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CASE REPORT

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Biomechanical gait parameters change with increasing virtual height in a child with spastic cerebral palsy: A case report

Regine Lohss[1,2] | **Rebecca Winter**[1,2] | **Beat Göpfert**[1,2] | **Rosa M. S. Visscher**[2,3] | **Morgan Sangeux**[1,2] | **Norbert Zentai**[2] | **Elke Viehweger**[1,2,4]

[1]Laboratory for Movement Analysis, University Children's Hospital Basel, Basel, Switzerland

[2]Department of Biomedical Engineering, University of Basel, Basel, Switzerland

[3]Careum School of Health, Kalaidos University of Applied Sciences, Zurich, Switzerland

[4]Department of Orthopedics, University Children's Hospital Basel, Basel, Switzerland

Correspondence
Regine Lohss, Department of Biomedical Engineering, University of Basel, Hegenheimermattweg 167c, 4123 Allschwil, Basel, Switzerland.
Email: regine.lohss@unibas.ch

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Key Clinical Message

Virtual height exposure coupled with motion capture is feasible to elicit changes in spatiotemporal, kinematic, and kinetic gait parameters in a child with cerebral palsy and should be considered when investigating gait in real-world-scenarios.

KEYWORDS

biomechanical phenomena, cerebral palsy, gait analysis, motion capture, virtual height

1 | INTRODUCTION

Cerebral palsy (CP) is a group of nonprogressive, neurodevelopmental disorders occurring in the early childhood due to an injury to the developing fetal or infant brain.[1,2] The most prevalent type of CP is spastic CP, which affects around 90% of all children with CP[2]. Spastic CP is mainly associated with an increased muscle tone, leading to contractures in the calf muscles and hamstrings, which can result in abnormal walking patterns such as toe-walking. These spastic hemiplegic gait patterns are known to limit static and dynamic stability.[3,4]

The clinical gait analysis (CGA) is a standardized method to quantify gait deviations in children with CP. The CGA is usually performed in a conventional gait laboratory using a 3D motion capture system, force plates, and electromyography.[5] Walking patterns in a gait laboratory are usually captured in a very secured, standardized, and repetitive way, which involves walking in a straight line at consistent speed. Providing instead more complex and challenging real-world-scenarios may reflect walking adaptations and compensation strategies the children with CP have to deal with. Gait data collected in real-world-scenarios may support diagnostic and therapeutic approaches with the aim to preserve the independent and safe walking of the child both within and outside the home environment.

Gaining insight into walking adaptations in real-world-scenarios can thus contribute to a more comprehensive understanding of the child's disability and functioning in different environments according to the International Classification of Functioning, Disability and Health framework.[6]

Virtual reality (VR) can be coupled with motion capture systems to simulate real-world-environments while

	Unaffected side	Affected side
Muscle strength hip		
Flexors	5	5
Extensors	3+	3
Abductors	3+	3+
Internal rotators	3+	2
External rotators	3+	2-
Muscle strength knee		
Flexors	4	3+
Extensors	4	4
Muscle strength foot		
Plantarflexors (knee extended)	4	2
Dorsiflexors	3+	3

TABLE 1 Manual muscle strength evaluation of the muscles surrounding the hip, knee, and ankle joint of the unaffected and affected side[30] (see Table S1 for a detailed description of the muscle strength classification levels).

maintaining secured controlled settings that allow standardized data collection. Virtual environments (VE) can be developed for a specific purpose, for example, virtual height exposure to elicit instability during walking.[7,8] Applying the VE through a head-mounted display (HMD) increases the perception of being physically present in a non-physical world. This perception makes the laboratory environment disappear and with it the feeling of being evaluated by an observer and being obliged to perform well, linked possibly to the so-called "Hawthorne effect".[9] The child might show different gait patterns during VR immersion and even fall back into the personal gait pattern, which has already been shown in studies analyzing walking outside compared to inside the gait laboratory.[10]

Currently VR is mainly used as a treatment tool to improve walking patterns,[11–13] static and dynamic balance,[12–16] and selective motor control[17–19] in children with CP. A recent scoping review revealed only few studies that investigated the immediate effect of VR on walking patterns.[20] Most of the studies analyzed the effect of VR on treadmill walking,[21–26] further combined with immersive biofeedback, modulation of treadmill speed and incline. There is a lack of studies analyzing the effect of more challenging VE that resemble real-life-scenarios on walking patterns. The results might enhance the understanding on how children with CP respond to more challenging scenarios, possibly by applying compensation mechanisms. Additionally further research should clarify the effect of VR notably on overground walking, which resembles more to natural walking compared to overground walking and is the most frequently analyzed condition in CGA.

