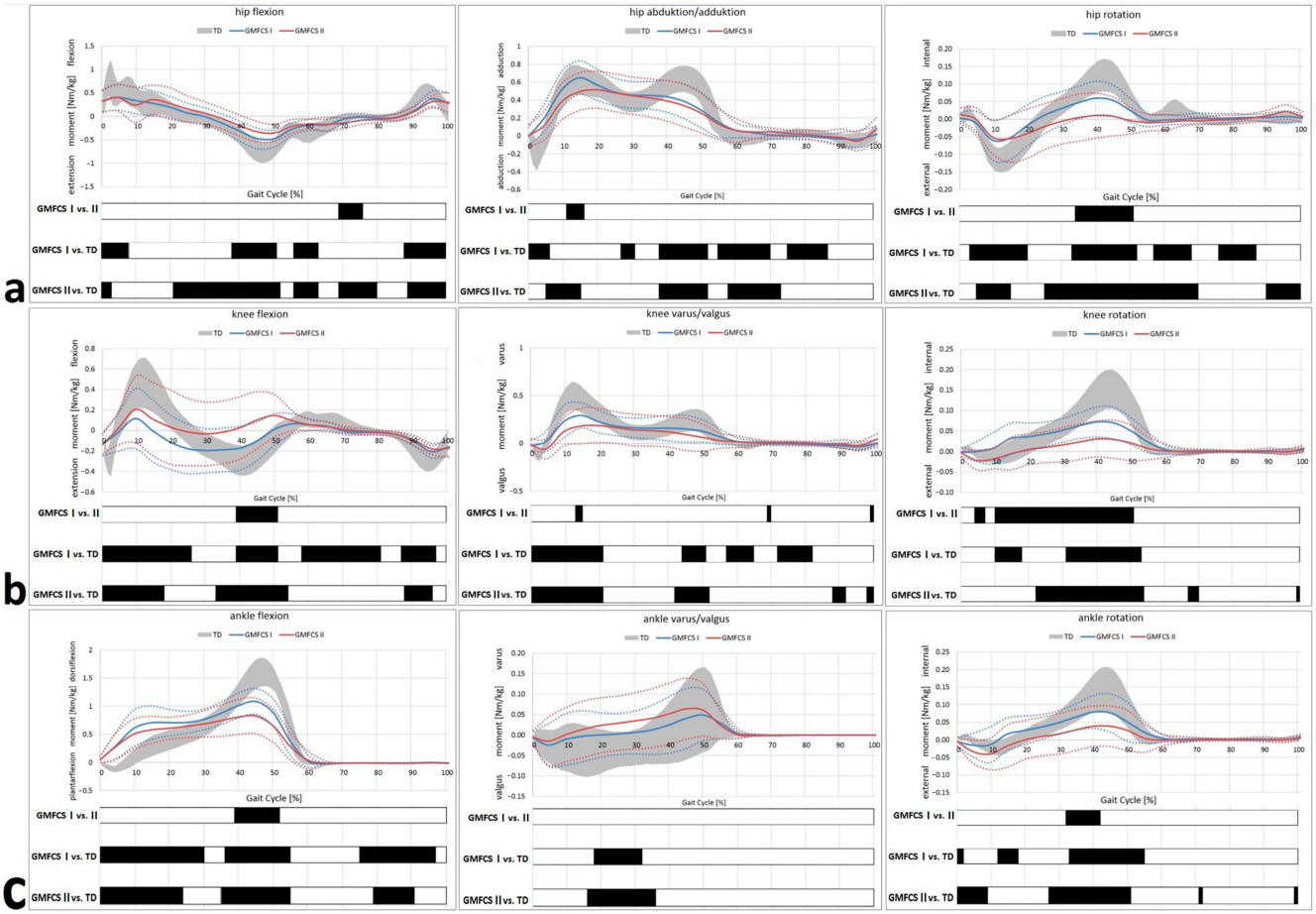


Figure 4. Complementary GMFCS-level-specific joint moments of the involved limb. Hip moments (**a**); knee moments (**b**); ankle moments (**c**). TD group (age-matched typically developing individuals) of the gait laboratory database. Solid lines represent the mean of the involved limb, whereas dotted lines indicate a range of ±1 standard deviation (SD). Black bars represent the results of SPM and indicate significant differences throughout the gait cycle. Adapted from [20].

