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Gait Changes Following Robot-Assisted Gait Training in Children With Cerebral Palsy

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Summary

This study investigated changes of gait pattern induced by a 4-week robot-assisted gait training (RAGT) in twelve ambulatory spastic diparesis children with cerebral palsy (CP) aged 10.4±3.2 years old by using computerized gait analysis (CGA). Pre-post intervention CGA data of children with CP was contrasted to the normative data of typically developing children by using cross-correlation and statistically evaluated by a Wilcoxon test. Significant pre-post intervention changes ($p<0.01$) include: decreased muscle activity of biceps femoris, rectus femoris, and tibialis anterior; a decrease in range of internal hip joint rotation, higher cadence, step length, and increased stride time. This study suggests that RAGT can be used in muscle reeducation and improved hip joint motion range in ambulatory children with CP.

Key words

Cerebral palsy • Spastic diparesis • Gait cycle • Computerized gait analysis • Robot-assisted gait training

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Introduction

Cerebral palsy

Cerebral palsy (CP) is a developmental disability that was first described in the 1840s, yet continues to be one of the most frequent pediatric disabilities with an incidence of 2-3 per 1000 children (Bax *et al.* 2005, Panteliadis 2004). Most physiotherapy approaches aim to improve movement quality and develop skills necessary to carry out activities of daily living, which often include tasks such as standing and walking (Novak 2014).

Robot-assisted gait training (RAGT)

Although manual assistance can be used to aid children with CP, RAGT allows for more advanced and customizable gait rehabilitation programs. RAGT was introduced 15 years ago and consists of bilateral robotic orthoses, body-weight support (BWS), and a treadmill.

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Being a computerized system, it is possible to adjust the amount of BWS to maintain extended posture and provide accurate loading of the lower limbs. The robotic orthoses guide a patient's leg movements throughout repeatable predefined trajectories of the hip- and knee-joints in the sagittal plane, and foot supports maintain passive ankle dorsiflexion, which can aid CP children while walking (Colombo *et al.* 2000, Riener *et al.* 2005, Meyer-Heim *et al.* 2007). The main aim of RAGT is to improve the motor learning process through repetitive stimulation of gait accompanied by audio-visual feedback (Schuler *et al.* 2011). RAGT provides a simplified and safe therapeutic environment that allows for prolonged training duration with many repetitions of steps while inducing a reproducible, kinematically consistent, symmetrical gait pattern (Colombo *et al.* 2000). RAGT seems to be a promising method for children with CP in improved selective voluntary motor control (Žarković *et al.* 2020), increased muscle activity, and inter limb symmetry (Schuler *et al.* 2011, Schuler *et al.* 2013, Bonikowski *et al.* 2012), restricted passive joint range of motion (Vrečar *et al.* 2013, Žarković *et al.* 2020), and improved gross motor abilities including improved spatiotemporal gait parameters (Meyer-Heim *et al.* 2007, Borggraeffe *et al.* 2010, Knecht *et al.* 2010, Žarković *et al.* 2020). Despite that, it is still unknown whether functional motor improvements following RAGT can also contribute to the improved quality of gait patterns. Therefore, the purpose of this experimental study was to investigate changes in gait pattern following RAGT as a monotherapy in ambulatory spastic diparesis children with CP. Knowing that motor learning is critical for neuroplasticity and that children with CP can improve motor function with practice (Hemayattalab *et al.* 2010, Gordon *et al.* 2012, Hemayattalab *et al.* 2013), we hypothesized that RAGT can induce physiological gait changes in lower limbs that can be comparable to the healthy children.

Methods

Ethics Committee approval

The study received ethics committee approvals from participating institutions (No. 120/2015). The parents of the children were informed of the study procedures, risks, and benefits, and provided written informed consent before their children participating in the study.

Children with CP

Inclusion criteria were: CP spastic diparesis with toe walking pattern; Gross Motor Function Classification (GMFCS) I-III; ability to walk independently for at least short distances; age range 5-17 years; femur length at least 21 cm to fit in orthoses of RAGT device; ability to communicate fear, pain, or discomfort; ability to follow simple instructions; no botulinum toxin in the last 3 months before RAGT; no orthopedic surgical intervention in the last 12 months; no severe contractures; and ability to attend 20 RAGT sessions scheduled in 20 consecutive weekdays (Vrečar *et al.* 2013, Wallard *et al.* 2018).