The aim of this case study was to investigate how immersive virtual height exposure change spatiotemporal, kinematic, and kinetic parameters in a 10-year-old boy with right hemiplegia attributable to spastic CP. Biomechanical gait parameters were captured using marker-based motion capture system[27] and were compared between overground walking in a conventional gait laboratory and walking in an immersive VE on a virtual plank of different heights. This case study is part of a pilot case–control investigation (NCT04879199), performed to optimize the study procedure for a future large case–control investigation including children with spastic CP and age-matched typically developing (TD) children with the overall objective to examine the effect of virtual height exposure on static and dynamic stability.

1.1 | Participant information

The participant was a 10-year-old boy (weight: 22.6 kg, height: 1.26 m) with right hemiplegia due to spastic CP. Main exclusion criteria for the pilot study (NCT04879199) were: orthopedic surgeries in the lower extremities (<1 year), or botulinum toxin A treatment (<6 months). The participant was classified level I according to the Gross Motor Function Classification System[28] and scored 6 for each walking distance of the Functional Mobility Scale[29] (see Table S1 for a detailed description of the classification levels). At the time of the study, the participant was not wearing any orthoses, but an orthotic insole on the affected side.

2 | CLINICAL FINDINGS

The clinical evaluation was performed prior to the CGA by an experienced physical therapist and included a muscle strength testing of the lower extremity,[30] spasticity

according to the modified Ashworth scale[31] and passive range of motion (ROM).[32] Muscle strength was 3+ or lower for the hip extensors, abductors, internal and external rotators and dorsiflexors of both the affected and unaffected side, and the knee flexors and plantarflexors of the affected side (Table 1; Table S1). Spasticity was clinically measured only in the gastrocnemius muscles of the affected side, classified level 1 (Table S1). Passive ROM was decreased for the hip external rotation and the ankle dorsiflexion of the affected side (Table 2). There was no leg length discrepancy. Both femoral and tibial torsion were normal. A recently performed eye test revealed no visual impairments.

2.1 | Gait analysis

The standard CGA was performed in a conventional gait laboratory. Reflective markers (9.5 mm in diameter) were attached to the participant's lower extremity according to the Conventional Gait Model 2.1.[33] A static trial was recorded to determine the knee flexion axis and verify that all markers are visible. The CGA was performed barefoot on a 5 m walkway at self-selected walking speed, until kinetic data (accurate hit of one of the force plates) and error-free data for the affected side from at least six trials were recorded. Errors included disappearing markers or unforeseen technical interruptions.

2.2 | Virtual reality immersion

Following the CGA, the participant was equipped with the Meta Quest 2 HMD (Reality Labs, Menlo Park (CA), US). A short period was provided for the participant to habituate to the VE. The VE was developed using the cross-platform game engine Unity (Version 2021.2.8f1, Unity Technologies, San Francisco (CA), US). It consisted of a forest since the surrounding trees supported the virtual height perception of the participant. In the VE, a plank was spanned between two platforms (Figure 1). A virtual fox was placed on one platform to motivate the participant's walking. Once the participant approached the fox, it disappeared and reappeared on the opposite platform. The participant performed six trials on each of the following plank heights: 0, 3, and 5 m (Figure 1).

Trials with VR were performed barefoot at a self-selected walking speed. Length, width, and thickness of the plank were set to 5, 0.3, and 0.03 m respectively for all trials. To verify whether the participant walks exactly on the plank, tapes were fixed on the floor along the boundaries of the plank.

2.3 | Data collection and analysis

Marker trajectories were collected at 150 Hz using a 12-camera Vicon Motion Capture system (Vicon Inc., Oxford, UK). Force plate data were collected at 1500 Hz using four Kistler force plates (Kistler Instrumente AG, Winterthur, Switzerland). Both the motion capture system and the force plates were synchronized. The gait events foot strike and foot-off were visually determined in Vicon Nexus (Vicon Nexus 2.9 Vicon Inc., Oxford, UK). Kinematic and kinetic parameters were time-normalized to a gait cycle by equating the time between two consecutive foot strikes of the same

TABLE 2 Passive range of motion (ROM) of the hip, knee, and upper ankle joint of the participant's unaffected and affected side. For comparison, normal range of motion from a healthy and age-appropriate population was provided.[32]

