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Balance control via tactile biofeedback in children with cerebral palsy

HANDE ARGUNSAH*, BEGUM YALCIN

Acibadem Mehmet Ali Aydinlar University, Faculty of Engineering and Natural Sciences,
Department of Biomedical Engineering, Istanbul, Turkey.

Purpose: Children with cerebral palsy have limitations in utilizing neural information to perform smooth movement and maintain balance during walking. This study aimed to develop a wearable sensor that tracks balance continuously and provides haptic biofeedback to its user through real-time vibration stimulus to assist patients with balance and postural control impairments such as cerebral palsy. *Methods*: Twelve children with cerebral palsy and 12 age-matched typically developed children used the sensor during walking at a self-selected speed. The lower extremity joint kinematics, center of mass, and spatial-temporal parameters were recorded with Xsens MVN during "with" and "without" biofeedback conditions. *Results*: The sensor did not disturb healthy gait. Pearson correlation coefficient and Root Mean Square Error techniques showed that biofeedback regulated the gait parameters and trunk stability of the CP group. The extended stance percentage (without BF: 73.91% ± 10.42, with BF: 63.53% ± 2.99), step width (without BF: 0.20 m ± 0.05, with BF: 0.18 m ± 0.07), and step time (without BF: 1.55 s ± 1.07, with BF: 0.73 s ± 0.14) parameters decreased. Similarly, cadence and walking speed increased. *Conclusions*: Obtained results indicated that this wearable sensor can be integrated into the physical therapy and rehabilitation process of children with balance and postural control impairments to improve motor learning and balance control. The present findings contribute to a better understanding of the adaptation of innovative engineering applications with rehabilitation processes, which, in turn, could assist patients with balance impairments and facilitate their integration into society.

Key words: *physical human–robot interaction, balance control, biofeedback, wearable sensor, sway, cerebral palsy*

1. Introduction

Cerebral palsy (CP) is the most common neurological disorder in the world that permanently affects body movements and muscle coordination [18]. Population-based studies around the world report prevalence estimates of more than 4 CP per 1000 live births or per child of a given age range [2], [8], [19], [27]. CP is a major cause of motor deficits in children. Asymmetrical agonist and antagonist muscles affect the position of the ankle during gait and cause pathological gait patterns in ambulatory children with CP that lead to plantar flexion contracture and shortening of the posterior muscle groups. Children with CP have inadequate equilibrium and defensive reflexes that compromise postural control [10]. Due to the weakness of their back and abdominal muscles, children with CP have poor core stability [25]. Programs for maintaining core stability have been demonstrated to increase limb mobility, improve muscle strength, and regulate trunk stability [11], [23]. Strengthening the muscles in the abdomen, back, pelvis, and shoulder – all of which keep the trunk stable and enduring during static and dynamic activities – improves core stability [6], [30]. Children with CP benefit from core stability training in terms of standing and walking abilities, as well as endurance and balance [9], [12], [17]. Wallard et al. [28] reported the variability of the head orientation relative to the trunk and emphasized the importance of the clinical evaluation of posture during gait in children with CP. Primary, mostly motor deficits brought on by brain damage resulting in a variety of persistent movement and postural abnormalities such as spastic-

* Corresponding author: Hande Argunsah, Acibadem University, Kerem Aydinlar Campus, Kayisdagi Cad. No:32 Atasehir, 34752, Istanbul, Turkey. Phone: +902165004145, e-mail: hande.argunsah@gmail.com

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ity, muscle tone issues, balance issues, etc. Additionally, during growing, a variety of muscle and bone deformities appear; these primarily affect the legs and trunk and frequently force the child to assume a stooped posture that significantly impairs locomotion. This results in a loss in the body's joint-related degrees of freedom as well as considerable postural instability and joint rigidity brought on by spasticity. Moreover, in another study, Wallard et al. [29] investigated the balance control of children with CP during gait and reported the divergent trajectories of center of mass and center of pressure parameters due to the inevitable adaptations to control dynamic equilibrium. Pierret et al. [21] investigated the dynamic stabilization of axial segments during sitting and reported a distinct impairment in axial segment postural control in children with CP. This study suggested that the impairment of axial segment postural control is crucial for standing and walking and it should be considered carefully during the planning of the rehabilitation programs for children with CP. These studies state the importance of trunk stability in the therapeutic management of CP.

Neuromuscular training is aimed at developing the potential of the nervous system to produce rapid and optimal muscle contraction, improve coordination/balance and relearn movement patterns and skills. The effectiveness of physical therapy and rehabilitation depends on its patient-specific design, the ability to keep the patient's performance at the optimal level during therapy, the patient's adaptation to treatment, the experience of the rehabilitation team and the team's ability to monitor the physical development of the patient instantly and accurately. The goal of rehabilitation is to restore muscle strength, range of motion, stability and overall functions to improve the patient's quality of life. Patient-specific rehabilitation programs, biofeedback applications and virtual reality integrated physical therapy programs have recently been utilized in pediatric rehabilitation [16], [21], [28], [29]. These practices, which are mostly founded on the concepts of sensorimotor learning, are increasingly being suggested as therapeutic options for people with locomotor problems. An appropriate rehabilitation can substantially improve the long-term motor functions in both neurological and orthopedic patients [5]. Innovative rehabilitation robots with cutting-edge interaction control architectures and integrated sensors allow for continuous monitoring and adaptation to patients' actual conditions [20].

