

Walking in the Hibbot, an innovative walking aid improves gait characteristics in children with cerebral palsy: a cross-sectional study

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Abstract

Background: Crouch gait is a common gait impairment in children with cerebral palsy (CP). Growing up and gaining weight, lever arm dysfunctions further deteriorate and walking efficiency progressively worsens over time with risk of losing ambulant capacity in adolescent life. The purpose of this study is to evaluate whether walking in an innovative walking aid can reduce the flexed gait pattern by improving alignment of the lower extremity joints and improving weight bearing.

Methods: A semi-robotic walking aid called "Hibbot" has been designed, which can be used in rehabilitation and daily-life settings. In a cross-sectional study, five children with CP, aged 3-7 years, were familiarized with the Hibbot, by using the walking aid for 30 minutes, twice a week during 3 months under the supervision of their physiotherapists, who were instructed how to use the Hibbot. Using 3D gait analysis kinematics of the lower limb and trunk as well peak vertical ground reaction forces were compared between walking in their habitual (or no) walking aid and walking in the Hibbot, using a paired samples t-test ($p < 0.05$, spm1d.org).

Results: After the familiarization period of 3 months, a significant improvement in hip extension (mean difference $9.4 \pm 1.4^\circ$) and knee extension (mean difference $10.1 \pm 0.5^\circ$) during stance was observed when walking in the Hibbot compared to habitual walking. Improvements were also observed in trunk posture. However, differences in peak forces between habitual walking and walking in the Hibbot could not be confirmed.

Conclusions: These results are promising as to the possibility of the Hibbot walking aid in counteracting a flexed gait pattern. Further research is necessary to investigate the net joint moments and muscle forces explaining the higher knee and hip extension and improved trunk posture while walking in the Hibbot. Furthermore research should focus on determining which children with CP would benefit most, what are contraindications and what dose effects are to be expected.

Trial Registration: ClinicalTrials.gov, NCT04172324. Registered November 21 st , 2019 - Retrospectively registered. <https://clinicaltrials.gov/ct2/show/NCT04172324>

Background

Cerebral palsy is the most common motor impairment in childhood with a worldwide incidence of 2.5/1000.(1) The damage in the central nervous system causes muscle weakness, shortening of muscle-tendon units, muscle spasticity and impaired selective motor control (SMC) (2, 3) which results in gait limitations to a varying degree, as classified by the GMFCS-level.(4)

One of the major gait difficulties is crouch gait. Crouch gait is defined as excessive ankle dorsiflexion, knee and hip flexion during the stance phase. This gait disorder is common among patients with cerebral palsy and results in gait inefficiency because of additional energy expenditure and increased muscular effort. (5-8)

A significant correlation between scores on the Selective Control Assessment of the Lower Extremities (SCALE) (9) and impaired gait has been found in children with CP.(2, 9)

These findings suggest that a crouch gait pattern may be related to impaired neuromuscular control and this might play a crucial role in the persistence of a flexed gait pattern.

Past interventions to alleviate crouch gait primarily worked on weakness, spasticity, range of motion or balance. Yet, improvements in isolated impairments do not necessarily carry over to functional activities i.e. improved walking.(10, 11)

Recent research showed that crucial conditions for effective interventions on activities (i.e. walking) should start at a young age to enhance experience-dependent neuroplasticity, should be task specific, highly intensive and should be integrated into functional daily activities to enhance motor learning.(12-18) Evidence for neuroplastic changes induced by early intervention on upper limb motor activity has been found in recent studies.(19-21) However, research on neuroplastic changes as a result of intervention on lower limb activity is lacking.

The actual practice of gait either over ground or on treadmill ,with or without partial body weight support, has been shown to improve gait speed and endurance in CP patients aged 5 – 25 years.(22, 23) To mimic a physiotherapist's manual gait facilitation for optimal extensor muscle activity and postural control, different robotic assisted gait training devices have been developed, initially for applicability in adult neurologic conditions. The benefit of robotic assisted gait training is the potential to reach a higher number of repetitions and higher intensity than can be produced without a therapist's manual assistance. However, at present, the level of evidence for robotic assisted gait training is still weak and inconsistent in children with CP.(24, 25) On top of that, these systems are not adapted for small children, have a high economic cost and poor portability.

In order to potentially fill in the gap for early intervention taking into account the requirement of task specificity and functionality, a new semi-robotic walking device for small children, is designed by a multidisciplinary team, and is called "Hibbot". Hibbot is an assistive mechanical device, lightweight and portable that can be used in small children during rehabilitation and in daily life. This study provides proof of concept of the possibility of the Hibbot walking aid in counteracting a flexed gait pattern in young children with CP.

Methods

The manuscript adheres to the Strengthening the Reporting of Observational studies in Epidemiology (STROBE) statement (checklist in supplementary material).

Aim

The purpose of this study was to evaluate whether walking in the Hibbot affects gait kinematics and dynamics. The mechanism of the Hibbot manages to control all degrees of freedom (3x rotation and 3x translation) at the level of the pelvis and lower trunk. (Figure 1a,1b). The goal is to maximize a child's own muscle activity and postural control while giving as minimal support as needed. We assume that the design of the Hibbot facilitates correct activation of the gluteal muscles necessary for postural stability. Furthermore, sufficient hip extension movement is required to walk in the Hibbot. When the legs are flexed, fall protection bars touch the ground and locomotion is inhibited.

