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Research article

The pilot study of the effect of six-week robot-assisted ankle training on mobility and strength of lower extremity and life habits for children with cerebral palsy

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ABSTRACT

Background: Children with cerebral palsy often have weak ankle muscles and reduced ankle dorsiflexion, which leads to activity limitations and eventually affects quality of life. Robotic ankle training was recently developed to facilitates muscle function through a high repetition of exercises. This study investigated the effect of six-week ankle training using the Anklebot device to improve lower limb structural and functional impairments and the resulting impact on quality of life.

Methods: Five children with spastic cerebral palsy aged between 4 and 11 years participated in six weeks of bilateral ankle assistive training using the Anklebot device. All lower limb muscle strength was measured with a hand-held dynameter, and range of motion was measured with a goniometer, at four different time points. Muscle architecture was assessed using a portable diagnostic ultrasound device, and quality of life was assessed using the Life Habits for Children scale, at two points in time only.

Results: Muscle strength and range of motion for all lower limb joints demonstrated significant improvement on both sides after training. The ankle muscle architecture showed non-significant improvement, while an overall significant improvement in the total score of the Life Habits for Children scale was detected after training.

Conclusion: Robot-assisted task-specific ankle training provides promising effects by allowing the required repetition to improve structural and functional muscle and joint impairments, which has a positive influence on the children's quality of life. However, due to a limited sample size, these results should be considered as preliminary; further study is needed.

1. Introduction

Cerebral palsy (CP) is a group of disorders that affects the developing brain, leading to various deficits in bodily functions and structures [1]. These can include problems with joint mobility, good muscle tone, muscle weakness and contractures [1].

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Consequently, impairments in body function and structure limit an affected child's functional activity and ability to participate and interact with their environment based on the International Classification of Functioning, Disability and Health (ICF) model [2].

The spastic type of CP affects up to 80 % of children [3]. Reduced flexibility and contracture are the results of spasticity's detrimental effects on muscle structure [4]. Consequently, compared to typically developed children, children with CP have weaker muscles because of decreased muscle thickness and a lack of motor unit activation [5]. Children with spastic CP have been reported to benefit from increased muscle strength [6]. Additionally, research has demonstrated a connection between enhanced muscle strength, decreased stiffness, and selective distal ankle control, all of which can improve a child's functional abilities [7].

Research by Damiano [8] suggests that to maintain the benefits of improved walking ability without increasing spasticity, it is necessary to perform strength training on a regular basis. The ankle joint complex plays an essential role in providing shock absorption and dynamic stability during walking [9]. Children with CP often have weak gastrocnemius muscles and reduced ankle dorsiflexion, but these issues can be addressed through strength training [10]. Therefore, an effective rehabilitation programme should focus on improving ankle joint muscle performance and function to elicit changes in activity and participation.

Motor learning theory emphasises the importance of an intense period of training for a short period of time to improve skill attainment [11,12]. Accordingly, repetition is required to acquire an ability and establish long-term behavioural changes once training is completed [13]. Evidence from animal studies demonstrated an increase in brain plasticity following higher repetitions that exceeded 400 [14], while a lower repetition of 60 failed to create new synapses in the brain [15].

For individuals with CP, concerns are mounting due to the high costs of their healthcare services and the quality that is delivered, along with insufficient and inconsistent clinical practice to meet the needs of this population [16,17]. Consequently, children with CP would benefit from an intervention that is cost-effective, requires less manual support from therapists and can reduce wait times to see a therapist. At the same time, it would provide the necessary dosage of training to acquire the skills needed.

One of the newest options in this area is the Anklebot (InMotion Technologies, Watertown, MA, USA), which was initially developed for stroke rehabilitation [18–20]. It has since been modified for use by children with neurological involvement [21]. This intervention allows for a high repetition of exercises that would not be feasible with traditional one-to-one PT sessions. The intervention is based on motor learning, neuroplasticity and dynamic system theories. There is growing evidence on the positive effects of ankle training using robotic technology in improving ankle strength, tone and range of motion in different populations [22–30]. However, there is limited reported work performed with young children with spastic cerebral palsy that considers the influence of structural and functional muscle impairments affecting the quality of life of those individuals.

This pilot study aimed to determine if children with spastic CP could benefit from six weeks of high-repetition ankle training with an ankle robotic in terms of increased lower limb muscular strength and range of motion (ROM). Additionally, the study intended to evaluate how this exercise affected the bilateral tibialis anterior and gastrocnemius muscles' pennation angle, thickness, and cross-sectional area. The study also looked at whether children with spastic CP would have better quality of life if their muscles were stronger and more flexible.

2. Methods

2.1. Study design

The study used a quasi-experimental design with repeated measures for a single group (Fig. 1). The participants completed two 45–60 min sessions a week during the six-week programme (a total of 12 sessions). Measurements were taken at four points in time: twice before the training and twice after the training. The first measurement was the initial baseline (IB), which was one month before the training. The second was the baseline (B), which was one week before the training. The two measurements performed prior to training was implemented to serve as a control condition of the intervention. The third measurement session was the immediate training (IT), which was one week after the training. The last measurement time point was the follow-up (FU), which was one month after the training.