Definition of limb impairment

Before the RAGT intervention, an experienced pediatric physiotherapist performed in all children a passive joint range of motion (PROM) goniometry evaluation of lower limbs (Janda *et al.* 1993), and the Selective Control Assessment for the Lower Extremity (SCALE) (Fowler *et al.* 2009). SCALE and PROM revealed "more impaired limb" (MIL) and "less impaired limb" (LIL), as well as evaluations excluded patients with severe joint contractures (Fowler *et al.* 2009, Syczewska and Świecicka 2016). These evaluations had an informatory purpose that was summarized in section results.

Data collection

Computerized gait analysis (CGA)

The CGA included a comprehensive 3D gait analysis consisting of joint kinematics, kinetics, sEMG, and spatiotemporal parameters. The CGA evaluation was performed by 2 well-trained physiotherapists and 2 biomechanics experts. First, the skin was gently abraded, and multi-purpose monitoring electrodes were placed on the following muscles bilaterally according to the SENIAM recommendations (Hermens *et al.* 1999): tibialis anterior (TA), medial gastrocnemius (MG), rectus femoris (RF), and biceps femoris (BF). A neutral reference electrode was attached to the tensor fascia latae muscle (Schuler *et al.* 2011). Subsequently, 17 reflective markers (Vicon, Oxford Metrics, Oxford, UK) were attached directly to the skin to ensure a fixed and precise position. Markers were attached bilaterally to the following body areas concerning the Vicon Plug-in-gait model (Davis *et al.* 1991, Dixon *et al.* 2014, Flux *et al.* 2020): second metatarsal joint; middle of the Achilles tendon; malleolus lateralis; center of the tibia; lateral femoral epicondyle; lateral side of the thigh; spina iliaca anterior superior (SIAS); L5; Th10; sternum. All children with CP were told to walk barefoot in the pre-designed 10-meter flat-surface pathway to adapt to space. Afterward, children with CP were appealed to walk barefoot without walking aids at preferred speed and according to physical capacities for a minimum of ten trials on the same pre-designed 10-meter flat-surface pathway in the gait laboratory. Kinematics, kinetics, and sEMG data were collected and recorded simultaneously. 3D kinematic data was recorded by using a 6-camera VICON system (0.3 MPix VICON, Oxford Metrics, Oxford, UK) with a sampling frequency of 50 Hz until the course of three completed trials was obtained. Kinetics was recorded by using AMTI force plates (AMTI OR6, Advanced Mechanical Technology Inc., Watertown, MA) at 1 kHz sampling frequency. Muscle activity was recorded with an 8-channel sEMG sampling frequency at 1 kHz (Noraxon TeleMyo 2400T, Noraxon U.S.A. Inc.).

RAGT intervention

The RAGT device Lokomat Pro (Hocoma AG, Volketswil, Switzerland) was used. The intervention consisted of twenty sessions scheduled for 20 consecutive workdays with a minimum duration of 30 and up to a maximum of 45 min (Vrečar *et al.* 2013, Wallard *et al.* 2017). The treadmill speed was synchronized with the movements of the robotic orthoses and set to a comfortable walking speed of every child individually. These parameters were set by following the child's ability to walk at a certain speed, follow the augmented feedback and maintain an upright posture. All children wore shoes during the RAGT. At the beginning of RAGT program, all children had an initial level of BWS set to 50 % of body weight (Schuler *et al.* 2013). The BWS was further decreased for every child individually until the knee started to collapse into flexion during the stance phase due to the increased load of body weight. All children walked with augmented biofeedback (Schuler *et al.* 2011, Schuler *et al.* 2013, Wallard *et al.* 2017). For consistency, the same physiotherapist was present at every RAGT session to follow the progression and encourage the child to walk actively and keep an extended posture (Fig. 1).