	Unaffected side		Affected side		Normal ROM	
Passive ROM hip						
Flex−/Extension [°]	120	10	130	10	135	20
Ab−/Adduction (knee extended) [°]	35	25	35	30	40	30
Abduction (knee flexed) [°]	35		35		-	
External-/Internal rotation [°]	50	50	30	55	50	40
Passive ROM knee						
Flex−/Extension (hip extended) [°]	100	0	110	0	100	5
Flex−/Extension (hip 90°) [°]	140	−60	145	−60	140	-
Passive ROM upper ankle						
Dorsiflexion (knee 90°, lower ankle fix) [°]	−5		−15		-	
Dorsiflexion (knee 0°, lower ankle fixed) [°]	0		−10		-	
Dorsi-/Plantarflexion (knee 0°, lower ankle free) [°]	20	40	−10	45	15	50

FIGURE 1 Virtual plank heights 0 m (left), 3 m (middle) and 5 m (right).

Parameter	CGA	0 m height	3 m height	5 m height
Walking speed [DN]	0.36 [0.02]	0.34 [0.04]	0.21 [0.06]	0.21 [0.06]
Double support [DN]	0.66 [0.09]	0.87 [0.21]	1.51 [0.56]	1.44 [0.52]
Single support [DN]	1.64 [0.08]	1.54 [0.11]	1.36 [0.17]	1.42 [0.23]
Cadence [DN]	0.25 [0.01]	0.24 [0.02]	0.22 [0.03]	0.22 [0.02]
Stride width [DN]	0.17 [0.03]	0.18 [0.06]	0.20 [0.03]	0.20 [0.03]

TABLE 3 Spatiotemporal parameters (mean [SD]) for the affected side during clinical gait analysis (CGA), walking on the 0, 3, and 5 m virtual plank height. Parameters were normalized by leg length (dimensionless numbers, DN).[34]

leg with 100 data points. Spatiotemporal parameters were normalized by leg length (dimensionless numbers, DN)[34] (see Table S2 for a detailed explanation of the spatiotemporal parameters). Calculated parameters were sagittal plane kinematics as well as external moments and total power for the hip, knee, and ankle joint.

All data were post-processed using custom-written MATLAB codes (Version R2021a, The MathWorks Inc., USA). Spatiotemporal data were analyzed with the statistical software package SPSS (Version 29, SPSS Inc., USA), kinematic data using statistical parametric mapping (SPM). One-way ANOVA was performed to compare the effect of the different walking conditions (CGA, 0, 3, and 5 m) on each of the spatiotemporal and kinematic parameters for the affected side. The Tukey post-hoc test was used for multiple comparisons between walking conditions and the p-value was adjusted accordingly. The kinetic changes were summarized descriptively due to a limited number of analyzed steps at each virtual height. For the spatiotemporal and kinematic parameters, all recorded steps were analyzed. For kinetics, only the steps with good force plate hits were analyzed. The significance level for all statistical tests was set to 0.05.

3 | OUTCOMES

3.1 | Spatiotemporal parameters

One-way ANOVA revealed statistically significant differences between walking conditions for all spatiotemporal parameters (Table S3). As determined by a Tukey post-hoc test, significant changes mainly occurred between 0 and 3 m with a decrease in walking speed ($p < 0.001$), single support ($p = 0.001$), cadence ($p = 0.002$), and an increase in double support ($p < 0.001$) (Tables 3 and 4).

3.2 | Sagittal plane kinematics

The Tukey post-hoc test revealed main changes in the sagittal plane kinematics between 0 m and 3 m (Figure 2). Hip flexion of the affected side increased from 0 to 3 m during 0%–64% of the gait cycle ($p < 0.001$), knee flexion

TABLE 4 Post hoc test (Tukey's HSD test) for the mean differences of the spatiotemporal parameters (affected side) between the different walking conditions (CGA, clinical gait analysis; 0 m virtual height, 3 m virtual height, 5 m virtual height). Parameters were normalized by leg length (dimensionless numbers, DN).[34]