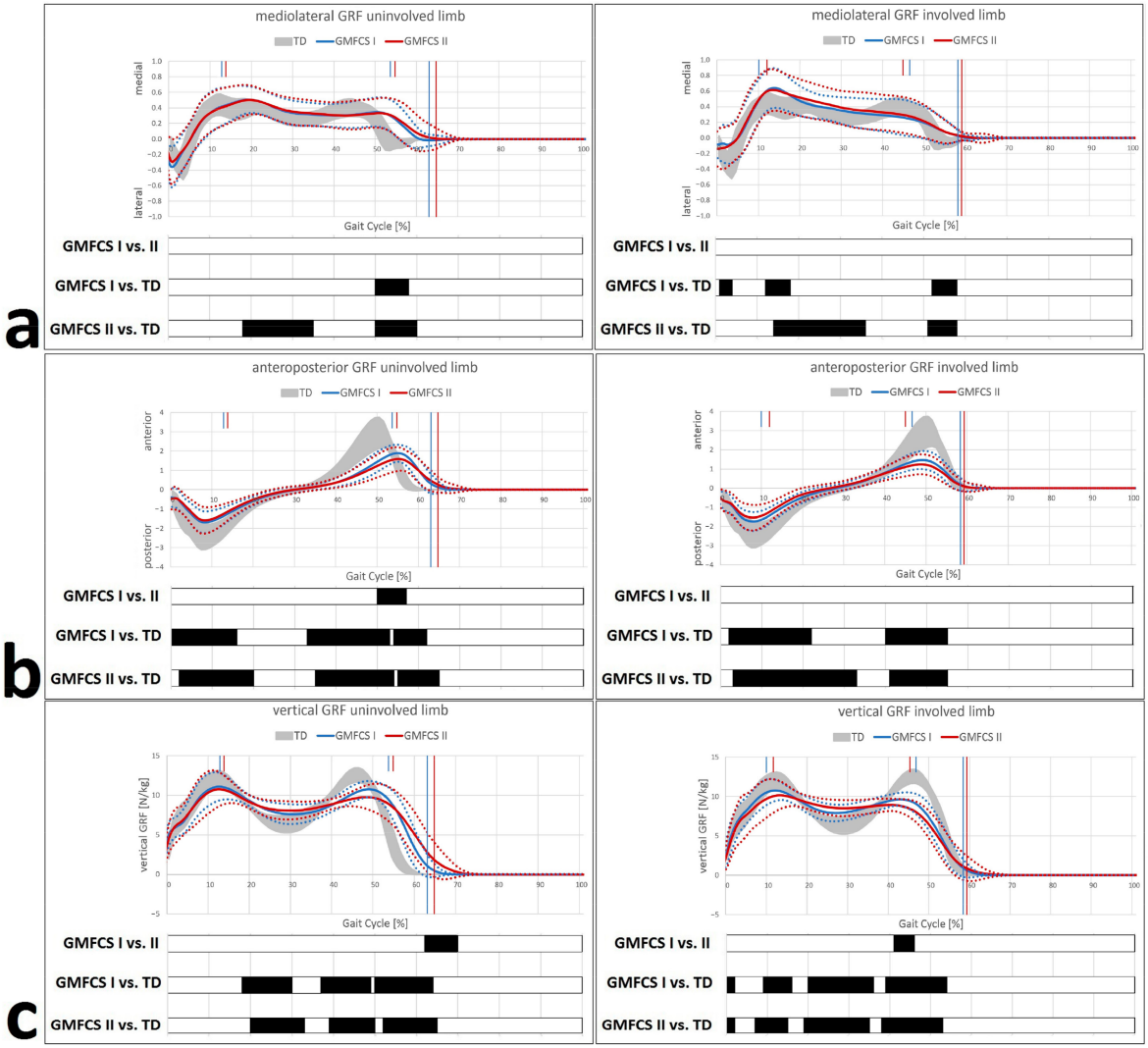


Figure 5. GMFCS-level-specific ground reaction forces (GRFs). Mediolateral GRF (**a**); anteroposterior GRF (**b**); vertical GRF (**c**). Vertical lines represent "opposite foot off", "opposite foot contact", and "foot off", in order to indicate double support phases and to divide the stance and swing phase. Solid lines represent the mean of the specific limb, whereas dotted lines indicate a range of ±1 standard deviation (SD). Black bars represent the results of SPM and indicate significant differences throughout the gait cycle.