Data evaluation

Data processing

Raw CGA data obtained from overground gait was high-pass filtered by the VICON system (VICON Nexus 1.8.3.) to enable analog data sampling with 1 kHz, and subsequently filtered with a 4th order low-pass Butterworth filter with a cut off frequency of 20 Hz (Kadaba *et al.* 1989, Baker 2013). The data was normalized and the Vicon Plug-in-Gait model was used to generate kinematic and kinetic data (Davis *et al.* 1991). Joint angles were calculated based on the 3D coordinates of markers. Internal joint moments and power were calculated based on joint kinematics and ground reaction forces recorded using force plates (Kadaba *et al.* 1989, MacWilliams *et al.* 2003, Baker 2013). Force plates measured ground reaction forces and center of pressure (COP) trajectory (Baker 2013). VICON Nexus 1.8.3. and Polygon 3.5.1. softwares (VICON, Oxford Metrics, Oxford, UK) were used to define the gait cycles, spatiotemporal parameters, joint angles, internal joint moments, and power. sEMG data was processed by MyoResearch XP 1.07 Master Edition software (Noraxon Inc., Scottsdale/USA). Raw sEMG signals were high-pass filtered with a bi-directional zero-lag Butterworth at a cut-off frequency of 10 Hz, rectified, and smoothed with a time window of 100 ms to create the linear envelope. The sEMG data was normalized to the maximum EMG recorded during the gait cycle (Fung *et al.* 1989, Burden and Bartlett 1999, Burden *et al.* 2003, Bojanic *et al.* 2011, Aurich-Schuler 2017, Ricklin *et al.* 2018). As subjects walked for a minimum of ten trials, gait cycles were identified in each trial. Heel strike and toe-off markers were set automatically by the software program and adjusted manually if necessary. The gait cycle starts and ends with a heel strike of the same lower extremity (Perry 2010, Baker 2013). Within the cycles, the mean value of these trials was calculated to obtain 1 gait cycle and separate gait phases. The gait cycle was represented by 51 evenly spaced samples (0-100 % in 2 % steps) that were marked as initial contact (IC), loading response (LR), midstance (MST), terminal stance (TS), pressing (PSW), initial swing (ISW), midswing (MSW), terminal swing (TSW) (Perry *et al.* 2010). This study aimed to explore whether RAGT can induce physiological gait changes in lower limbs that will be comparable to healthy children. Therefore, all collected CGA variables were contrasted to the normative data (Sutherland 2002, Hof *et al.* 2005, Winter *et al.* 2009) assessed in typically developing children, and differences in individual phases of the gait cycle (Perry 2010) were examined to explain the pathological gait mechanism and compensatory movements. Normative data represent an integral part that is built in VICON and Myoresearch softwares. Subsequently, data was used for statistical evaluation by using a custom-written MatLab program (MatLab software processes, MatLab R2010b, Mathworks, Inc., Natick, MA, USA).

Fig. 1. A 5-year-old boy with spastic diparesis during RAGT using the Lokomat Pro.

Statistical evaluation

Comprehensive CGA resulted in a statistical evaluation of 43 variables embracing sEMG; motion range of thorax, pelvis, hip, knee, and ankle joints in all three planes; joint moments in sagittal/ frontal planes and power of hip, knee, and ankle joints; center of pressure, center of mass and ground reaction forces in all three planes. First, the deviation of CP signals from the normative values was calculated by cross-correlation for every variable and particular phases of the gait cycle. It was performed for LIL and MIL separately pre- and post-intervention. The statistical evaluation was performed to compare the pre- and post-intervention conditions of children with CP. The Shapiro-Wilk test was used to verify data normality. As normal data distribution has been rejected at the 0.05 significance level, the non-parametric Wilcoxon sign rank test was used for further statistical calculation of each variable and gait cycle phase separately (0.05 significance level). The calculation was completed by Bonferroni correction ($p<0.01$), median values and effect sizes of cross-correlation coefficients (Cohen 1988).

Results

Children with CP

Twelve CP children with spastic diparesis (2 girls; 10 boys) with apparent equinus gait pattern; aged 10.4±3.2 years; GMFCS I-III; with decreased selective voluntary motor control of lower extremities as per SCALE evaluation (total score MIL 5, total score LIL 7 out of max. score 10), and with hip-knee-ankle joint contractures (≤10° for both extremities) completed the RAGT program. The program was well-tolerated by all of the children with CP and no adverse events were reported.

CGA results

Significant improvements contrasted to the normative data were found in bilaterally decreased activity of BF, RF, TA muscles and decreased internal hip joint rotation. There were no significant changes in kinetic variables. Spatiotemporal parameters showed increased cadence and step length, and decrease in time needed for double support and stride. A detailed summary of results is shown in Tables 1-3.

Table 1. Table shows an overview of Wilcoxon sign rank tests for CGA variables with corrected p-value, median values and effect sizes of cross-correlation coefficients. Statistically significant results (p≤0.01) are bolded and marked with an asterisk (*).