						95% Confidence interval	
Dependent variable	**Condition 1**	**Condition 2**	**Mean difference (Condition 1 – 2)**	**SE**	**Sig.**	**Lower bound**	**Upper bound**
Walking speed [DN]	CGA	0 m	0.027	0.026	0.733	−0.041	0.095
	0 m	3 m	0.130*	0.015	<0.001	0.092	0.168
	3 m	5 m	0.001	0.012	1.000	−0.030	0.032
Double support [DN]	CGA	0 m	−0.213	0.222	0.771	−0.791	0.364
	0 m	3 m	−0.639*	0.124	<0.001	−0.962	−0.316
	3 m	5 m	0.070	0.101	0.898	−0.192	0.333
Single support [DN]	CGA	0 m	0.106	0.084	0.591	−0.114	0.327
	0 m	3 m	0.179*	0.047	0.001	0.055	0.302
	3 m	5 m	−0.057	0.038	0.450	−0.157	0.043
Cadence [DN]	CGA	0 m	0.011	0.010	0.663	−0.014	0.036
	0 m	3 m	0.020*	0.005	0.002	0.006	0.034
	3 m	5 m	−0.003	0.004	0.901	−0.015	0.008
Stride width [DN]	CGA	0 m	−0.019	0.016	0.610	−0.061	0.022
	0 m	3 m	−0.020	0.009	0.109	−0.043	0.003
	3 m	5 m	0.000	0.007	1.000	−0.019	0.019

*Mean differences are significant at the 0.05 level.