Our hypothesis is that walking in Hibbot would (a) improve trunk posture and extension in the lower limbs (b) improve weight bearing during the single stance phase. To test these hypotheses, lower limb joint angles and ground reaction forces were compared between walking with the Hibbot and habitual walking in a cross-sectional study.

Design

We performed a cross-sectional study comparing walking in the Hibbot to walking without walking aid/using a habitual walking aid in 5 children diagnosed with CP. The study was approved by the local ethics committee of the Antwerp University Hospital (18/44/509 B300201838159) and retrospective registered as Clinical Trials.gov Protocol Record NCT04172324.

Setting

The study was performed in collaboration with a licensed care provider and multifunctional centre directed at children and adolescents with a disability providing directly accessible care, short stay and respite care in Antwerp, Belgium. Participants were recruited in November 2018. Over a period of 3 months, between January 1st and March 31st in 2019, the children were familiarized with the Hibbot by using the walking aid for 30 minutes, twice a week, under the supervision of a physiotherapist. Physical examination and gait analysis were performed before (December 17 – 21, 2018) and after (April 1 – 5, 2019) the familiarization period, at the local gait lab.

Participants

Children had to meet the following inclusion criteria: confirmed diagnosis of CP, GMFCS level II-IV, age between 2 and 7 years, stature less than 1.25 meters and body weight less than 30 kilograms. Exclusion criteria were: fixed contractures in the lower limbs, hip dysplasia, infiltration with botulinum toxin 3 months or less prior to the start of the study, orthopaedic operations 6 months or less prior to the start of the study, insufficient mental capacity to understand instructions, insufficient motivation to walk and no prior experience in walking with the Hibbot.

Treating physicians provided the researchers with the information for possible inclusion. Subsequently, study information was provided to parents. After parents had signed an informed consent, patients were screened for eligibility.

To describe the study population age, gender, height, weight, BMI, GMFCS level(4) and mobility by passive range of movement measurement (PROM)(26), strength by manual muscle testing (MMT) (27), spasticity by the Modified Ashworth Scale (MAS)(28) and lower limb selectivity by Selective Control Assessment of the Lower Extremity (SCALE)(29) were assessed. The data of the clinical examination was meaningful by interpretation of the gait parameters i.e. step length, (a)symmetry in, maximal hip and knee extension during stance phase.

Measurements

Kinematics and kinetics of gait were recorded by an optical motion capture system (8 camera's, 120 Hz., Qualysis Proreflex, Göteborg, Sweden) surrounding a 10-meter walkway and synchronised with 3 force-platforms (two of 0.5m x 0.5m and one of 1.0m x 0.5m; AMTI Accugait, 1000 Hz., Advanced Medical Technology Inc., Massachusetts, USA). Reflective markers were attached to the skin over the processus spinosus of the 7th cervical vertebra (C7), incisura jugulars (IJ), processus xyphoideus (PX) and bilaterally over the clavicular head (CC), major trochanters (TM), lateral epicondyles (LE), lateral malleoli (LM), calcanei (CA) and 2nd metatarsal heads (MT). Marker trajectories were tracked and labelled in QTM (Qualisys Track Manager) software after which kinematic and kinetic data were combined in C3D file format. In addition, two Sony HD video cameras (Type: HDRCX240E, 50Hz.) were placed to record the sagittal and frontal plane kinematics. Children were encouraged to walk at self-selected speed over the walkway in Hibbot and using their habitual walking aid (if necessary, Table 1) in a randomized order. Patients walked either barefoot or with ankle-foot orthoses, if necessary. Prior to gait analysis a standard physical examination was performed by the physiotherapist to assess joint mobility (ranges of motion of hip, knee and ankle towards flexion/extension, ab/adduction and internal/external rotation) and strength, spasticity and selectivity of lower limb muscles (psoas, adductors, quadriceps, hamstrings, gracilis, gastrocnemius and soleus).

Data analysis

Gait analysis data in C3D file format was analysed using visual 3D software (Visual3D Professional v5.01.9, C-motion, Kingston, ON, Canada) and custom models. The body was modelled as an interconnected chain of rigid segments: CC – TM for trunk, TM – LE for thigh, LE – LM for leg and LM – MT for foot. In addition, the thorax was modelled as a 6 – degrees – of – freedom segment with the segment coordinate system definitions partially adapted from the ISB recommendations.⁽³⁰⁾ The segment origin coincided with IJ; the vertical axis (Z) was defined by the line connecting a virtual point at a fixed distance from PX in the direction of the IJ – C7 axis to the midpoint between IJ and C7 (pointing upwards); the medio-lateral axis (X) was defined as the line connecting the left to right CC; the antero-posterior axis was the common line perpendicular to Z and X, pointing forward.

Events of heel strike and toe off were determined from force plate recordings, CA and MT marker trajectories using the “Automatic Gait Events” command in Visual 3D software. Automatically assigned events were visually inspected.