sEMG	**Gait cycle phases**							
	p-value after Bonferroni correction/effect size of cross-correlation coefficient							
	IC	**LR**	**MST**	**TS**	**PSW**	**ISW**	**MSW**	**TSW**
BF MIL	<0.01/0.54	<0.01/0.52	**<0.01*/0.56**	**<0.01*/0.57**	**<0.01*/0.56**	<0.01/0.51	<0.01/0.52	**<0.01*/0.56**
BF LIL	<0.01/0.50	<0.01/0.47	<0.01/0.52	**<0.01*/0.57**	<0.01/0.36	**<0.01*/0.62**	<0.01/0.52	**<0.01*/0.57**
RF MIL	**<0.01*/0.59**	**<0.01*/0.57**	**<0.01*/0.62**	**<0.01*/0.59**	**<0.01*/0.62**	<0.01/0.51	**<0.01*/0.56**	**<0.01*/0.60**
RF LIL	**<0.01*/0.59**	**<0.01*/0.60**	**<0.01*/0.60**	**<0.01*/0.62**	>0.01/0.20	<0.01/0.43	<0.01/0.43	<0.01/0.51
MG MIL	<0.01/0.46	<0.01/0.35	<0.01/0.43	<0.01/0.44	<0.01/0.43	<0.01/0.35	<0.01/0.48	<0.01/0.44
MG LIL	<0.01/0.39	>0.01/0.36	>0.01/0.35	<0.01/0.41	>0.01/0.38	<0.01/0.52	<0.01/0.52	<0.01/0.40
TA MIL	<0.01/0.46	<0.01/0.48	<0.01/0.35	<0.01/0.38	<0.01/0.43	<0.01/0.40	<0.01/0.28	<0.01/0.43
TA LIL	**<0.01*/0.59**	**<0.01*/0.62**	**<0.01*/0.60**	**<0.01*/0.62**	<0.01/0.54	<0.01/0.54	<0.01/0.44	<0.01/0.52
Kinematics	**IC**	**LR**	**MST**	**TS**	**PSW**	**ISW**	**MSW**	**TSW**
Pelvic tilt MIL	>0.01/0.19	>0.01/0.17	>0.01/0.11	>0.01/0.16	>0.01/0.17	>0.01/0.20	>0.01/0.20	>0.01/0.20
Pelvic tilt LIL	>0.01/0.19	>0.01/0.19	>0.01/0.19	>0.01/0.20	>0.01/0.17	>0.01/0.12	>0.01/0.14	>0.01/0.19
Pelvic obliquity MIL	1/0	>0.01/0.01	>0.01/0.20	>0.01/0.35	<0.01/-0.44	>0.01/-0.25	>0.01/-0.04	>0.01/-0.04
Pelvic obliquity LIL	<0.01/0.43	>0.01/-0.32	>0.01/-0.19	>0.01/0.01	>0.01/0.06	>0.01/0.17	>0.01/0.35	<0.01/0.43
Pelvic rotation MIL	>0.01/-0.09	>0.01/-0.08	>0.01/-0.22	>0.01/0.33	>0.01/0.28	>0.01/0.14	>0.01/0.04	>0.01/0.03
Pelvic rotation LIL	>0.01/0.36	>0.01/0.28	>0.01/0.19	>0.01/-0.09	>0.01/-0.01	>0.01/-0.11	>0.01/-0.24	>0.01/-0.25
Hip flexion/ extension MIL	>0.01/0.04	>0.01/0.04	>0.01/0.12	>0.01/0.09	>0.01/-0.20	>0.01/0.28	>0.01/0.25	>0.01/0.163
Hip flexion/ extension LIL	>0.01/0.22	>0.01/0.25	>0.01/0.33	<0.01/0.44	>0.01/-0.24	>0.01/0.36	>0.01/0.36	>0.01/0.28
Hip abduction/ adduction MIL	>0.01/-0.30	>0.01/0.24	>0.01/0.33	>0.01/0.22	>0.01/-0.28	>0.01 /-0.25	>0.01 /-0.22	>0.01/-0.24
Hip abduction/ adduction LIL	>0.01/0.28	>0.01/-0.28	>0.01/-0.14	>0.01/-0.11	>0.01/-0.08	>0.01/-0.03	>0.01/-0.03	>0.01/0.19
Hip rotation MIL	**<0.01*/0.57**	**<0.01*/0.59**	**<0.01*/0.62**	**<0.01*/0.62**	**<0.01*/0.62**	**<0.01*/0.62**	**<0.01*/0.59**	**<0.01*/0.56**
Hip rotation LIL	>0.01/0.28	>0.01/0.32	**<0.01*/0.56**	**<0.01*/0.56**	**<0.01*/0.56**	**<0.01*/0.56**	**<0.01*/0.56**	**<0.01*/0.56**
Knee flexion/ extension MIL	>0.01/-0.16	>0.01/-0.06	>0.01/-0.19	>0.01/-0.27	>0.01/-0.11	>0.01/-0.38	>0.01/-0.24	>0.01/-0.24
Knee flexion/ extension LIL	>0.01/0.08	>0.01/0.08	>0.01/0.08	>0.01/0.17	>0.01/0.08	>0.01/0.03	>0.01/-0.04	>0.01/-0.01
Knee abduction/	<0.01/0.43	<0.01/0.43	<0.01/0.40	>0.01/0.33	<0.01/0.43	<0.01/-0.48	<0.01/0.46	<0.01/0.48