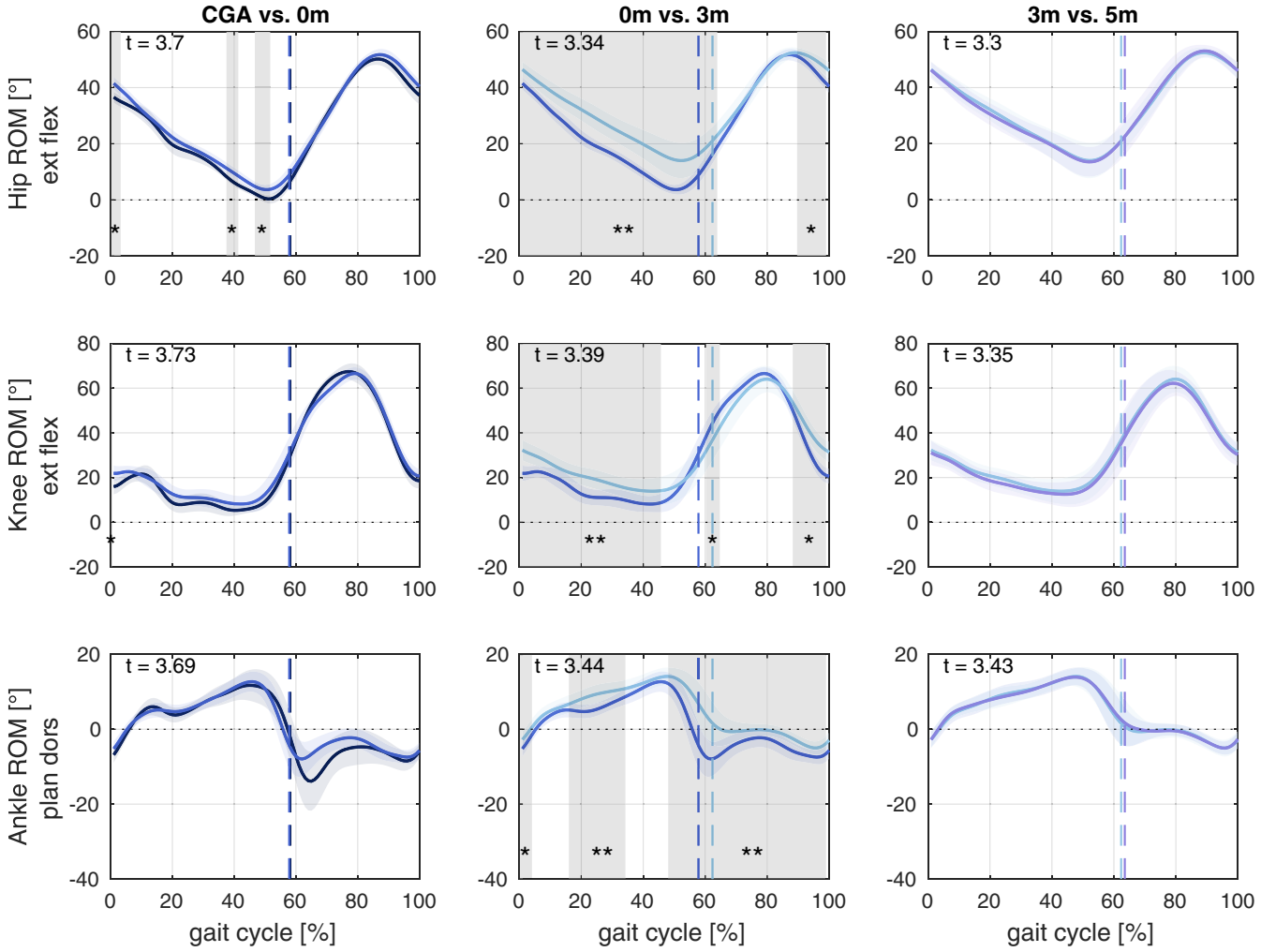

FIGURE 2 Sagittal plane kinematics (mean [SD] of 6 trials) for the hip (top row), knee (middle) and ankle (bottom). Comparisons between standard clinical gait analysis (CGA) versus 0 m virtual plank height (first column), 0 m versus 3 m height (second column), and 3 m versus 5 m plank height (third column). Displayed are the curves for the affected side. The darker colored line in the first column represents the CGA, in the second column the 0 m condition and in the third column the 3 m condition. The x-axes show the angle [°] of each joint, the y-axes the course of the gait cycle [%]. The vertical dashed lines separate the stance phase (leT part of the graph) from the swing phase (right part). *p<0.05, **p<0.001. CGA, clinical gait analysis; ROM, Range of Motion; ext, extension; flex, flexion; plan, plantarflexion; dors, dorsiflexion.

increased during 0%–46% ($p < 0.001$) and ankle dorsiflexion increased during 16%–34% and 48%–99% of the gait cycle ($p < 0.001$).

3.3 | Sagittal joint moments

From 0 to 3 m, there was mainly a decrease in the hip flexion moment of the affected side, directly followed by an increased moment during initial stance. Also, the knee flexion moment at initial stance decreased. Further changes occurred mainly between 0 and 3 m with a decreased ankle flexion moment on the affected side during stance (Figure 3).

3.4 | Total joint power

From the CGA to the 0 m condition, there was mainly an increased power absorption of the affected ankle during stance. From 0 to 3 m, the power generation of the affected ankle further decreased at terminal stance (Figure 4).

4 | DISCUSSION

This case study showed that virtual height exposure is feasible to change biomechanical gait parameters in a child with right hemiplegia attributable to spastic CP. Overall,