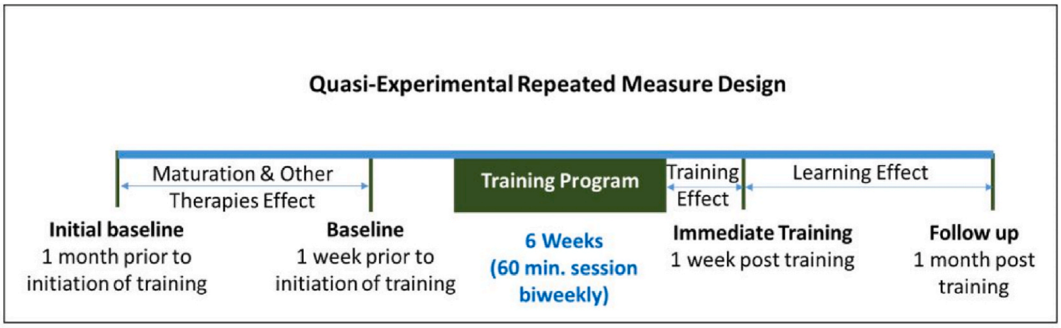

Fig. 1. Study design flow diagram.

2.2. Sample size calculation

The estimated sample size was calculated using G × Power software (version 3.1), found that 52 subjects were required for one group to achieve 90 % power with a 5 % type 1 error. In this pilot study, we recruited 5 subjects for one group.

2.3. Participants

Flyers at different clinics in Indianapolis, USA, were used to enlist a convenient sample of children with cerebral palsy. The following conditions had to be met for a participant to be considered for inclusion: the participant had to be diagnosed with cerebral palsy (CP), be between the ages of four and twelve, be classified as Level I–III in the Gross Motor Function Classification System (GMFCS), be able to stand and walk both with and without assistance, have the ability to understand instructions, and have ankle plantar flexor muscles that show Grade 3 or less on the Tardieu Spasticity Scale of the Lower Extremities. The study excluded children who had severe visual or hearing impairments, bone instability, open skin lesions, circulatory issues, uncontrollably recurring seizures, cardiac conditions that prevented them from engaging in physical activity, severely disproportionate leg growth, or permanent contractures.

The research has been approved by the institutional review bord Indiana University's Office of Research Administration (IRB #1206008957R003). Each participant provided informed consent and assent after being recruited.

2.4. Outcome measures

The outcome measures in this study were selected to cover the three domains of the ICF. The lower limb muscle strength, joint mobility, muscle tone and ankle muscle architecture measures were used to cover the body structure and function domain of the ICF model, and the life habits were selected to cover the influence of participation. All measurements were taken at all four time points except ankle muscle architecture and life habits, which were taken at only two time points: baseline (B) and follow-up (FU).

A hand-held dynamometer (HHD) designated the MicroFet 2 HHD (Hoggan Health, Salt Lake City, UT, USA) was used to test muscle strength. Previous research has demonstrated that this type of HHD has good reliability [31,32]. The following muscles were measured with it: knee flexors and extensors, hip abductors and adductors, hip flexors and extensors, ankle dorsiflexors and planterflexors, ankle evertors and invertors. The location and delivery of the exercise were in line with earlier research, and the participants were told to achieve maximum isometric contraction against the HHD [33,34].

Joint mobility was assessed through an active and passive ROM for the ankles, knees and hips using a goniometer following the positioning and instructions reported in previous work [35]. Goniometric measurement has been proven to be reliable and valid for measuring joint mobility [36].

Muscle architecture was assessed using a portable diagnostic ultrasound device (MyLab™ 25 Gold, Esaote, Florence, Italy) to measure the cross-sectional area (CSA), muscle thickness (MT) and pennation angle (PA) for the bilateral tibialis anterior, gastrocnemius muscle, and Achilles tendon. Based on the literature, it has been found that ultrasound is a highly reliable method for measuring CSA and MT in children with CP [37]. The administration and positioning of the participants were carried out in accordance with the literature [38,39].

Participation was assessed using the Life Habits for Children (LIFE-H) scale. It is a self-report questionnaire designed for children aged between 5 and 12 years old to evaluate 62 life habits in 12 different areas [40]. Each participant responded using a 5-point scale to measure difficulty and a 4-point scale to report the type of assistance needed. This questionnaire was found to be reliable and valid for children with CP [40–42].

Fig. 2. The anklebot intervention.

2.5. Intervention

The intervention consisted of playing three games “Race”, “Shipwreck” and “Soccer” while using the Anklebot [21]. Two games (“Race” and “Shipwreck”) required 132 repetitions of ankle dorsiflexion/plantar-flexion, and 44 repetitions of ankle inversion/eversion for each side. In addition, the repetition of a combination of ankle movements for “Race” was 44 and for “Soccer” was 132 for each ankle. This means that there was a total of 528 repetitions of each ankle during each training session for each participant.