Hip and knee kinematics in the sagittal plane

Hip flexion and extension were calculated as the planar angle between by CC – TM – LE in the sagittal plane, expressed relative to gait cycle duration (0 – 100%). Knee flexion and extension was characterised as the planar angle between TM – LE – LM as a function of gait cycle duration. The anatomical position with full extension of the hip and knee is characterised by angles of 180°. Angles are calculated against clockwork direction. At the hip, an angle < 180° indicates extension, whereas an angle > 180° indicates flexion. At the knee, an angle < 180° indicates flexion.

Thorax kinematics

Kinematics of the thorax was characterised by Euler/Cardan angles (XYZ) of the thorax coordinate system relative to the global reference frame, normalized to 100% of gait cycle duration. Flexion and extension of the thorax were measured around the X-axis (anteflexion positive, retroflexion negative). Lateral flexion of the thorax was measured around the Y-axis (ipsilateral side positive).

Peak vertical ground reaction force (F_z)

The peak vertical ground reaction force was determined as the maximum value of the vertical component of the ground reaction force vector during stance.

Step-time parameters

Using the “Temporal Distance Calculations for Gait” command, speed (m/s), normalised speed (statures/second), stride length (m), step length (m), stride width (m), stance time (s), swing time (s) and double limb support time (s) were calculated.

Statistical analysis

Discrete outcome variables were analysed using the Statistical Package for social Sciences Software (SPSS version 24 for Windows, IBM Statistics). Per subject, data were averaged over different gait cycles (3 – 8 gait cycles per condition). Wilcoxon signed-rank test was performed to evaluate the difference of gait kinematics and kinetics between the Hibbot- and habitual condition. The significance level was set at $p < 0.05$. Data were analysed separately for the before- and after-measurements. Missing data will be treated as missing.

Differences in the time profiles of hip, knee and thorax kinematics across the entire gait cycle were analysed by statistical parametric mapping (spm1d.org) using custom MatLab scripts (version R2018a for Windows). Kinematic time profiles were compared between Hibbot and habitual walking condition, separately for pre- and post-measurements, by means of spm1D paired samples t-test. If the null hypothesis was true, identical curves would be observed in both conditions. The null hypothesis was rejected when the t value exceeded the critical test statistical value t^* . Significance level was set at $p < 0.05$.

Results

Participants

In November 2018 ten potential participants were recruited, of whom both parents signed informed consent. After screening, two participants were excluded because of prior experience with Hibbot. During the familiarisation period, 3 additional children were excluded: one because of lack of understanding and lack motivation to walk, one because of a fixed flexion contracture in the hip joint and one because of infiltration with botulinum toxin in March 2019. Flowchart of participants can be found in fig.3.

Descriptive data

Demographic characteristics, GMFCS level and results from the physical examination can be found in table 1 and table 2.

[INSERT TABLE 1 HERE]

[INSERT TABLE 2 HERE]

Outcome data

Peak vertical ground reaction forces and step-time parameters are shown in table 3. Figure 4 represents the kinematic time profiles of the hip, knee and thorax as a function of gait cycle duration. Time profiles are represented before and after the familiarization period

[INSERT TABLE 3 HERE]

Main results

Hip and knee kinematics in the sagittal plane

Before the familiarisation with Hibbot (left panel in Figure 4), only a significant increase in hip flexion (Mean difference $7.0 \pm 0.02^\circ$) during loading response is observed when walking in Hibbot compared to the habitual condition. After the familiarisation period (right panel in Figure 2), a significant increase in hip extension (Mean difference $9.4 \pm 1.4^\circ$) is seen from 20 to 75% of the gait cycle (spm1D paired samples t-test, $p < 0.001$) using the Hibbot in comparison with the habitual walking aid/no walking aid.

Before the familiarisation with Hibbot (left panel in figure 4), a significant increase in knee flexion during terminal swing (Mean difference $13.8 \pm 0.8^\circ$) is observed when walking in Hibbot compared to the habitual condition. After the familiarisation period (right panel in Figure 2), the knee is significantly more extended (Mean difference $10.1 \pm 0.5^\circ$) from 32 to 74% of the gait cycle (spm1D paired samples t-test, $p < 0.001$) while from 85 to 98% the knee is more flexed (Mean difference $1.9 \pm 0.8^\circ$) during terminal swing (spm1D paired samples t-test, $p = 0.0002$)

Thorax kinematics

Before familiarisation (left panel in figure 4), during stance and early swing (from 0 to 78% of the gait cycle) the thorax is significantly more in retroflexion (Mean difference $7.4 \pm 1.3^\circ$) when walking in Hibbot compared to the habitual condition (spm1D paired samples t-test, $p < 0.001$). After the familiarisation period, this retroflexed position of the thorax normalizes (Figure 4, right panel), although the range of motion appears to be limited. In the frontal plane, initially lateral flexion of the thorax is constrained which appears to improve after the familiarisation period of 3 months.

Peak vertical ground reaction force (F_z)

Differences in peak vertical ground reaction force between Hibbot and habitual walking condition were not significant for the entire group.