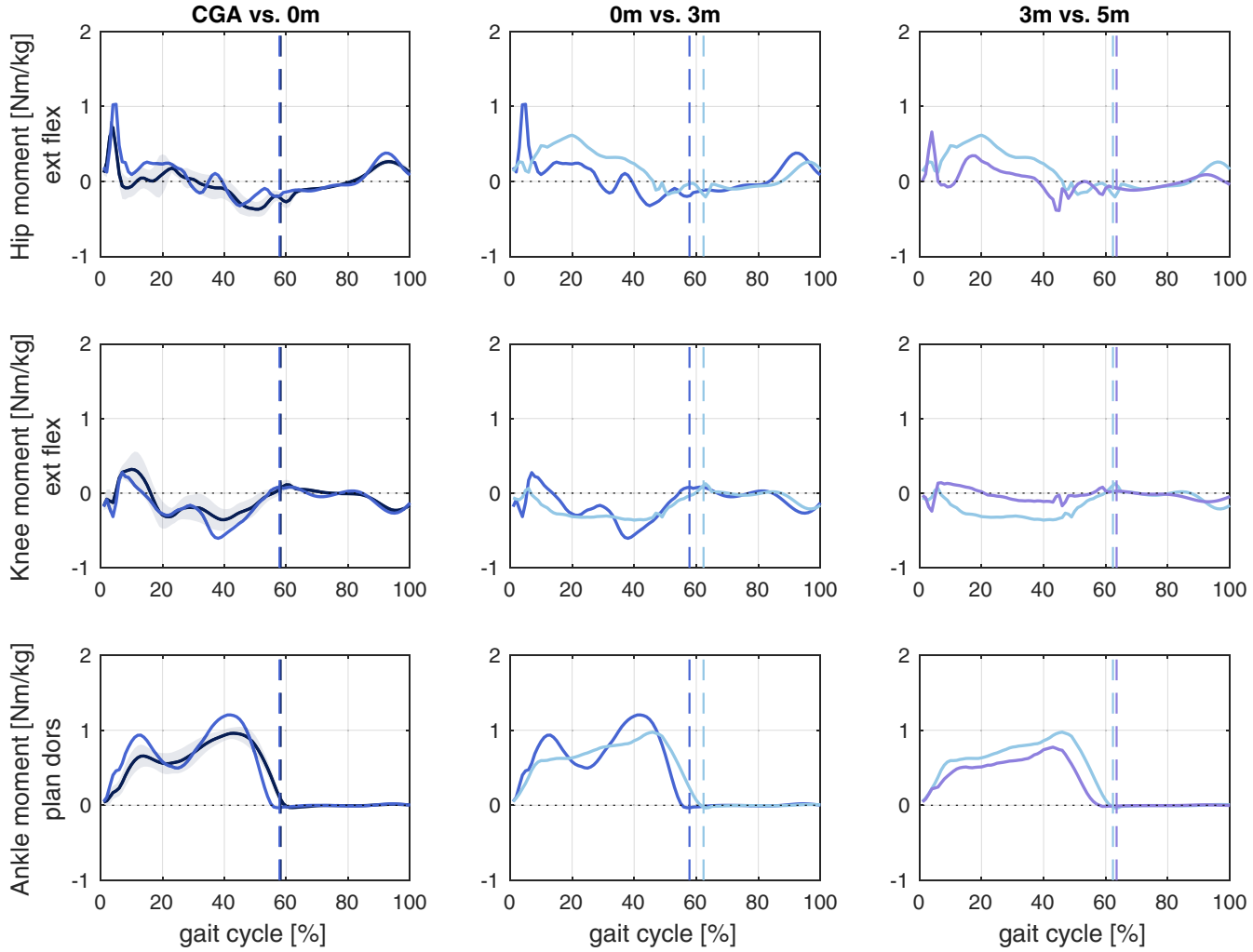

FIGURE 3 Sagittal plane moments for the hip (top row), knee (middle) and ankle (bottom) of the affected side. Comparisons between standard clinical gait analysis (CGA) versus 0 m virtual plank height (first column), 0 m versus 3 m (second column), and 3 m versus 5 m (third column). The darker colored line in the first column represents the CGA, in the second column the 0 m condition and in the third column the 3 m condition. Mean [SD] of six trials was calculated for the standard GCA, one trial for the 0 m, 3 m and 5 m height respectively. The x-axes show the moment [Nm/kg] of each joint, the y-axes the course of the gait cycle [%]. The vertical lines separate the stance phase (leT part of the graph) from the swing phase (right part). CGA=clinical gait analysis; ext=extension; flex=flexion; plan=plantarflexion; dors, dorsiflexion.

the most remarkable changes in the analyzed gait parameters were observed when increasing the virtual height from 0 m to 3 m, compared to standard CGA versus 0 m and 3 m versus 5 m. The gait parameters were adapted towards gaining more stability.

For all calculated spatiotemporal parameters except stride width, main differences occurred between 0 and 3 m. There were no significant changes between CGA and 0 m, suggesting that the VR immersion itself might not have affected walking patterns. One investigation comparing overground walking in a conventional gait laboratory with treadmill walking in a VE[25] also revealed no differences in walking speed between both conditions. Another study comparing treadmill walking with and without VR in CP found no differences in walking speed, step length and step width.[24] However, it should be stated that treadmill walking may not entirely be comparable with overground walking. The more remarkable gait adaptations between 0 and 3 m in our study might have occurred to compensate for increased instability, which could be elicited by virtual height exposure. Another study found that children with CP react to unstable situations by increasing double support time and decreasing step length,[35] which is consistent with our findings. The lack of changes in stride width with increasing height could be explained by the fact that the plank width was fixed for all conditions and the participant was asked to exactly walk on the plank.

Both knee and hip flexion of the affected side increased during stance with increasing the height from 0 to 3 m. Increasing the flexion angles during stance could