adduction MIL								
Knee abduction/ adduction LIL	>0.01/0.22	>0.01/0.22	>0.01/0.27	>0.01/0.09	>0.01/0.25	>0.01/-0.38	>0.01/0.33	<0.01/0.43
Ankle plantar/ dorsal flexion MIL	>0.01/0.24	>0.01/0.20	>0.01/0.14	1/0	>0.01/-0.04	>0.01/0.28	>0.01/0.28	>0.01/0.03
Ankle plantar/ dorsal flexion LIL	>0.01/0.11	>0.01/0.14	>0.01/-0.01	>0.01/-0.19	>0.01/-0.19	>0.01/0.12	>0.01/0.22	>0.01/0.09
Foot tilt MIL	>0.01/-0.21	>0.01/-0.18	>0.01/-0.16	>0.01/0.06	>0.01/0.14	>0.01/-0.04	>0.01/-0.24	>0.01/-0.25
Foot tilt LIL	>0.01/0.32	>0.01/0.35	>0.01/0.38	>0.01/0.30	>0.01/0.16	>0.01/0.16	>0.01/0.04	>0.01/0.22
Foot progress MIL	<0.01/0.50	<0.01/0.49	**<0.01*/0.56**	**<0.01*/0.57**	<0.01 /0.49	<0.01 /0.51	<0.01/0.44	<0.01/0.40
Foot progress LIL	**<0.01*/0.56**	<0.01/0.54	<0.01/0.46	<0.01/-0.60	<0.01/-0.62	>0.01/-0.38	>0.01/-0.32	<0.01/-0.43
*Thorax tilt MIS**	<0.01/0.39	<0.01/0.39	<0.01/0.39	<0.01/0.46	<0.01/0.48	<0.01/0.48	<0.01/0.41	<0.01/0.43
*Thorax tilt LIS**	<0.01/0.44	<0.01/0.44	<0.01/0.43	<0.01/0.43	<0.01/0.43	<0.01/0.44	<0.01/0.46	<0.01/0.44
Kinetics	**IC**	**LR**	**MST**	**TS**	**PSW**	**ISW**	**MSW**	**TSW**
Hip flexion/ extension moment MIL	>0.01/-0.14	>0.01/-0.46	>0.01/-0.35	>0.01/-0.12	>0.01/0.09	>0.01/0.19	>0.01/-0.28	>0.01/-0.05
Hip flexion/ extension moment LIL	>0.01/0.19	>0.01/-0.30	>0.01/0.04	>0.01/0.03	>0.01/-0.16	>0.01/-0.09	>0.01/0.48	>0.01/0.01
Hip abduction/ adduction moment MIL	>0.01/0.22	>0.01/-0.17	>0.01/-0.01	>0.01/-0.04	1/0	1/0	>0.01/-0.08	>0.01/-0.07
Hip abducttion/adduction moment LIL	>0.01/0.27	>0.01/-0.14	>0.01/-0.09	>0.01/-0.09	>0.01/0.11	>0.01/-0.06	>0.01/-0.20	1/0
Hip power MIL	>0.01/-0.01	>0.01/0.16	>0.01/-0.08	>0.01/0.08	>0.01/0.22	>0.01/0.21	>0.01/0.01	>0.01/0.36
Hip power LIL	>0.01/0.38	>0.01/0.23	>0.01/0.30	>0.01/-0.24	>0.01/-0.30	>0.01/-0.11	>0.01/0.09	>0.01/0.25
Knee flexion/ extension moment MIL	>0.01/-0.51	>0.01/-0.17	>0.01/-0.20	>0.01/0.35	>0.01/-0.11	>0.01/-0.09	>0.01/0.04	>0.01/-0.35
Knee flexion/ extension moment LIL	>0.01/-0.28	>0.01/-0.52	>0.01/-0.38	>0.01/0.32	>0.01/-0.25	>0.01/-0.20	>0.01/0.09	>0.01/-0.08
Knee valgus/ varus moment MIL	>0.01/0.06	>0.01/-0.20	>0.01/-0.38	>0.01/0.06	>0.01/-0.12	>0.01/0.41	>0.01/0.12	>0.01/0.24
Knee valgus/ varus moment LIL	>0.01/-0.36	>0.01/-0.01	>0.01/-0.03	>0.01/-0.03	>0.01/0.19	>0.01/-0.14	>0.01/-0.33	>0.01/-0.22
Knee power MIL	>0.01/-0.16	>0.01/0.14	>0.01/0.06	>0.01/-0.14	>0.01/-0.13	>0.01/-0.21	>0.01/0.04	>0.01/0.25
Knee power LIL	>0.01/-0.01	>0.01/-0.05	>0.01/-0.14	>0.01/-0.28	>0.01/0.29	>0.01/0.36	>0.01/0.01	>0.01/-0.14