Step-time parameters

No significant differences were found in any of the step-time parameters between walking in Hibbot and walking in the habitual walking aid (Table 3).

Discussion

The primary goal of this study was to evaluate our hypothesis that walking in Hibbot would (a) improve posture (i.e. reduce flexion) of the lower limbs and (b) improve weight bearing during single stance phase. While individual effects on walking with the Hibbot were variable, as expected in this heterogeneous patient population, several statistically significant trends were observed across the cohort.

The findings support our first hypotheses of improved posture when walking with the Hibbot, after a familiarization period. A significantly higher hip and knee extension in stance phase was found while walking with the Hibbot compared to habitual walking as well as improved lateral trunk control. Few studies compared the effects of walking devices on gait kinematics and spatiotemporal gait parameters.(31-34) Walking with handheld walkers (anterior walkers, posterior walker or crutches) in comparison to walking without any device resulted in increased knee extension, which corroborates our findings. On the other hand, walking with handheld walkers resulted in an increased anterior pelvic tilt, while walking with the Hibbot resulted in improved trunk posture in both the sagittal and frontal plane. When comparing an anterior versus posterior walker, a posterior walker may enhance posture alignment.(31)

At least on the level of kinematics, walking in the Hibbot thus results in a better hip and knee extension during stance phase. This is in line with previous research showing that support on the level of the pelvis and lower trunk by the brace could enhance synergic movements of the legs as well as upper trunk righting. (35) However, it is important to investigate the net joint moments and muscle forces explaining the higher knee and hip extension and improved trunk posture while walking in the Hibbot. Kinetics, revealing the load on upper extremities using a handheld walker have been studied (36, 37). Handheld walkers induce a partial weight lift effect through the arms. Secondly, the centre of mass is moved anteriorly, moving the onset of the ground reaction force forward in relation to the knees, which will increase externally extending knee moments (31). This compensatory mechanism, especially used in weak patients, compromises postural alignment.

The second hypothesis that walking with the Hibbot resulted in augmented weight bearing during single stance phase could not be confirmed. Walking speed and step length decreased when walking with the Hibbot in comparison with the habitual walker, although not significant. This might account for a smaller peak vertical ground reaction force. (38) Possibly, higher inertial forces were needed to start walking with the Hibbot because of its additional weight (7kg) in comparison to the habitual situation (posterior walker or no device) which may partially explain the decreased walking speed. Furthermore, the compensation strategies used by

the child in his/her habitual gait pattern to generate propulsion and speed may be inhibited or not available while walking in the Hibbot. Potentially the reduction in walking speed can also be considered as an advantage. Even in typically developing children lower walking speed is related to trunk righting and more extension in the lower limbs.(39) A decreased walking speed may be an advantage to learn the correct postural alignment during walking, but further research is needed to confirm this.

This study has several limitations. First, the intensity of the training period was too low to be considered as a real intervention. A 3-month period at a rate of 2 times a week training for 20 minutes per session must be considered a familiarization to the Hibbot instead of an intervention. Evidence for a high intense dose of intervention has been found regarding efficient interventions for upper limb activities.(40) A long-term follow up study is recommended to judge the impact on gait related parameters as well as transfer to real life settings.

The second limitation was the small sample size. The recruitment of 10 patients at only one school and the occurrence of dropouts, because of lack of cognition/cooperation, fixed contractures and Botox intervention, resulted in a sample of 5 patients. These 5 remaining patients were very heterogeneous both on motor and cognitive function; the 3 patients with GMFCS-level II were 8 years old by post measurements while the 2 patients with GMFCS-III were younger than 6 years old and showed weak cognitive function. Finally, although the braces were custom made, some pressure points did result in pain, which could influence the gait pattern. Regarding data analysis, the spm1D method has the advantage that the entire time curve can be analysed but a limitation is that changes in range of motion cannot be detected.

Future research should include registration of the muscular activation patterns as well as net joint moments. These outcome measurements are clinical important to interpret the kinematic changes and to determine if the Hibbot indeed elicits a different neuromuscular control. Next to investigating neuromuscular parameters, also parameters in the domains of activity and participation should be investigated.

Further studies should also be done to specify the indications (inclusion criteria) of usefulness of the Hibbot, as well as specify exclusion criteria. Inclusion of a larger and more homogenous sample size and implementing adequate concurrent controls is mandatory.

Conclusion

These results are promising as to the possibility of the Hibbot walking aid in counteracting a flexed gait pattern. The design of an optimal early intervention study based on task specific gait training with the Hibbot has to be worked out, based on the knowledge available regarding motor learning of walking and gait rehabilitation.

Declarations

Ethics approval and consent to participate

The current study was approved by the local ethics committee of the Antwerp University Hospital (18/44/509 B300201838159) and retrospective registered as Clinical Trials.gov Protocol Record (NCT04172324).

The parents/legal representatives of the eligible participants were provided with information letter and written informed consent letters were obtained for all the participants prior to their participation in the experiment.

Consent for publication

Consent was obtained for the publication of the pictures in figure 1.

Availability of data and materials

The datasets and analyses used during the current study are available from the corresponding author on reasonable request.