At the ankle/foot level, in the sagittal plane, pronounced dorsiflexion/reduced plantarflexion, especially during TSt/PSw with altered sagittal joint moments from TSt to ISw, was found in level I and level II participants (Figures 1e and 3c). There were no differences or negligible differences between levels I and II (Figures 1e and 3c). Differences compared to the TD were significant from TSt to ISw (Figures 1e and 3c). In the coronal plane, kinematic measures showed ankle valgus for levels I and II throughout the majority of GC with altered coronal joint moments from TSt to ISw (Figures 1e and 3c). Relevant significant differences were found with regard to the kinematic measures for levels I and II compared to TD (Figures 1e and 3c). For both subgroups, foot progression was mainly within the range of the TD (Figure 1e), whereas reduced internal/increased external rotation moments were evident (Figure 3c). Here, transversal joint moments were significantly altered between levels I and II during TSt and for levels I and II compared to the TD during the majority of St and ISw (Figure 3c).

3.3. Ground Reaction Forces

With regard to the GRF, there were almost identical patterns between GMFCS levels I and II (no differences or statistically significant differences for only a very short percentage of the GC) with very similar statistically significant differences of both subgroups compared to the TD evident (Figure 5a–c). Furthermore, altered GRFs were found for both the involved and uninvolved sides. On the uninvolved side, the ML-GRF showed medialization during MSt in GMFCS level II and during late TSt/PSw for both subgroups (Figure 5a). The AP-GRF showed reduced amounts for the anterior- and posterior-orientated peaks. The V-GRF for both subgroups was increased during MSt/single support, decreased during the second peak and again increased during PSw (Figure 5c). The alterations on the uninvolved side were also caused to a large extent by the prolonged stance phase (indicated by the vertical lines within the figures). On the involved side, particularly GMFCS level II individuals showed increased medialization of the ML-GRF during MSt, whereas both subgroups showed medialization during PSw (Figure 5a). The AP-GRF on the involved side showed a similar pattern to that on the uninvolved side (considering the prolonged stance phase on the uninvolved side) (Figure 5b). The V-GRF on the involved side showed reduced peaks with an increase between those peaks during MSt for both subgroups (Figure 5c).

4. Discussion

A variety of secondary gait disorders and different levels of functional impairment represent the manifestations of CP as a neuromuscular disease [1,2,4,10]. However, little is known about the impact of neuromuscular pathologies of the impaired limb on the uninvolved limb in individuals with unilateral CP. In particular, the effects of possible deviations of the uninvolved limb that might influence overall functional outcome are unknown.

Therefore, the primary objective of this current work was a detailed survey and assessment between different functional subgroups (represented by GMFCS levels) considering kinematic features and joint moments of tertiary gait deviations of the uninvolved lower limb, as well as the assessment of ground reaction forces and the extent of asymmetry.

In summary, regarding the spatiotemporal parameters, our results indicate the stabilization/optimization of gait via a prolonged StP-duration, ss-duration, and shortened SwP-duration of the uninvolved limb, thus unloading the involved side, with significant differences between GMFCS levels and with level II showing pronounced alterations (Table 1). Additionally, concerning kinematic, kinetic, and GRF data (Table 2), our results indicate statistically significant differences for the vast majority of parameters and therefore a significant extent of asymmetry between the involved and uninvolved limbs and, further, no consistent influence of gender within the GMFCS levels concerning the extent of asymmetry (Table 2).

Furthermore, our results (as shown in Figures 1 and 3) suggest significantly altered kinematics and joint moments of the uninvolved side in unilateral CP at all levels (from trunk to ankle) and in all three planes for individuals with GMFCS level I and level II compared to TD. Anterior trunk and pelvic tilt, trunk lean/pelvic obliquity, pelvic protraction, hip adduction, and external hip rotation, as well as pronounced flexion (ankle dorsiflexion) at all joint levels, were the most remarkable kinematic alterations. Regarding the joint moments obtained, most remarkable alterations compared to the TD concerned hip and ankle flexion, hip abduction, knee varus/valgus, and transversal joint moments at all levels (external rotation moments in particular). Most remarkable differences between GMFCS levels were seen particularly at proximal segments (trunk and hips in sagittal and coronal planes), with alterations being more present in GMFCS level II patients. With regard to GRF, there were almost identical patterns between GMFCS levels I and II. The extent of LLD was in general noticeable, relevant, and almost identical between the subgroups, though not statistically significant between the involved and uninvolved limbs (Table 1). Concerning the often encountered and different compensation mechanisms for drop foot, in this work, both subgroups did not show vaulting of or pelvic hike toward the uninvolved side during the swing phase of the involved limb. Taking previous work regarding the

involved limb into account, pronounced knee flexion (particularly during swinging) was predominantly the compensation for drop foot [20].