A back-drivable robot with three degrees of freedom—dorsiflexion/plantar flexion, inversion/eversion, and internal/external rotation—the Anklebot has a low intrinsic mechanical resistance [19,21]. The unmodified version of Anklebot has been shown to be valid and reliable with an estimation of standard error $\leq 1^\circ$, and the error in torque <1 Nm [43].

During each training session, the participant was asked to sit in front of a computer screen and place one foot on the footplate, which was then secured with two straps over the metatarsals. Once the foot was secured, the robot was calibrated, and customised assistance was provided to each participant as needed. The screen displayed visual feedback at the end of each game about the performance of the participant and the amount of assistance provided (see Fig. 2).

2.6. Data analysis

The characteristics of the participants were summarized using descriptive statistics, and the mean scores of the various parameters were compared over time using a repeated measures analysis of variance (ANOVA). The statistical software SPSS (version 24) was used for all analyses. A significant threshold of $\alpha = 0.05$. The Bonferroni correction was applied to post hoc testing in order to detect variations in mean scores between time intervals.

3. Results

Six participants were enrolled in the study based on the inclusion criteria, however one participant has withdrawn from the study. Table 1 shows the characteristics of each participant.

3.1. Muscle strength

The results indicated a statistically significant improvements in muscle strength for both less affected (LA) and more affected (MA) sides for all ankle muscles; dorsiflexors, evertors, invertors, planterflexors at one month follow up (see Table 2). In addition, a statistically significant differences in mean scores between all four time points for both LA and MA ankles were found (see Table 3). All the improvements were significant between different time points for all ankle muscles except for the LA ankle invertors.

The mean scores of the LA and MA knee flexors showed 64 % and 78 % increases at FU, respectively. In Table 2, these improvements were statistically significant between different time points for the LA ($p = 0.021$) and MA ($p = 0.019$) knee flexors. In Table 3, a statistically significant differences were found in mean scores between between IB and FU for the LA ($p = 0.011$) and the MA ($p = 0.017$) knee flexors. Additionally, a significant differences between B and IT for the LA ($p = 0.024$) and MA ($p = 0.035$) knee extensors were found.

The results showed significant improvements in the mean score between before and after training in hip flexors, extensors, adductors, abductors muscle strength in the MA side (see Table 2). Whereas, at the LA side only hip flexors and adductors showed statistically significant improvements in muscles strength after training. However, as seen in Table 3, no statistically significant differences were found in mean scores between different time points except for hip flexors only between IB and FU for the LA ($p = 0.034$) and MA ($p = 0.023$).

3.2. Muscle architecture

The ultrasound data were analysed at B and FU only. Findings showed a decrease in both LA and MA of achilles tendon CSA (6 % and 2 % respectively) with an increase in medial gastrocnemius CSA (12 % and 13 % respectively). However, these were not significant (see Table 6). Whereas the LA tibialis anterior CSA showed a significant increase by 11 % ($p = 0.042$), while the MA side did not show any significant improvements. The results showed no significant increase in both LA and MA of tibialis anterior PA and MT (see Table 4).

Table 1
Participants’ characteristics.

Participant	Age	Sex	GMFCS Level	Impairment	Current Use of Orthosis
1	5	Male	III	Right hemiplegia	Yes
2	9	Female	I	Right hemiplegia	Yes
3	11	Male	I	Diplegia	No
4	10	Male	I	Left hemiplegia	Yes
5	4	Male	I	Right hemiplegia	Yes

Table 2
Mean ± SD ankle, knee and hip muscles strength changes at four time points.