Ankle flexion/ extension moment MIL	>0.01/-0.08	>0.01/0.04	>0.01/-0.12	>0.01/-0.20	>0.01/0.16	>0.01/0.27	>0.01/-0.20	>0.01/-0.28
Ankle flexion/ extension moment LIL	>0.01/0.09	>0.01/0.27	>0.01/-0.01	>0.01/-0.25	>0.01/0.03	>0.01/0.11	>0.01/0.09	>0.01/-0.19
Ankle power MIL	>0.01/-0.06	>0.01/-0.41	>0.01/-0.12	>0.01/-0.17	>0.01/-0.03	>0.01/-0.13	>0.01/-0.14	>0.01/-0.09
Ankle power LIL	>0.01/0.22	>0.01/-0.01	>0.01/0.12	>0.01/-0.08	>0.01/-0.47	>0.01/0.15	>0.01/-0.14	>0.01/0.04
GRF X MIL	>0.01/-0.09	>0.01/-0.30	>0.01/-0.16	>0.01/-0.30	>0.01/0.28			
GRF X LIL	1/0	>0.01/-0.32	>0.01/-0.28	>0.01/-0.24	>0.01/-0.25			
GRF Y MIL	>0.01/-0.16	>0.01/-0.16	>0.01/0.24	>0.01/0.22	>0.01/0.17			
GRF Y LIL	>0.01/-0.03	>0.01/0.14	>0.01/0.06	>0.01/-0.14	>0.01/-0.03			
GRF Z MIL	>0.01/0.14	>0.01/0.12	>0.01/-0.01	>0.01/0.12	>0.01/0.11			
GRF Z LIL	>0.01/0.05	>0.01/0.23	>0.01/0.17	>0.01/-0.01	>0.01/-0.49			
COM MIL	>0.01/0.05	>0.01/0.01	>0.01/0.24	>0.01/0.09	>0.01/0.03			
COM LIL	>0.01/0.16	>0.01/0.14	>0.01/0.08	>0.01/0.06	1/0			
COP X MIL	>0.01/0.12	>0.01/-0.03	1/0	>0.01/-0.24	>0.01/-0.03			
COP X LIL	>0.01/0.03	>0.01/0.03	>0.01/0.04	>0.01/0.01	>0.01/-0.02			
COP Y MIL	>0.01/-0.32	>0.01/-0.38	>0.01/-0.30	>0.01/-0.22	>0.01/-0.24			
COP Y LIL	>0.01/0.18	>0.01/-0.11	>0.01/-0.30	>0.01/-0.22	>0.01/-0.25			

sEMG (surface electromyography); BF (biceps femoris); RF (rectus femoris); TA (tibialis anterior); MG (medial gastrocnemius); MIL (More impaired limb); LIL (Less impaired limb); IC (Initial contact); LR (Loading response); MST (Midstance); TS (Terminal stance); PSW (Preswing); ISW (Initial swing); MSW (Midswing); TSW (Terminal swing).

Table 2. Table shows an overview of Wilcoxon sign rank tests for spatiotemporal parameters with corrected p-value and median values. Statistically significant results (p≤0.01) are bolded and marked with an asterisk (*).

Spatiotemporal parameters	**Median MIL pre**	**Median MIL post**	**MIL p-value/ effect size**	**Median LIL pre**	**Median LIL post**	**LIL p-value/ effect size**
Cadence (steps/min)	109.04	111.57	**<0.01*/0.62**	109.55	112.45	**<0.01*/0.61**
Double support (s)	0.36	0.34	**<0.01*/0.63**	0.37	0.33	**<0.01*/0.62**
Foot off (%)	64.35	64.19	<0.01/0.52	65.04	64.97	**<0.01*/0.61**
Opposite foot contact (%)	48.48	48.91	>0.01/0.04	51.67	51.18	>0.01/0.04
Opposite foot off (%)	13.87	13.59	>0.01/0.04	16.66	15.08	>0.01/0.04
Single support (s)	0.39	0.39	>0.01/0.06	0.39	0.39	>0.01/0.04
Step length (m)	0.43	0.46	**<0.01*/0.61**	0.43	0.45	**<0.01*/0.60**
Step time (s)	0.6	0.58	>0.01/0.05	0.55	0.54	>0.01/0.05
Step width (m)	0.11	0.12	>0.01/0.05	0.11	0.12	>0.01/0.05
Stride length (m)	0.87	0.85	<0.01/0.52	0.87	0.83	<0.01/0.52
Stride time (s)	1.16	1.13	**<0.01*/0.59**	1.16	1.12	**<0.01*/0.59**
Walking speed (m/s)	0.8	0.87	<0.01/0.52	0.81	0.86	<0.01/0.52

MIL (More impaired limb); LIL (Less impaired limb).