Apparently, the kinematic features and joint moments of the uninvolved limb in patients with unilateral CP differ relevantly from those of healthy individuals. These findings can be interpreted partially as concomitant and partially as a compensatory motor strategy/tertiary deviation to the secondary gait deviations of the involved limb [20]. Especially gait-phase-dependent trunk and pelvic kinematics in all three planes seem to be concomitant (and mirrored) to the gait deviations of the involved side (anterior pelvic tilt/excessive hip flexion, trunk lean/Duchenne limp, and pelvic retraction due to internal hip rotations/transversal malalignment) [20]. Kinematic alterations at the hip level in all three planes of the uninvolved limb are therefore determined by and compensatory for the pelvic movement pattern due to the gait pathologies of the involved limb [20] but are still less pronounced compared to the involved limb (pelvic anterior tilt leading to increased hip flexion, pelvic protraction causing increased hip external rotation to maintain physiological foot orientation, and pelvic obliquity causing increased hip adduction). The sound hip maintains the ability for extension during late StP (in contrast to the involved side) [20]. The same is evident for knee and ankle kinematics in all three planes. The collected joint moments were mainly concomitant to the more flexed posture and the relatively externally rotated orientation of the uninvolved side, particularly leading to increased hip-flexion and knee-flexion moments sustaining increased loads as well as increased external rotation moments on all joint levels. Increased hip adduction moments, particularly during PSw, might be, on the one hand, the result of prolonged stance phase (indicated by vertical lines within the figures) and, on the other hand, due to pelvic obliquity caused by leg-length discrepancy (LLD). Our results are consistent with those previously reported [7,21,28,29]. Absolute values comparable to those encountered during our investigations were reported, though only considering sagittal joint kinematics and partial joint moments for the uninvolved limb [28,30]. Generally, the movement pattern of the sound limb was assumed to be the result of the secondary deviation of the involved limb and a strategy to provide increased stability in order to optimize gait [8,9,21].

Moreover, increased hip and knee flexion, increased dorsiflexion during swing, and stance and valgus foot deformity of the uninvolved limb in unilateral CP were reported to be associated with and compensatory for LLD in order to reduce the functional leg length of the sound limb and thus to improve symmetry at the pelvic level [7,21,28]. The described alterations were observed during our analyses and are furthermore important to ensure ground clearance. With regard to LLD, our results suggest that knee flexion might be the most important and most capable factor for ensuring ground clearance, as it was the most pronounced and evident/predominant for the longest period of the GC (during the stance and particularly during the swing phase).

Furthermore, particularly in the transversal plane (which underlines the relevance of transversal plane deviations for gait function and walking capability), despite distinct gait deviations at the pelvic level, the sound limb is able to compensate for excessive pelvic protraction and to maintain transversal kinematics within the range of the TD below the pelvic level and thus to ensure sufficient lever arm function [13–15]. In their analysis of anatomical and dynamic rotational alignment in unilateral CP, Riad et al. describe comparable transversal kinematic characteristics of the uninvolved limb as found in our study [29]. While pelvic transversal asymmetry due to internal hip rotation of the involved limb was evident, transverse plane alignment (hip and knee rotation, as well as foot progression) was found to be within the range of the TD on the uninvolved side [29], whereas our results indicate that additional external hip and knee rotation can be assumed as a compensatory motor strategy to maintain the neutral foot progression of the uninvolved limb. The authors concluded that rotational malalignment may contribute to gait deviations, even in individuals with mild unilateral CP [9,29].

These reports support our findings suggesting that the uninvolved hip joint in particular plays a key role in compensating for gait asymmetry. Tretiakov et al. found limited compensations on the uninvolved limb side if the anatomic alignment was significantly asymmetric [9]. This was concluded to be a reason why transversal plane changes in the pelvis after femoral rotation osteotomy are unpredictable [9]. Generally, the obtained data suggest that the hip level is the most relevant joint level for an effective compensatory movement strategy, as it shows the most dimensions of freedom. Additionally, joint levels below the hip—especially in the transversal plane—show a decreasing extent of deviation (e.g., foot progression and level I vs. level II), which supports the assumption that the hip can effectively compensate especially for transversal malalignment. Compensations for leg-length discrepancies are seen in hip and knee flexion.

Regarding the GRF, it seems that patients with unilateral CP (both GMFCS levels I and II) try to unload the involved limb, which is particularly indicated by the medialized ML-GRF during single support and late preswing on the involved side, the reduced V-GRF at its first peak on the involved side, and the prolonged stance phase on the uninvolved side, and thereby to a large extent causes alterations of the GRF. The increased V-GRF on the involved side during MSt might correspond to a shift in the body weight toward the involved side in order to unload the weak hip abductors (trunk lean/Duchenne limp [20]). Furthermore, the altered AP-GRF indicates a reduced step length on both sides. These are commonly seen alterations of GRF in hemiplegic patients [21,31,32]. The reduced V-GRF during the late stance (particularly the second peak) and the prolonged stance phase of the uninvolved limb are especially shown to be a result of not being able to support the body weight and to unload the involved side [21,33].