	(1) IB	(2) B	(3) IT	(4) FU	*F*	*df*	*p-value*
LA ankle DF	6.52 ± 1.56	6.84 ± 1.95	13.16 ± 3.46	14.24 ± 3.34	45.23	1.06, 4.24	**0.002***
MA ankle DF	4.56 ± 1.40	5.82 ± 2.32	11.46 ± 4.67	12.08 ± 3.34	25.20	1.31, 5.26	**0.003***
LA ankle PF	7.36 ± 2.06	7.96 ± 2.52	15.12 ± 4.58	15.92 ± 3.59	60.28	1.08, 4.32	**0.001***
MA ankle PF	5.80 ± 2.07	6.30 ± 2.47	12.26 ± 5.36	14.06 ± 3.11	29.96	1.06, 4.25	**0.004***
LA ankle EV	4.98 ± 1.47	4.90 ± 0.836	10.92 ± 3.15	11.32 ± 2.33	35.82	1.11, 4.46	**0.003***
MA ankle EV	3.88 ± 1.10	4.20 ± 0.900	9.52 ± 2.70	9.50 ± 2.71	20.31	1.10, 4.41	**0.008***
LA ankle IN	6.60 ± 1.46	6.92 ± 1.55	12.78 ± 3.67	12.40 ± 3.31	19.48	1.09, 4.36	**0.009***
MA ankle IN	5.06 ± 1.25	5.34 ± 1.10	11.26 ± 3.30	11.26 ± 2.88	24.43	1.05, 4.23	**0.007***
LA knee EX	12.92 ± 4.22	13.94 ± 4.49	17.02 ± 4.55	16.88 ± 8.75	2.44	1.12, 4.50	0.187
MA knee EX	10.40 ± 3.84	12.04 ± 4.06	15.78 ± 5.17	14.20 ± 6.95	3.97	1.15, 4.62	0.106
LA knee FX	10.78 ± 3.82	11.24 ± 5.53	14.28 ± 4.55	14.52 ± 3.29	7.87	1.63, 6.52	**0.021***
MA knee FX	10.40 ± 4.30	10.04 ± 5.18	13.48 ± 3.74	14.42 ± 3.73	11.68	1.18, 4.72	**0.019***
LA hip AB	9.56 ± 2.69	10.18 ± 2.99	14.74 ± 6.18	13.84 ± 5.83	3.33	1.11, 4.45	0.134
MA hip AB	9.12 ± 3.49	10.02 ± 2.45	14.18 ± 4.86	12.64 ± 4.17	12.99	1.50, 5.99	**0.008***
LA hip AD	12.56 ± 6.96	12.42 ± 5.63	19.50 ± 9.66	20.30 ± 8.87	10.95	2.05, 8.22	**0.005***
MA hip AD	11.18 ± 5.88	10.88 ± 5.77	16.34 ± 8.21	16.12 ± 8.53	8.26	1.40, 5.60	**0.026***
LA hip EX	10.70 ± 5.29	10.16 ± 3.22	13.46 ± 5.62	13.12 ± 5.04	3.81	1.61, 6.45	0.086
MA hip EX	9.76 ± 3.77	9.10 ± 3.59	12.74 ± 4.74	11.06 ± 3.99	8.63	2.01, 8.06	**0.010***
LA hip FX	10.30 ± 1.60	11.78 ± 3.28	13.86 ± 3.86	14.50 ± 2.78	10.25	1.39, 5.57	**0.017***
MA hip FX	9.34 ± 2.39	10.22 ± 2.87	14.44 ± 4.79	12.72 ± 2.77	13.15	2.01, 8.04	**0.003***

*Significant difference ($p < .05$).
IB = initial baseline, B = baseline, IT = immediate training, FU = follow up, LA = less affected, MA = more affected, DF = dorsiflexion, PF = planterflexion, IN = inversion, EV = eversion, Fx = flexion, Ex = extension, AB = abduction, AD = adduction.

Table 3
Post hoc test showed the differences of ankle, knee and hip muscles strength between time points.

p-value	IB-B	IB-IT	IB-FU	B-IT	B-FU	IT-FU
LA ankle DF	1	**0.029***	**0.013***	**0.017***	**0.007***	**0.006***
MA ankle DF	0.476	0.066	**0.010***	0.098	**0.014***	1
LA ankle PF	0.634	**0.025***	**0.002***	**0.014***	< **0.001***	1
MA ankle PF	1	0.123	**0.002***	0.081	< **0.001***	1
LA ankle EV	1	**0.039a**	**0.006***	**0.046***	**0.009***	1
MA ankle EV	1	**0.044***	**0.040***	0.085	0.086	1
LA ankle IN	1	0.058	0.060	0.074	0.079	1
MA ankle IN	0.996	**0.048***	**0.028***	0.068	**0.041***	1
LA knee EX	0.823	0.068	1	**0.024***	1	1
MA knee EX	0.344	**0.017***	1	**0.035***	1	1
LA knee FX	1	0.101	**0.011***	0.563	0.370	1
MA knee FX	1	**0.020***	**0.017***	0.248	0.218	0.238
LA hip AB	1	0.494	0.506	1	1	1
MA hip AB	1	0.092	0.050	0.170	0.175	0.464
LA hip AD	1	0.178	0.095	0.161	0.091	1
MA hip AD	1	0.279	0.241	0.207	0.234	1
LA hip EX	1	0.063	0.308	0.727	0.422	1
MA hip EX	1	0.171	0.518	0.126	0.269	0.104
LA hip FX	1	0.320	**0.034***	0.096	0.071	1
MA hip FX	1	0.070	**0.023***	0.109	0.073	1

*Significant difference ($p < .05$).
IB = initial baseline, B = baseline, IT = immediate training, FU = follow up, LA = less affected, MA = more affected, DF = dorsiflexion, PF = planterflexion, IN = inversion, EV = eversion, Fx = flexion, Ex = extension, AB = abduction, AD = adduction.

3.3. Joints ROM

Data from the goniometer were analysed at all four time points. The results showed a significant increase in the mean active and passive ROM for both the LA and MA ankle dorsiflexors, plantarflexors, evertors and invertors (see Table 5). The post hoc tests revealed statistically significant differences in the mean scores of active and passive ROM in all ankle movements between B and IT for the MA side. However, there were no significant difference between B and IT except for ankle inversion of the LA ankle (see Table 6).

There was no significant improvement seen in all mean scores of ROM of the LA and MA knee extensors and flexors, except the active ROM of the MA knee flexors (see Table 5). There were a statistically significant differences in the mean scores between B and IT ($p = 0.009$) only. In addition, the mean scores of the active and passive ROM of the LA and MA hip abductors, adductors, extensors and flexors all showed a minimal increase, which was not statistically significant among the different time points (see Tables 5 and 6).