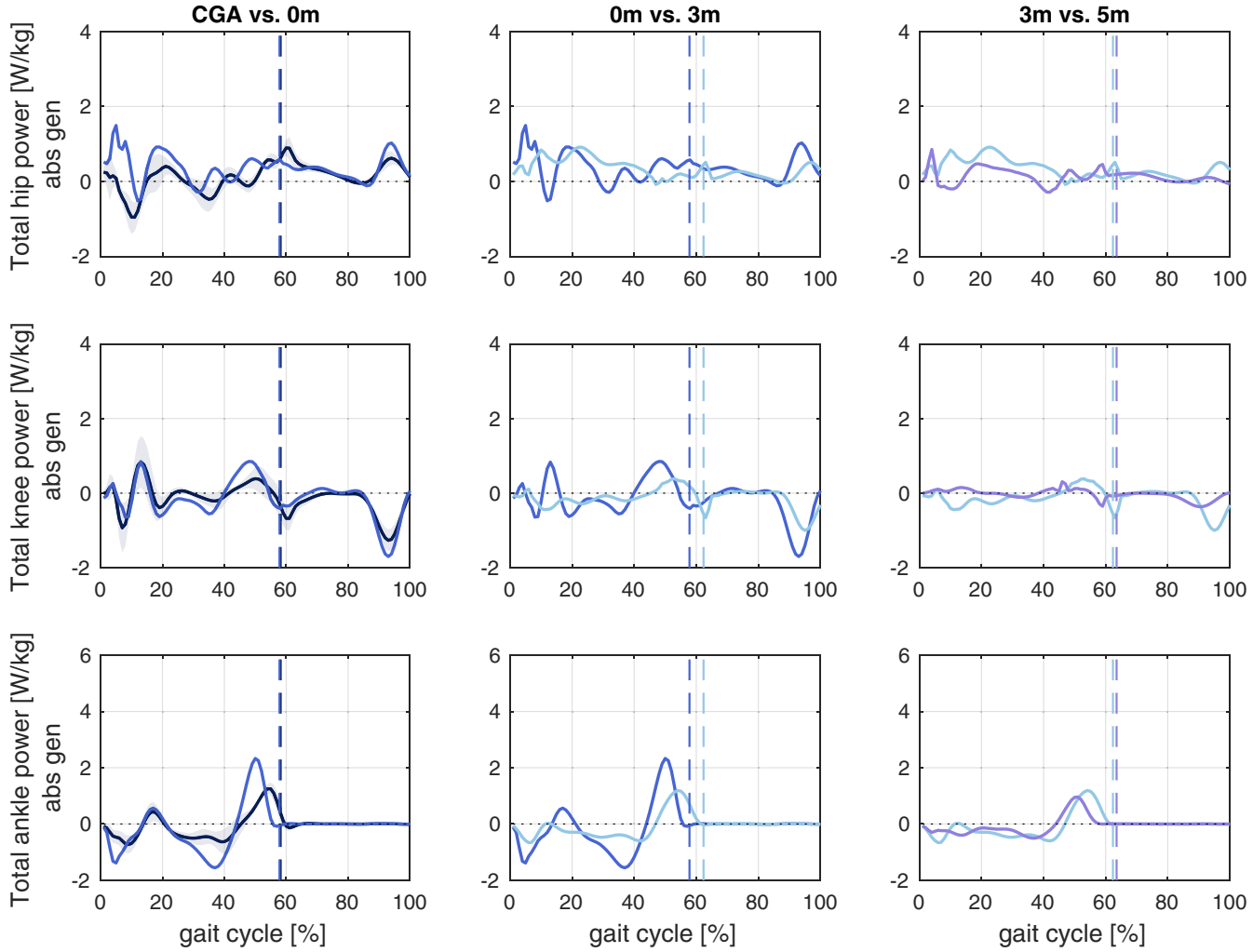

FIGURE 4 Total power for the hip (top row), knee (middle) and ankle (bottom). Comparisons between standard clinical gait analysis (CGA) versus 0 m virtual plank height (first column), 0 m versus 3 m (second column), and 3 m versus 5 m (third column). The darker colored line in the first column represents the CGA, in the second column the 0 m condition and in the third column the 3 m condition. Mean [SD] of six trials was calculated for the standard GCA, one trial for the 0 m, 3 m and 5 m height, respectively. The x-axes show the power [W/kg] of each joint, the y-axes show the course of the gait cycle [%]. The vertical lines separate the stance phase (leT part of the graph) from the swing phase (right part). CGA=clinical gait analysis; abs, absorption; gen, generation.

be a mechanism to gain more stability by vertically displacing the center of mass.[36] The increased knee flexion might also be a result of the measured ankle plantarflexion contracture or the spasticity of the plantarflexors on the affected side, which could have also increased with increasing height. Remarkable differences were found for the decreased plantarflexion at terminal stance from 0 to 3 m, which could be a result of the limited strength of the plantarflexors.

The ankle on the affected side showed a "double bump" moment pattern during gait analysis and the 0 m plank condition, ranging from a short dorsiflexion moment to a short plantarflexion moment and back to a short dorsiflexion moment until a final plantarflexion moment at terminal stance. This pattern could be associated with triceps surae spasticity. With increasing height, the participant showed a long and progressive dorsiflexion moment, leading into a plantarflexion moment at terminal stance, which could be linked to a dynamic hypertonia of the triceps surae to gain more stability.[37] Both types of walking patterns are common gait deviations in children with CP.[38]

Both knee and hip joints showed a tendency towards increased power generation during stance phase, which could be linked to an increased proximal stability as a compensation to less power generation in the ankle.