Financial competing interests

R.C., pediatric physiotherapist, is co-developer of the Hibbot and became in 2018 Clinical Advisor for the use of the Hibbot in the Norwegian company Made for movement, that is marketing the Hibbot. R.C. is shareholder in the company Made for movement.

D.W., engineer, is co-developer of the Hibbot and became in 2018 Research and Development engineer in the company Made for movement. D.W. is shareholder in the company Made for movement.

P.C. is co-developer of the Hibbot and became in 2018 Product Manager engineer in the company Made for movement. P.C. is shareholder in the company Made for movement.

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Authors' contributions

JL, EF, AH, ST, MM and RC participated in the study design and method process. AH performed the data extraction and data analysis. RC and AH wrote the manuscript. DW and PC provided the technical description and gave technical assistance during the intervention and gait analysis. JL supervised the study and revised the manuscript.

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Abbreviations

3D: 3 Dimensional

AFO: Ankle Foot Orthosis

BMI: Body Mass Index

C7: Cervical Vertebra

CA: Calcanei

CC: Clavicular Caput

CP: Cerebral Palsy

F: Female

GMFCS: Gross Motor Functional Classification Scale,

IJ: Incisura Jugularis

ISB: International Society of Biomechanics

L: Left

LE: Lateral Epicondyles

LM: Lateral Malleoli

M: Male

MAS: Modified Ashworth Score

MMT: Manual Muscle Testing

MT: Metatarsal Heads

NT: Not Tested

PROM: Passive Range of Movement

PX: Processus Xyphoideus

QTM: Qualisys Track Manager

R: Right

ROM: Range of Movement

SCALE: Selective Control Assessment of the Lower Extremity

SMC: Selective Motor Control

SMO: Supra Malleolar Orthosis

TM: Trochanter Major

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Tables

Table 1: Demographic characteristics of the participating children

	<i>Age</i>	<i>Gender</i>	<i>GMFCS</i>	<i>Diagnosis</i>	<i>Height (cm)</i>	<i>WEIGHT (kg)</i>	<i>BMI</i>	<i>Walking Aid</i>	<i>AFO</i>
1	4j 6m	F	III	Spastic bilateral	94	14	15.84	Kaye walker	yes
2	5j 9m	M	III	Spastic bilateral	110	16	13.22	Kaye walker	yes
3	7j 10m	F	II	Dyskinetic bilateral	120	19.5	13.54	none	yes
4	7j 9m	F	II	Ataxic bilateral	114	20	15.39	none	no
5	7j 9m	M	II	Dyskinetic bilateral	131	28	16.32	none	SMO

Abbreviations: F=Female, M= Male, AFO = Ankle Foot Orthosis, BMI = Body Mass Index, SMO = Supra Malleolar Orthosis

Table 2: Results from the physical examination of the participating children.

	<i>SIDE</i>	<i>HIP EXTENSION*</i>	<i>KNEE EXTENSION**</i>	<i>KNEE POPLITEAL ANGLE **</i>	<i>SPASTICITY PSOAS (MAS)</i>	<i>SPASTICITY HAM STRINGS (MAS)</i>	<i>STRENGTH HIP EXTENSORS (MMT)</i>	<i>STRENGTH KNEE EXTENSORS (MMT)</i>
1	L	+10°	0°	40/40	NT	NT	NT	NT
	R	+5°	-5°	40/40	NT	NT	NT	NT
2	L	0°	0°	-90/-70	1	1+	NT	NT
	R	-5°	0°	-95/-75	1	1+	NT	NT
3	L	0°	0°	-60/-50	1+	1	3	4+
	R	-5°	-5°	-70/-45	1+	1+	3	4+
4	L	0°	0°	-70/-40	1	1+	NT	NT
	R	0°	0°	-80/-40	1	1+	NT	NT
5	L	-5°	-5°	-60/-30	1+	1	NT	4+
	R	-5°	-5°	-50/-30	1	1+	NT	4

Abbreviations: L=Left, R= Right, ROM=Range of Movement, MAS=Manual Ashworth Score, MRT= Manual Muscle Testing, NT = Not Tested

* Modified Thomas test: Goniometer scoring of hip range of movement, the angle is determined from the zero or neutral position of the hip. A plus (+) angle refers to the ROM of hip extension, a minus (-) angle refers to a limitation in ROM of hip extension.

** ROM measured with a goniometer in supine position, the angle is determined from the zero or neutral position of the knee. A plus (+) angle refers to hyperextension of the knee, a minus (-) angle refers to a limitation in ROM of knee extension.