Table 3. Table shows an overview of median values for cross-correlation coefficients for CGA variables that were statistically significant (p≤0.01). This optimization was done due to an extensive amount of variables.

EMG	Median of cross-correlation			Kinematics	Median of cross-correlation	
	Before	**After**			**Before**	**After**
BF MIL MST	**1.57E-07**	**9.74E-08**		Hip rotation MIL IC	**-104.813168**	**-35.353415**
BF MIL TS	**4.19E-08**	**2.18E-08**		Hip rotation MIL LR	**-407.577837**	**-131.401828**
BF LIL TS	**5.09E-08**	**2.63E-08**		Hip rotation MIL MST	**-131.317739**	**-60.436948**
BF MIL PSW	**1.07E-08**	**5.36E-09**		Hip rotation LIL MST	**-56.233293**	**-11.707981**
BF LIL ISW	**1.52E-08**	**1.10E-08**		Hip rotation MIL TS	**-225.096715**	**-85.055612**
BF MIL TSW	**1.25E-07**	**7.77E-08**		Hip rotation LIL TS	**-80.912522**	**-50.977734**
BF LIL TSW	**1.33E-07**	**9.78E-08**		Hip rotation MIL PSW	**-198.098633**	**-91.203742**
RF MIL IC	**1.85E-08**	**1.07E-08**		Hip rotation LIL PSW	**-91.927671**	**-61.537886**
RF LIL IC	**1.54E-08**	**1.15E-08**		Hip rotation MIL ISW	**-100.699038**	**-35.898468**
RF MIL LR	**5.83E-08**	**3.50E-08**		Hip rotation LIL ISW	**-46.63385**	**-33.898337**
RF LIL LR	**5.23E-08**	**4.10E-08**		Hip rotation MIL MSW	**568.936576**	**370.747144**
RF MIL MST	**8.21E-08**	**4.15E-08**		Hip rotation LIL MSW	**359.984115**	**161.270348**
RF LIL MST	**7.05E-08**	**5.33E-08**		Hip rotation MIL TSW	**256.714316**	**106.666952**
RF MIL TS	**2.30E-08**	**1.31E-08**		Hip rotation LIL TSW	**166.934347**	**12.34891**
RF LIL TS	**2.07E-08**	**1.37E-08**		Foot progress LIL IC	**-53.74**	**7.65**
RF MIL PSW	**1.13E-08**	**6.67E-09**		Foot progress MIL MST	**-80.71**	**14.77**
RF MIL MSW	**1.44E-08**	**9.01E-09**		Foot progress MIL TS	**-81.67**	**265.39**
RF MIL TSW	**1.92E-08**	**1.23E-08**				
TA LIL IC	**1.45E-07**	**8.02E-08**				
TA LIL LR	**4.23E-07**	**2.14E-07**				
TA LIL MST	**2.78E-07**	**1.57E-07**				
TA LIL TS	**5.93E-08**	**4.08E-08**				

sEMG (surface electromyography); BF (biceps femoris); RF (rectus femoris); TA (tibialis anterior); MG (medial gastrocnemius); MIL (More impaired limb); LIL (Less impaired limb); IC (Initial contact); LR (Loading response); MST (Midstance); TS (Terminal stance); PSW (Preswing); ISW (Initial swing); MSW (Midswing); TSW (Terminal swing).