Table 4
Mean ± SD Muscle Architecture changes at baseline and follow up.

	Baseline	Follow Up	*F*	*df*	*p-value*
LA Achilles tendon CSA (mm^2)	37.50 ± 9	34.52 ± 6.80	1.58	1,4	0.277
MA Achilles tendon CSA (mm^2)	36.30 ± 10.70	36.50 ± 9.04	0.024	1,4	0.884
LA medial gastrocnemius CSA (cm^2)	2.57 ± 1.01	2.85 ± 1.08	1.76	1,4	0.255
MA medial gastrocnemius CSA (cm^2)	2.30 ± 0.551	2.59 ± 0.650	3.73	1,4	0.125
LA tibialis anterior CSA (cm^2)	2.57 ±0 .81	2.89 ± 1.04	8.70	1,4	**0.042***
MA tibialis anterior CSA (cm^2)	2.76 ±0 .703	3.07 ± 1.05	3.47	1,4	0.136
LA Tibialis anterior PA	15.09 ± 4.26	15.60 ± 4.80	0.338	1,4	0.592
MA Tibialis anterior PA	13.03 ± 1.63	13.24 ± 2.26	0.059	1,4	0.820
LA tibialis anterior MT	22.77 ± 3.87	24.61 ± 3.79	2.95	1,4	0.161
MA tibialis anterior MT	23.47 ± 4.37	24.53 ± 3.13	1.14	1,4	0.344

*Significant difference ($p < .05$).
LA = less affected, MA = more affected, CSA = cross-sectional area, MT = muscle thickness, PA = pennation angle.

Table 5
Mean ± SD ankle, knee and hip joints ROM (deg.) changes prior to and after training.