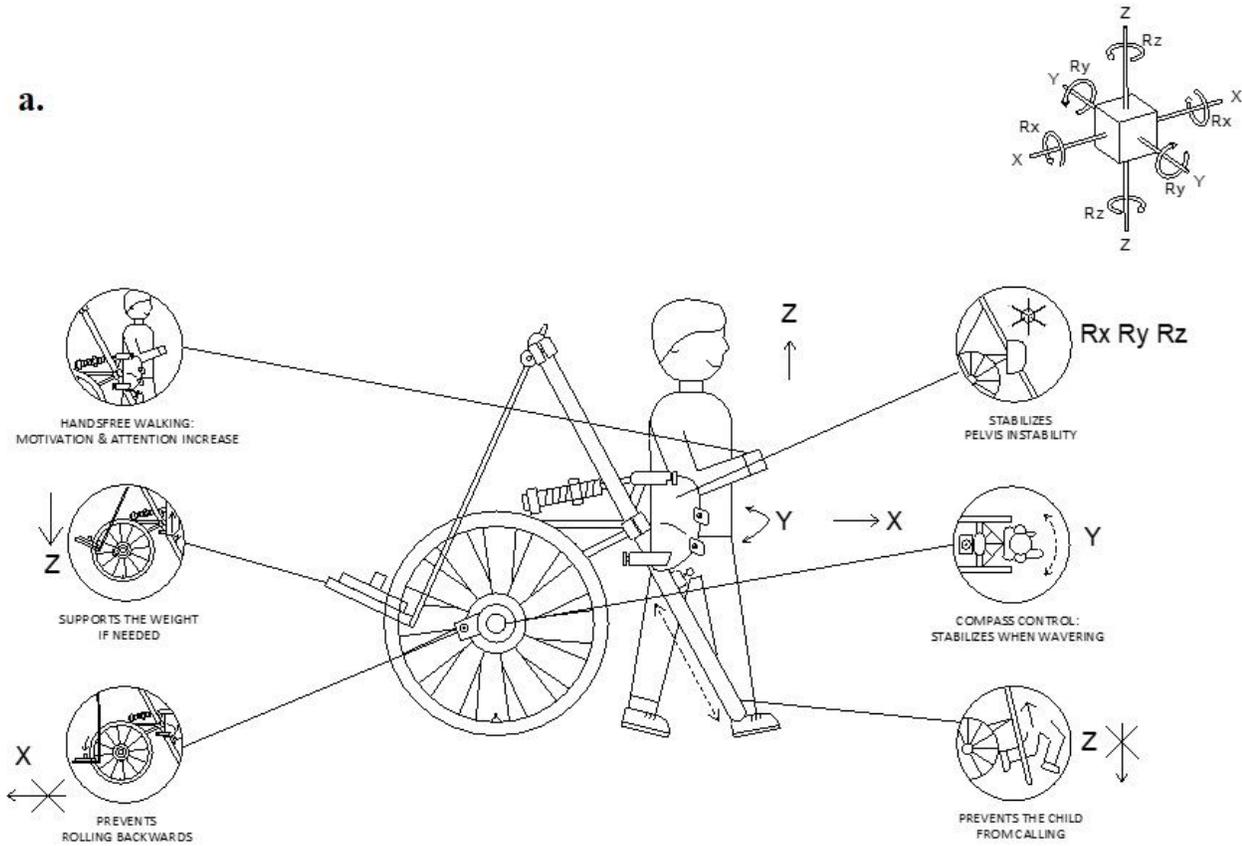
Table 3:Step-time parameters

CONDITION	HABITUAL WALKING			HIBBOT		WILCOXON RANK TEST	
		n*	Mean	<i>stdev</i>	mean	<i>stdev</i>	p-value
SPEED (m/s)	Before	3	0.51	<i>0.32</i>	0.47	<i>0.11</i>	0.882
	After	5	0.59	<i>0.15</i>	0.39	<i>0.20</i>	0.076
STATURES PER SECOND	Before	3	0.45	<i>0.27</i>	0.41	<i>0.09</i>	0.882
	After	5	0.51	<i>0.10</i>	0.32	<i>0.20</i>	0.076
STRIDE_LENGTH (m)	Before	3	0.68	<i>0.19</i>	0.55	<i>0.10</i>	0.297
	After	5	0.65	<i>0.08</i>	0.51	<i>0.20</i>	0.117
STEP_LENGTH (m)	Before	3	0.33	<i>0.09</i>	0.26	<i>0.01</i>	0.655
	After	5	0.33	<i>0.06</i>	0.24	<i>0.11</i>	0.175
STRIDE_WIDTH (m)	Before	3	0.09	<i>0.03</i>	0.08	<i>0.04</i>	0.655
	After	5	0.11	<i>0.04</i>	0.10	<i>0.04</i>	0.465
STANCE_TIME (s)	Before	3	1.76	<i>1.73</i>	1.36	<i>1.30</i>	0.807
	After	5	0.70	<i>0.19</i>	1.00	<i>0.24</i>	0.117
SWING_TIME (s)	Before	3	0.39	<i>0.13</i>	0.47	<i>0.22</i>	0.624
	After	5	0.39	<i>0.09</i>	0.37	<i>0.12</i>	0.465
DOUBLE LIMB SUPPORT TIME (s)	Before	3	1.18	<i>1.55</i>	0.50	<i>0.31</i>	0.624
	After	5	0.35	<i>0.13</i>	0.52	<i>0.16</i>	0.117

* Before the familiarisation period 2 out of 5 participants were not yet able to walk in the Hibbot. After the familiarisation period of 3 months, all 5 participants successfully completed several walking trials.

Figures

a.



b.