Discussion

Interpretation of sEMG results

Since active training seems to be more effective than passive training for motor learning and cortical reorganization in central motor impairments, RAGT likely improved muscle activation of children with CP due to active training performed with a high-repetition-rate of guided movements (Meyer-Heim *et al.* 2009, Bonikowski *et al.* 2012, Aurich-Schuler 2017). Although this research study did not explore spasticity in children with CP, it could be one of the supportive explanations for why RAGT led to the decrease of muscle activity. Cyclic motion has been reported to be effective in decreasing spasticity in stroke patients (Monaghan 2017). In children with CP, the RF muscle tends to be shortened and spastic. This leads to hip joint flexion contractures that do not allow active and controlled knee extension during the stance phase (Foran 2005, Katz 1989, Schuler *et al.* 2011, Schuler *et al.* 2013). BF is typically weakened due to the dominant activity of the antagonist RF. Despite that in some children with CP this muscle can be spastic (Goldberg *et al.* 2012). Although our findings showed the bilaterally decreased activity of both muscles (Bonikowski *et al.* 2012) almost across all gait cycle phases, it is worth elaborating on increased number of treatments (e.g. up to 40) in a longer period of time such as in the study of Verazaluce-Rodriguez *et al.* (2014) to explore whether it is possible to induce even more physiological muscle activity. Children with CP often have spastic calf muscles, foot deformities and difficulties performing dorsiflexion and foot inversion resulting in a lack of TA activity (Brunner *et al.* 2008). In this study, TA muscle was active post-intervention during swing up to the loading response phases as previously shown in studies performed on healthy subjects (Brutsch *et al.* 2010, Schuler *et al.* 2013, Schuler *et al.* 2017). Thus, our findings further support that RAGT can enhance the physiological activity of TA, although the ankle joint during RAGT is only passively positioned to the neutral position (Colombo 2000). MG is a biarticular muscle often considered the main contributor to abnormal gait patterns as it causes Achilles tendon shortening which can result in contracture and foot deformities (Patikas *et al.* 2007, Perry 2010, Stewart *et al.* 2010). Therefore, if the MG muscle is influenced, either by stretching, relaxation, or positioning the affected joint in the neutral position, it can contribute to the increased range of motion in the ankle joint, as well as it can reciprocally allow the activation of the antagonist TA muscle (Katz *et al.* 1989, Colombo *et al.* 2000, Colombo *et al.* 2005). This is an interesting finding because it indicates that perhaps the active support and active movement of the proximal musculature may help encourage a similar adaptation in the distal musculature despite a lack of active support (Radziminska *et al.* 2012, Vrečar *et al.* 2013).

Interpretation of joint kinematics and kinetics results

Despite the lack of studies that explored the effect of RAGT on joint kinematics and kinetics in children with CP (Druzbicki *et al.* 2013, Schuler *et al.* 2017, Wallard *et al.* 2018), to the best of the authors' knowledge, this is the first study reporting on changes that followed RAGT in hip joint rotations. It is assumed that RAGT likely decreased internal hip joint rotations due to a high repetition rate of guided movements in joint centered position of the pelvis and lower limbs (Kolář 2002, Žarković and Šorfová 2017). In conditions with impaired motor control, such as in children with CP, joints are in a so-called decentralized position that also contributes to improper muscle function. The centered joint position allows for optimal loading of the joint in both static and dynamic conditions, as well as it enhances physiological muscle patterns. This is an interesting finding because it indicates that the combination of task-specific guided movements in a high-repetition-rate, and centered position of joints resulted in a decreased pathological internal hip joint rotations in ambulatory children with CP. Although RAGT allows very detailed adjustment of gait parameters, it has a fixed strategy to control the motion trajectory of the robotic orthoses and pelvis, which are limited to one degree of freedom in the sagittal plane. Indeed, it is the absence of lateral weight shift to the standing limb, rotational pelvic movements and kinematic variability that may be the main causes of therapy irresponsiveness in lower limb kinematic and kinetic variables. This is also supported by studies that have found that lower limb and pelvic kinematic variability could facilitate the transfer of motor skills from robotic therapy to over-ground walking (Reinkensmeyer *et al.* 2006, Koopman *et al.* 2013, Wu *et al.* 2017).

Interpretation of spatiotemporal parameters

Definition of spatiotemporal parameters allows for an objective definition of where, when, how long, and how rapidly the individual is in contact with the ground (Perry 2010, Baker 2013, Armand *et al.* 2016). In this research study, the most important changes were observed in increased cadence and step length, and a decrease in time needed for double support and stride. This could potentially contribute to more economic gait pattern in ambulatory children with CP who need to walk farther distances. Similar findings were reported by Meyer-Heim *et al.* 2007, Knecht *et al.* 2010, Beretta *et al.* 2015.

Conclusions

Findings suggest that RAGT as monotherapy can contribute to muscle reeducation and improvement of hip joint motion range in ambulatory children with CP. This is the first research study that extended the explanation of RAGT by centered joint position. Authors are aware of study limitations such as the small sample size, lack of control group and long-term follow-up data. For that, there is no tendency to generalize the study results to a wider spectrum of the CP population. However, this research study provides a foundation on which future studies can be built as RAGT should be investigated over longer periods in different populations to further determine its effectiveness.

Conflict of Interest

There is no conflict of interest.

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