		(1) IB	(2) B	(3) IT	(4) FU	*F*	*df*	*p-value*
Active ROM	*LA ankle DF*	0.00 ± 10	−1.40 ± 11.90	7.80 ± 12.39	7.40 ± 11.14	16.17	1.45, 5.81	**0.005***
	MA ankle DF	−27 ± 7.31	−26.60 ± 10.43	−18 ± 10.65	−13.20 ± 7.72	14.40	1.32, 5.30	**0.009***
	LA ankle PF	48.80 ± 7.79	49.80 ± 8.25	62 ± 3.67	61.20 ± 4.14	13.10	1.79,7.19	**0.004***
	MA ankle PF	42.80 ± 7.59	47.80 ± 8.19	58.60 ± 3.97	56 ± 6.04	29.30	2.27,9.08	**< 0.001***
	LA ankle EV	13.80 ± 6.01	13 ± 4.69	19.20 ± 7.53	20.80 ± 7.19	17.99	2.37,9.47	**< 0.001***
	MA ankle EV	8.20 ± 2.38	9.40 ± 2.88	15.80 ± 3.76	19.20 ± 6.41	21.83	1.04,4.18	**0.008***
	LA ankle IN	18.20 ± 6.64	20 ± 9.72	33 ± 10	30.80 ± 8.10	15.68	1.75,7	**0.003***
	MA ankle IN	14.80 ± 8.87	18.80 ± 9.03	26.80 ± 8.10	26.80 ± 7.39	17.21	1.84,7.38	**0.002***
	LA knee Ex	−1± 3.46	−2± 4.47	−0.80 ± 4.86	−0.40 ± 0.89	0.607	1.44,5.75	0.525
	MA knee Ex	−1.80 ± 4.60	−3± 6.70	−1.80 ± 5.76	−0.20 ± 1.64	1.26	1.10,4.41	0.326
	LA knee Fx	142.40 ± 6.10	136.40 ± 8.64	143.60 ± 4.72	138.20 ± 5.02	2.16	2.10,8.40	0.173
	MA knee Fx	135.80 ± 7.15	128.80 ± 6.38	142.20 ± 3.83	132.40 ± 9.73	9.66	2.03,8.14	**0.007***
	LA hip AB	36.40 ± 10.50	34 ± 10.58	37.20 ± 10.47	36.20 ± 13.42	0.262	1.90,7.62	0.767
	MA hip AB	32.60 ± 6.98	29.20 ± 12.98	33.40 ± 10.76	34.20 ± 9.33	0.580	1.88,7.54	0.574
	LA hip AD	24.40 ± 6.18	22.60 ± 6.54	25.40 ± 6.14	27.80 ± 4.26	1.35	1.77,7.10	0.312
	MA hip AD	21 ± 5.38	18.80 ± 6.68	23.60 ± 6.10	26 ± 4	3.52	1.19,4.77	0.121
	LA hip Ex	10.80 ± 12.37	12 ± 8.09	12 ± 7.34	12.20 ± 6.97	0.158	1.17,4.70	0.747
	MA hip Ex	9.40 ± 11.61	10.60 ± 6.91	11.60 ± 5.22	12.20 ± 4.26	0.457	1.55,6.21	0.607
	LA hip Fx	110.80 ± 10.03	110.60 ± 12.64	115 ± 11.26	116.40 ± 9.83	1.12	1.58,6.33	0.366
	MA hip Fx	105.60 ± 6.26	106 ± 11.42	115.20 ± 9.52	112 ± 7.48	2.16	1.90,7.63	0.181
Passive ROM	*LA ankle DF*	7.60 ± 9.34	8.8 ± 8.81	14.2 ± 10.15	14.4 ± 9.81	10.69	2.03, 8.12	**0.005***
	MA ankle DF	−10 ± 12.43	−10.40 ± 11.97	−0.80 ± 10.80	2.60 ± 11.95	30.952	1.97, 7.88	**< 0.001**
	LA ankle PF	58 ± 10.65	60 ± 8.38	67.40 ± 4.33	69.60 ± 7.95	11.42	1.56,6.24	**0.010***
	MA ankle PF	54.20 ± 9.75	58.20 ± 7.46	63.80 ± 6.72	66 ± 7.90	31.19	2.01,8.04	**< 0.001***
	LA ankle EV	18.40 ± 6.84	19.20 ± 8.01	27 ± 8.42	29.60 ± 7.70	8.82	1.33,5.32	**0.025***
	MA ankle EV	15.20 ± 3.11	16.20 ± 3.96	25 ± 8.39	28.20 ± 7.25	11.97	1.81,7.27	**0.006***
	LA ankle IN	30 ± 4.63	31.80 ± 7.01	39.40 ± 7.66	39.40 ± 6.87	15.73	1.55,6.21	**0.005***
	MA ankle IN	27.40 ± 4.09	29.60 ± 4.15	38.20 ± 5.49	39 ± 4.35	47.07	1.35,5.41	**0.001***
	LA knee Ex	1.60 ± 2.96	1.40 ± 3.91	1.60 ± 1.81	1.60 ± 0.548	0.014	1.24,4.97	0.945
	MA knee Ex	0.60 ± 3.20	0.80 ± 3.42	1.0 ± 1.73	1.60 ± 1.14	0.516	1.64,6.58	0.586
	LA knee Fx	147.20 ± 7.15	146.40 ± 5.50	147.60 ± 6.34	146.60 ± 7.26	0.081	1.18,4.74	0.827
	MA knee Fx	143.80 ± 7.88	138.40 ± 5.17	145.40 ± 4.98	143.20 ± 7.72	2.07	1.51,6.05	0.205
	LA hip AB	41.80 ± 10.71	39.20 ± 12.31	43.40 ± 9.31	45 ± 11.22	0.877	1.25,5.01	0.419
	MA hip AB	38.80 ± 8.07	37 ± 8.21	42.20 ± 7.22	42.20 ± 7.69	1.75	1.81,7.27	0.239
	LA hip AD	27.40 ± 4.56	28.60 ± 7.53	31.60 ± 6.06	33 ± 6.08	2.32	1.25,5.02	0.191
	MA hip AD	26 ± 4.18	25.80 ± 8.58	27.80 ± 6.34	31 ± 6.40	2	1.67,6.68	0.208
	LA hip Ex	23.80 ± 7.39	24.60 ± 8.82	26 ± 6.96	25.80 ± 4.60	0.439	2.04,8.18	0.663
	MA hip Ex	20.20 ± 7.72	22 ± 8.80	23.60 ± 4.03	24.40 ± 3.57	1.30	1.73,6.94	0.324
	LA hip Fx	122.20 ± 8.10	126.60 ± 9.04	125.80 ± 13.64	128 ± 13.92	0.963	1.48,5.92	0.406
	MA hip Fx	119.60 ± 8.79	122 ± 9.19	124.40 ± 11.26	125.40 ± 9.99	1.09	2.19,8.75	0.381

*Significant difference ($p < .05$).
IB = initial baseline, B = baseline, IT = immediate training, FU = follow up, LA = less affected, MA = more affected, DF = dorsiflexion, PF = planterflexion, IN = inversion, EV = eversion, Fx = flexion, Ex = extension, AB = abduction, AD = adduction.

3.4. Life habits for children (LIFE-H)

The LIFE-H questionnaire findings showed no significant differences in the mean scores in any of the subscales. However, a significant improvement were seen in the mean total score. (see Table 7).

Table 6

Post hoc test showed the difference between time points.