Figure 1

The “Hibbot” a) Different adjustable spring mechanism support the child in 6 degrees of freedom of direction. The 3 rotational directions (frontal, sagittal and vertical axis) are working at the level of the brace. The mobility of the brace can be adjusted by screws for the rotational and frontal axis and by a spring for the sagittal plane. The range of movement (ROM) in these 3 rotational planes can be set up gradually at the level of the brace. Set at zero ROM the brace is fixed static and gives more stability in that specific direction. The 3 translational directions (back/forward, up/down and sideways) are controlled by spring mechanism working at the wheel axes, fall prevention sticks and a reverse break. The compass in the wheel axes controls sideways swaying by

pulling the child back to the centre. The force that is controlling this lateral sway can gradually scaled. The reverse brake has an on/off button. When the brake is off, the Hibbot can roll backwards which might happen if the child performs insufficient hip extension during mid-stance. The fall prevention sticks do not touch the ground when walking but catch the child when falling. When the sticks touch the ground, the Hibbot is stuck and the child has to stand up before restart walking. b) The Hibbot or 'hip-robot' is an innovative walking aid designed to replicate the manual support provided by a therapist at the pelvis and lower trunk. A brace attached to the Hibbot is the communication between the child and the device, so there is no saddle to lean on. A child has his or her hands free and there is no frame in front of the child.

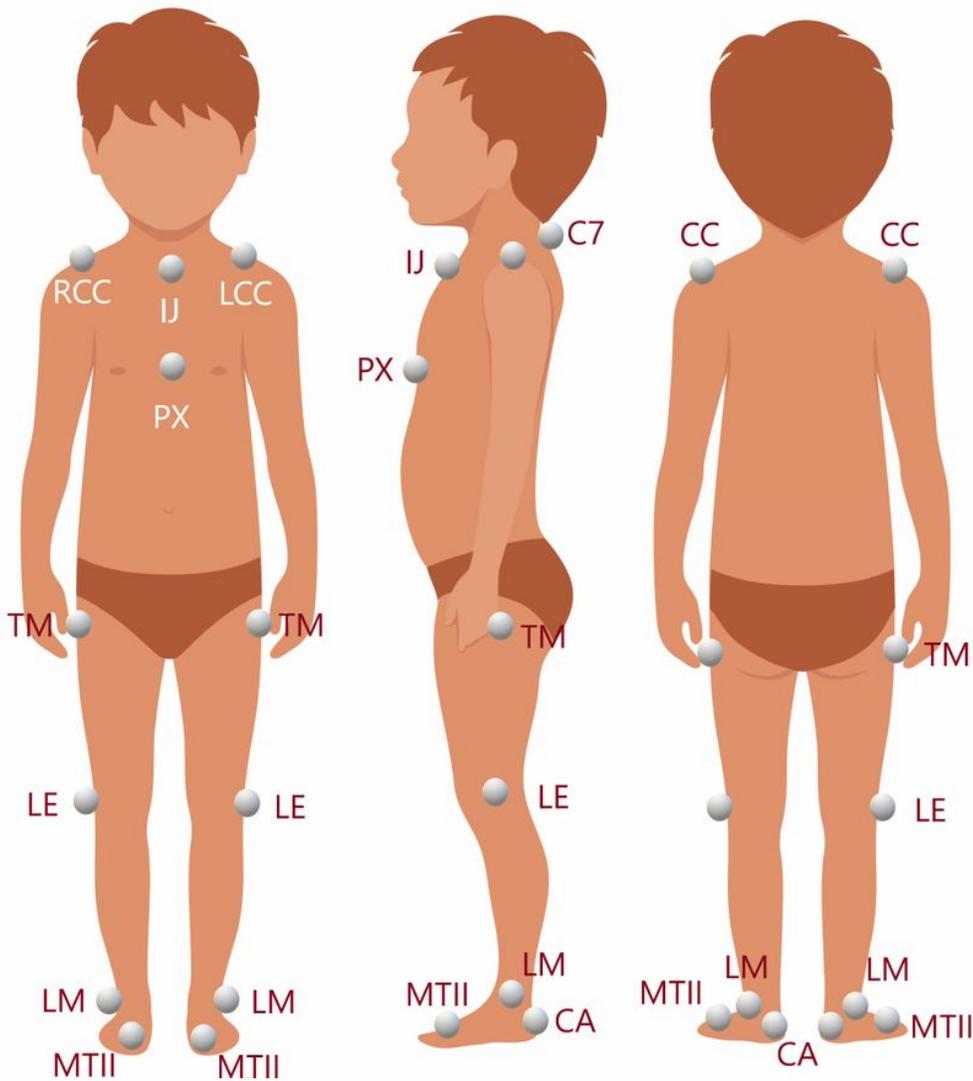


Figure 2

Marker Positioning Markers were placed on processus spinosus of the 7th cervical vertebra (C7), incisura jugulars (IJ), processus xyphoideus (PX) and bilaterally over the clavicular head (CC), major trochanteres (TM), lateral epicondyles (LE), lateral malleoli (LM), calcanei (CA) and 2nd metatarsal heads (MT).