The interpretation of the results could be limited for various reasons. It remains unclear, whether the changes in the collected gait parameters are explainable solely by the virtual height exposure. The participant's subjective experience with the VR environment and the extent to which the virtual height is perceived as

being plausible might have affected gait. Furthermore, the wearing of the HMD and the associated additional weight, together with possible psychological factors such as fear of heights could have also changed gait patterns. The width of the virtual plank was the same for all conditions; however, it remains unclear whether and how a smaller or larger width would have affected gait. Also, the lower extremity muscle strength of the participant was already overall low at the beginning of the measurement, and the length of the study procedure itself might have led to a further decrease in muscle strength, which again might have influenced the gait parameters. Among all analyzed parameters, the kinetic data for the virtual heights should be interpreted carefully. Since the gait patterns were in general more variable during the virtual height conditions, the number of force plate hits decreased, and with it the possibility to collect sufficient kinetic data to perform appropriate statistical tests. However, since our aim was to capture the immediate walking adaptations to each virtual height, we performed each condition not more than six times, which might have resulted in a habituation to the virtual height and less pronounced walking adaptations. Another limitation of the study could be that the feet were not tracked in the VE. This means that the participant was not aware of his feet position on the plank, leading to an additional proprioceptive challenge. Since children with CP tend to process visual information to compensate for proprioceptive deficits and gain stability during walking,[39] visualizing their feed in the VE may reduce the confounding factor proprioception. As main changes of the measured parameters occurred between 0 and 3 m, one could argue that a ceiling effect of the measured parameters was reached. Another explanation could be, that the participant experienced both 3 and 5 m as rather similar and there was no need to further adapt walking patterns. Also, the participant could have already habituated to the virtual height due to possible motor learning effects.

Considering the increasing relevance of VR applications in clinical settings there is an urgent need for future studies integrating VR into the CGA including larger sample sizes. To address our limitations, foot tracking should be implemented in the VR environment to ensure proprioceptive feedback. The extent of how much the participant feels being immersed could be verified by a questionnaire. To avoid ceiling effects, the virtual heights could be increased to verify if further changes in gait occur. Finally, future studies should include participants with various GMFCS-levels to allow conclusions on gait changes depending on the individual functional impairments.

5 | CONCLUSIONS

This case study is to our knowledge the first study that investigated effects of virtual height exposure on biomechanical gait parameters in a child with spastic CP. The results showed that virtual height exposure is feasible to elicit changes in different gait parameters. Adaptation of spatiotemporal, kinematic, and kinetic parameters mainly occurred from 0 to 3 m plank height towards gaining more stability during walking, whereas only slight to no changes were observed by a further elevation from 3 to 5 m.

Incorporating more challenging VE into the standard CGA can provide further insights on gait adaptations and compensation strategies in environments resembling real-life-scenarios more than the conventional gait laboratory. This leads to a more comprehensive understanding of the individual gait patterns in children with spastic CP and the application of the most appropriate treatment strategy to improve walking in daily life situations. Considering that VR also showed promising findings in increasing motivation during gait rehabilitation, VR applications may be used as a complementary diagnostic tool to the CGA to inform clinical decision-making.

AUTHOR CONTRIBUTIONS

Regine Lohss: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; validation; visualization; writing – original draft; writing – review and editing. **Rebecca Winter:** Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; validation; visualization; writing – original draft; writing – review and editing. **Beat Göpfert:** Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; validation; visualization; writing – original draft; writing – review and editing. **Rosa Visscher:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing – original draft; writing – review and editing. **Morgan Sangeux:** Data curation; formal analysis; methodology; supervision; validation; visualization; writing – review and editing. **Norbert Zentai:** Conceptualization; methodology; resources; software; visualization; writing – original draft; writing – review and editing. **Elke Viehweger:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision;

validation; visualization; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interests to declare.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

ETHICS STATEMENT

The Ethics Commission of Northwestern and Central Switzerland (EKNZ) approved the study (BASEC 2021-00435), that was performed according to the Declaration of Helsinki.

CONSENT STATEMENT

Written informed consent was obtained from the parents (minor patient) prior to study inclusion according to the local ethical regulations.

CLINICAL TRIAL REGISTRATION

This case report is part of a case–control pilot study, that was prospectively registered on clinicaltrials.gov (NCT04879199).

ORCID

Regine Lohss https://orcid.org/0000-0001-9633-9452

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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