	p-value	IB-B	IB-IT	IB-FU	B-IT	B-FU	IT-FU
Active ROM	LA ankle DF	1	0.094	**0.034**	0.111	0.062	1
	MA ankle DF	1	0.131	**0.008***	**0.012***	0.071	1
	LA ankle PF	1	0.135	0.111	0.060	0.060	1
	MA ankle PF	0.613	**0.005***	**0.005***	**0.043***	0.118	0.635
	LA ankle EV	1	0.091	**0.016***	0.106	**0.036***	1
	MA ankle EV	0.196	**0.020***	0.067	**0.014***	0.065	0.375
	LA ankle IN	1	**0.030***	0.099	**0.018***	0.242	1
	MA ankle IN	0.636	**0.018***	0.059	**0.021***	0.249	1
	LA knee Ex	1	1	1	1	1	1
	MA knee Ex	1	1	1	0.652	1	1
	LA knee Fx	1	1	1	0.570	1	0.769
	MA knee Fx	0.211	0.729	1	**0.009***	0.652	0.222
	LA hip AB	1	1	1	1	1	1
	MA hip AB	1	1	1	1	1	1
	LA hip AD	1	1	1	1	1	1
	MA hip AD	1	1	**0.018***	0.108	0.532	1
	LA hip Ex	1	1	1	1	1	1
	MA hip Ex	1	1	1	1	1	1
	LA hip Fx	1	1	1	0.177	1	1
	MA hip Fx	1	0.645	1	**0.029***	1	1
Passive ROM	LA ankle DF	1	0.170	0.068	0.083	0.197	1
	MA ankle DF	1	**0.013***	**0.022***	**0.040***	**0.004***	0.976
	LA ankle PF	0.538	0.234	0.088	0.199	0.098	1
	MA ankle PF	0.148	**0.025***	**0.006***	**0.018***	**0.015***	1
	LA ankle EV	1	0.272	0.152	0.346	0.220	1
	MA ankle EV	1	0.232	0.084	0.157	0.092	1
	LA ankle IN	1	0.116	0.070	0.058	**0.030***	1
	MA ankle IN	0.515	**0.030***	**0.003***	**0.014***	**0.001***	1
	LA knee Ex	1	1	1	1	1	1
	MA knee Ex	1	1	1	1	1	1
	LA knee Fx	1	1	1	1	1	0.534
	MA knee Fx	1	1	1	**0.001***	0.553	1
	LA hip AB	1	1	0.499	1	1	1
	MA hip AB	1	1	1	0.866	0.671	1
	LA hip AD	1	0.347	0.341	0.349	1	1
	MA hip AD	1	1	0.494	0.775	1	1
	LA hip Ex	1	1	1	1	1	1
	MA hip Ex	1	1	1	1	1	0.596
	LA hip Fx	0.258	1	1	1	1	1
	MA hip Fx	1	1	1	1	1	1

*Significant difference ($p < .05$).

IB = initial baseline, B = baseline, IT = immediate training, FU = follow up, LA = less affected, MA = more affected, DF = dorsiflexion, PF = planterflexion, IN = inversion, EV = eversion, Fx = flexion, Ex = extension, AB = abduction, AD = adduction.

Table 7

Mean ± SD for changes in LIFE-H categories prior to and after training.

LIFE-H Category	Baseline	Follow-Up	Change (%)	*F*	*df*	*p*	*ES*
Communication	8.99 ± 1.08	9.52 ± 0.69	5.89 %	3.39	1, 4	0.139	0.82^{L}
Community Life	4.66 ± 5.05	6.00 ± 5.47	28.75 %	0.15	1, 4	0.717	0.20^{S}
Education	7.53 ± 1.18	8.55 ± 1.37	13.54 %	5.07	1, 4	0.087	1.00^{L}
Employment	2.00 ± 4.47	4.00 ± 5.47	100.00 %	1.00	1, 4	0.374	0.45^{S}
Fitness	8.27 ± 1.18	9.10 ± 0.66	10.00 %	3.22	1, 4	0.147	0.80^{L}
Housing	8.10 ± 1.98	9.15 ± 0.89	12.96 %	2.22	1, 4	0.210	0.70^{L}
Interpersonal Relationships	9.91 ± 0.20	10.00 ± 0.00	0.90 %	1.00	1, 4	0.374	-0.11^{S}
Mobility	7.65 ± 1.20	9.00 ± 2.23	17.64 %	2.27	1, 4	0.206	0.70^{L}
Nutrition	8.55 ± 2.06	8.55 ± 2.10	0.02 %	0.00	1, 4	0.999	-2.95^{L}
Personal Care	7.37 ± 1.85	8.60 ± 0.80	16.68 %	3.34	1, 4	0.141	0.80^{L}
Recreation	8.40 ± 1.26	9.10 ± 1.01	8.33 %	3.86	1, 4	0.121	0.87^{L}
Responsibilities	8.27 ± 2.02	9.15 ± 1.05	10.64 %	1.85	1, 4	0.245	0.60^{L}
Total Score	8.48 ± 0.89	9.10 ± 0.64	7.31 %	14.00	1, 4	**0.020***	1.60^{L}

*$p < .05$. ES: effect size. ^{L}Large effect (Cohen's d ≈ .8). ^{M}Moderate effect (Cohen's d ≈ .5). ^{S}Small effect (Cohen's d ≈ .2).

4. Discussion

This pilot study aimed to assess the potential benefits of using ankle robotic technology to provide high-repetition active-assistive training that can improve muscle strength and ROM. The results also highlight how this training can increase the level of participation among children with CP as it improves their structural and functional impairments. The findings indicate significant improvement in strength, ROM and overall life participation.