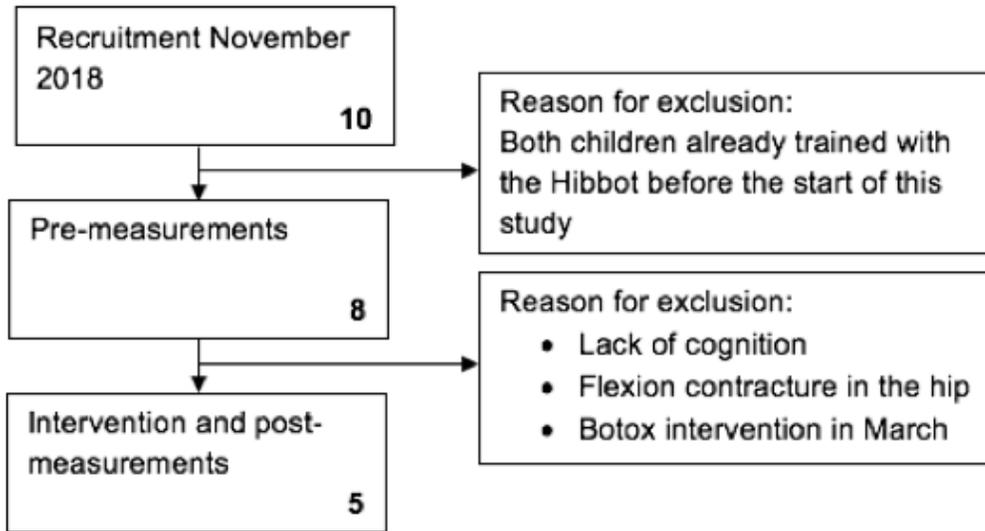


Figure 3

Flowchart of participant selection Initially, ten children were recruited to participate. Before the first measurement, two children were excluded because of prior experience with the Hibbot. During the familiarisation period, an additional 3 children were excluded because of lack of cognition, a fixed hip flexion contracture and the necessity for an intervention with Botox.

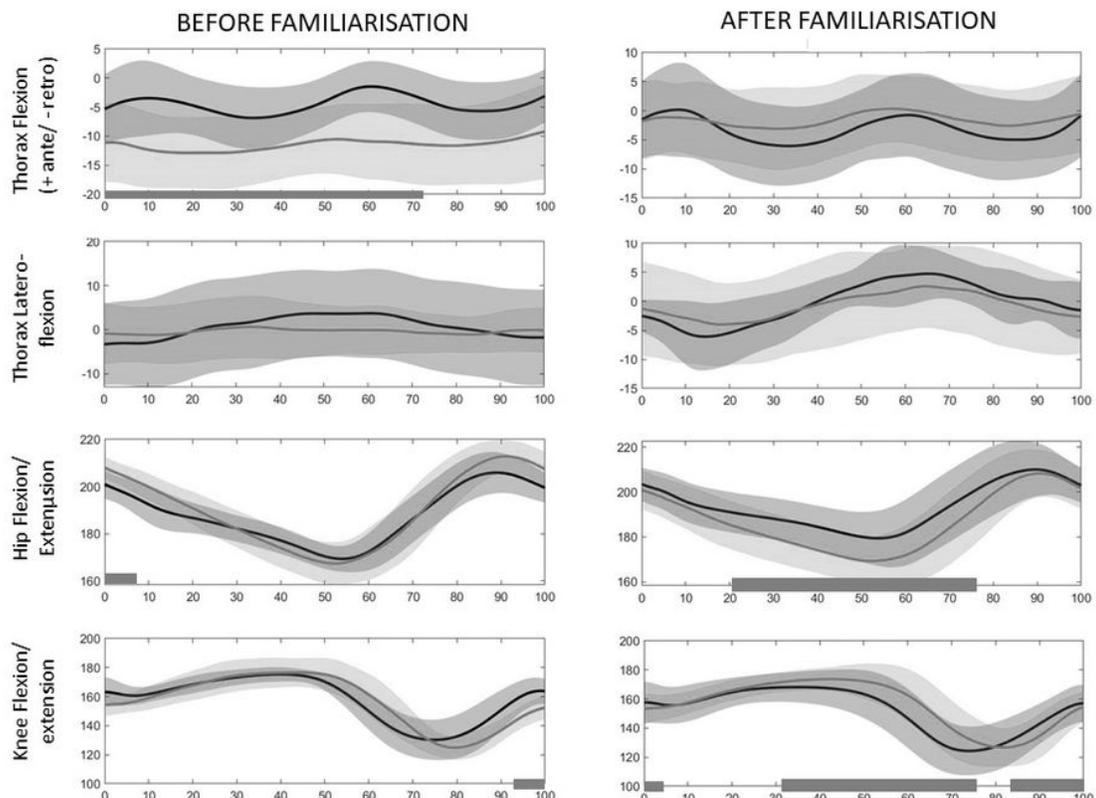


Figure 4

Flowchart of participant selection Initially, ten children were recruited to participate. Before the first measurement, two children were excluded because of prior experience with the Hibbot. During the familiarisation period, an additional 3 children were excluded because of lack of cognition, a fixed hip flexion contracture and the necessity for an intervention with Botox.

Supplementary Files

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