Differences between GMFCS levels were noticeable but not distinguished enough to cause functional differences. The main factor for overall functional outcome mainly seems to be the severity of the impairment of the involved side [20]. Compensatory motor strategies of the sound limb seem to not have an impact on the overall functional outcome, but gain relevance, as, on the one hand, considering these deviations of the originally uninvolved limb supports the clinician with decision making for treatment concerning the causative secondary deviation of the involved limb. On the other hand, tertiary deviations should be considered in treatment decision making, as they themselves overload the uninvolved limb and therefore predispose the individual to or at least might be associated with secondary conditions as hip impingement or osteoarthritis of the hip and knee joints [21,34–37].

The main limitation of this current work is that subgroup allocation was realized based on functional impairment, disregarding morphologic subtypes and gait patterns. Thus, different gait patterns are included in the different subgroups, compromising the interpretability and comparability of our findings to the often-used gait-pattern-based classification of individuals with CP. Hence, information on gait deviations of the uninvolved side according to morphological subgroups cannot be given this way. Further studies are needed to evaluate, for example, if these fingerprint-like gait patterns of the uninvolved side would resolve themselves or persist after the treatment of the impaired limb.

5. Conclusions

Kinematic features and joint moments of the sound limb in patients with unilateral CP differ significantly from those of healthy individuals. Trunk and pelvic deviations are mainly concomitant to those of the involved side, leading to pelvic asymmetry. Deviations of the sound limb (external rotation of the hip/knee and increased hip/knee flexion and ankle dorsiflexion) function as motor strategies to compensate for pelvic asymmetry/transversal malalignment and LLD of the involved limb should be taken into account for therapeutic decision making. Furthermore, the GRFs of the involved and uninvolved limbs indicate the unloading of the involved limb and overloading of the uninvolved limb. However, tertiary deviations of the sound limb do not have an impact on the overall functional outcome but might lead to unphysiological and overloading, causing secondary

conditions on the uninvolved side. Future studies should, on the one hand, focus on gender-specific biomechanical differences, especially in treatment decision-making in terms of personalized therapy, and, on the other hand, should focus on the evaluation of applied therapies in pre- and post-treatment comparisons of patient biomechanics, including the involved and uninvolved sides, and thus to assess the effectiveness of therapy with respect to the extent of asymmetry.

Author Contributions: Conceptualization, S.T. and P.H.; methodology, S.T., S.H. and M.G.; formal analysis, S.T., P.M., J.D. and T.R.; investigation, S.T., P.H., T.R. and M.G.; data curation, S.T. and S.C.; writing—original draft preparation, S.T.; writing—review and editing, S.T., S.C., P.M., J.D., S.H., T.R., M.G. and P.H.; visualization, S.T.; supervision, M.G.; project administration, S.T., M.G. and P.H. All authors have read and agreed to the published version of the manuscript.

Funding: For the publication fee we acknowledge financial support by Deutsche Forschungsgemeinschaft within the funding programme "Open Access Publikationskosten" as well as by Heidelberg University.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of the Medical Faculty of the Ruprecht Karls University of Heidelberg (S-198/2019).

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: Essential participation in the conception and design of the study and the acquisition, analysis and interpretation of data were carried out by all authors. The manuscript was edited and approved by all mentioned authors. For the publication fee we acknowledge financial support by Deutsche Forschungsgemeinschaft within the funding programme "Open Access Publikationskosten" as well as by Heidelberg University.

Conflicts of Interest: The authors declare no conflict of interest related to this specific research. The funders mentioned below had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results. Prof. Tobias Renkawitz has received research support and personal fees from Arbeitsgemeinschaft Endoprothetik (AE), DGOU, DGOOC, BVOU, DePuy International, Otto Bock Foundation, Deutsche Arthrose Hilfe, Aesculap, Zimmer, German Research Foundation (DFG), Stiftung Oskar Helene Heim Berlin, Vielberth Foundation Regensburg, the German Ministry of Education and Research, and the German Federal Ministry of Economic Cooperation and Development. He is the Medical Director and Chair at the Orthopaedic Department at Heidelberg University Hospital, a board member of the German Society for Orthopaedics and Trauma (DGOOC), and the vice president of the Professional Association of Orthopaedic Specialists and Trauma Surgeons (BVOU). For the remaining authors, no conflicts of interest were declared.

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