When it comes to children with CP, the impact of weakened muscles is more significant than the impact of spasticity [7]. Therefore, building muscle strength is crucial for improving activity levels and participation [6]. The muscles that are most affected in the lower extremities are the ankle dorsiflexers and plantar flexors. Distal strength impairments are a recognised limiting factor in spastic CP children acquiring an increase in functional activity [44–48]. Children with spastic CP may have defects in ankle movement on both the MA and LA limbs as they strive for a more balanced gait pattern [49]. In this study, both ankles were trained, regardless of the level of involvement, leading to significant improvements in muscle strength and mobility for the ankle, knee and hip muscles on both sides. These findings align with other studies that have shown similar results in improving muscle strength through training for children with CP [23,24,50].

According to Cho et al. [51], children with CP respond well to progressive resistance training. However, in their study, the training focused specifically on ankle-assisted tasks; however, improvements were seen in muscle strength and mobility. In the current study, the Anklebot device provided assistance to the child as required. In addition, unlike most studies that use wearable exoskeletons while a child walks or stands [52–54], this study involves open-chain active-assistive training while the child is sitting and playing video games.

Children with CP generally have smaller muscle volume compared to typically developing children [55]. This study found an increase in the cross-sectional area of the gastrocnemius and tibialis anterior muscles. Unfortunately, these changes were only significant in the LA tibialis anterior CSA, while the rest were all not significant. This might be due to the small sample size of only five participants. However, the tibialis anterior showed a significant increase in strength at follow-up compared to baseline, which may explain the significant result in the TA CSA compared to other muscles. In this study, we observed changes in muscle architecture parameters associated with changes in muscle strength. Previous research indicates that strength training promotes cell enlargement through the synthesis of more myofilaments [56], which is consistent with our findings. Multiple studies have shown that muscle size and structure are strongly linked to strength [56,57]. Additionally, CSA and thickness are positively correlated with force production [58]. This means that larger and thicker muscle fibres are capable of generating more force. Despite the lack of resistance provided by the robot, the child's physical activity still resulted in force production and strengthening, which led to changes in the muscle architecture.

The significant improvements elicited by improving body structure and function in children with CP in this study were also translated into enhanced participation levels. This was evidenced by substantial increases in the total score on the LIFE-H questionnaire, indicating a significant change over time compared to a minimum detectable change score of 0.68 [40]. Additionally, the improvements in physical categories were linked to enhancements in impairments, physical functioning, and mobility [59]. The findings also showed a non-significant change with a large effect size in recreational activity among all participants, which is a crucial skill for children to build friendships, develop identities, enhance competence, and improve their quality of life [60,61]. However, there are only a few studies on participation in children with CP, and information on leisure activities is limited [60–63].

5. Limitations

This study is designed to be a pilot study and the findings should be considered preliminary due to the following limitations: a sample size of five which was small and the lack of a control group. Pilot studies are not recommended for calculating sample sizes or response rates for large scale studies [64]. In addition, most of the children who participated in this study were at Level I GMFCS and were males with right hemiparesis. Thus, the dissemination of study findings should be taken with caution.

6. Conclusion

Robot-assisted task-specific ankle training has an effective influence on all lower limb muscle strength and range of motion on both sides. This shows the potential of the Anklebot six-week intervention as a promising therapeutic option for use with children with CP. It can provide improvement at multiple levels without causing undue fatigue or disengagement from training. These improvements can be seen in body structure and function as one domain of the ICF that impacts the participation domain, which also showed a significant difference. The study's results suggest that this intervention can be considered as an alternative option in rehabilitation for children with CP, as it provides high repetition and requires less manual support from a therapist. However, further research with a larger and more heterogeneous sample that represents the overall CP population is needed to confirm and extends the findings of this study. Future work should prioritize the application of this promising intervention through well-designed randomized control trials to ensure the robustness and generalizability of the study. It is crucial to incorporate divers subgroups within the CP population, including variations in age, gender and severity of symptoms to fully understand the interventions' efficacy.

Disclosure statement

The authors report there are no competing interests to declare.

Ethics statement

The research has been approved by the institutional review bord Indiana University's Office of Research Administration (IRB #1206008957R003 in June 2016). Each participant provided informed consent and assent after being recruited.

List of Abbreviations

Cerebral Palsy	CP
International Classification of Functioning, Disability and Health	ICF
Range of Motion	ROM
Initial Baseline	IB
Baseline	B
Immediate Training	IT
Follow-Up	FU
Gross Motor Function Classification System	GMFCS
Hand-Held Dynamometer	HHD
Cross-Sectional Area	CSA
Muscle Thickness	MT
Pennation Angle	PA
Life Habits for Children	LIFE-H
Repeated Measures Analysis of Variance	ANOVA
More Affected	MA
Less Affected	LA

Data availability statement

Data will be made available upon request.

CRediT authorship contribution statement

Madawi Alotaibi: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Brent L. Arnold:** Writing – original draft, Validation, Supervision, Resources, Methodology. **Niki Munk:** Supervision, Resources, Formal analysis. **Tracy Dierks:** Supervision, Resources, Methodology, Formal analysis. **Peter Altenburger:** Supervision, Resources, Methodology, Investigation. **Samiah Alqabbani:** Writing – review & editing, Formal analysis. **Afrah Almuwais:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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