Conventional physiotherapy and rehabilitation techniques require several sessions of one-on-one manual interactions with therapists for a prolonged period. In addition, the evaluation of patients' progress and assessment of treatment efficacy are usually subjective and not well documented with objective measures. Additionally, conventional physiotherapy and rehabilitation techniques for managing balance impairments may have some limitations resulting in poor patient compliance and difficulties for patients to participate in the treatment for long durations. For this reason, it is very important to support conventional physical therapy with innovative engineering applications. Biofeedback is one of these tools that favor motor control during static and dynamic tasks via augmenting motor information for improving patient motivation and adaptation.

Biofeedback is used to increase the motivation and performance of the individual during physical therapy [26]. It is a technique of providing instantaneous physiological data, as stimulated auditory, visual or tactile feedback to enhance the efficiency of the activity by modifying the participant's motivation, concentration, attention and to reduce anxiety. Biofeedback integrates information technology into physical therapy and rehabilitation; hence, the awareness of the immediate condition increases the learning ability, adaptability and willingness to continue physical therapy of the patient [15]. Real-time movement, postural control, proprioception and force produced by the body are typically involved in biomechanical biofeedback applications. Proprioception is the motion, equilibrium and position sense of the body in space to stabilize the posture via biological information from various visual, vestibular and proprioceptive inputs [4]. Static proprioceptive information involves the control of postural orientation; on the other hand, dynamic proprioceptive information involves the control of postural stability [3]. Accurate awareness of this information is required for maintaining an upright loading and sustaining normal ambulation. Tactile biofeedback has been integrated into physical therapy and rehabilitation programs of children and adult patients previously, hence its effect on balance control [14] and minimizing sway [24] has been reported. This manuscript proposed a sensor, which serves both aims: it promotes physical activity adaptation of the patient and regulates gait through continuous and real-time balance control. Additionally, patients with balance and postural control issues can practically use it by themselves during daily activities and away from physical therapy facilities thanks to its small and simple-to-wear design. The effectiveness of the sensor was examined using biomechanical data collected during walking from children with CP and typically developed children.

2. Materials and methods

2.1. Participants

Twelve children with CP (3 female, 9 male) between the ages of 9 and 16 (mean = 11.4 ± 3.6 years) participated in this cross-sectional study. Participants had a Gross Motor Functional Classification System (GMFCS) level of I-III and a Modified Ashworth Scale (MAS) score of 3 or below. Included participants had no previous history of surgical intervention for spasticity. All participants were ambulatory and did not use assistive devices during data collection. They had the ability to follow simple instructions. Children who are non-ambulatory and who walked with the aid of an assistive device were excluded from the study.

Twelve (5 female, 7 male) age-matched typically developed children (mean = 14.9 ± 5.5 years) were involved in the study. Selection criteria for the control group included no prior history of cardiovascular, neurological nor musculoskeletal disorders (Table 1). Ethics committee approval was obtained prior to data collection. Consent was obtained from the participants and their parent(s) prior to the investigation.

Table 1. Participant's physical and demographic information

	CP group	Control group
Age [year]	11.4 ± 3.6	14.9 ± 5.5
Gender	3 female, 9 male	5 female, 7 male
Height [cm]	138.9 ± 20.6	146.0 ± 21.2
Weight [kg]	24.6 ± 20.2	33.2 ± 20.6

2.2. Materials

The wearable sensor was developed by the authors [1] and was composed of a motion processor unit (MPU--9-axis IMU with 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer), a microprocessor, and 4 vibration units, which were shielded in stereolithographic 3D printed cases (Fig. 1). The MPU is placed on the sternum (T8 level posteriorly) of the user. The microprocessor and 4 vibration units were placed on a belt, which was positioned on the user's under-bust and natural waistline with an adjustable strap (Fig. 2). The vibration units and the MPU were controlled by Raspberry Pi (Raspberry Pi Foundation, https: www.raspberrypi.org). The vibration motors were placed on the belt in a way that corresponds to the front, back, right and left directions. The waist was chosen as the location for the vibration motors be

Fig. 1. 3D printed cases (using stereolithography) of the vibration units (Autodesk Fusion 360 TM CAD (https://www.autodesk.com) Formlabs Form 2® (https://formlabs.com))

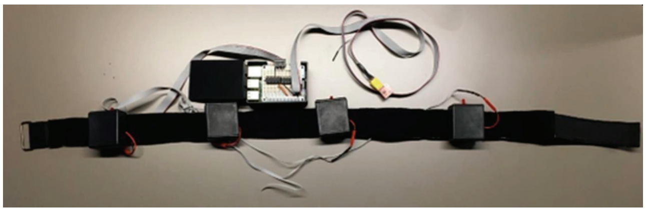

Fig. 2. Components of the wearable real-time tactile biofeedback device (MPU unit and 4 vibration units for front-back-left-right directions operated by a Raspberry Pi® (Raspberry Pi Foundation, https://www.raspberrypi.org)

Fig. 3. Placement of the wearable real-time tactile biofeedback device and Xsens MVN IMU sensors (shown on a healthy subject)

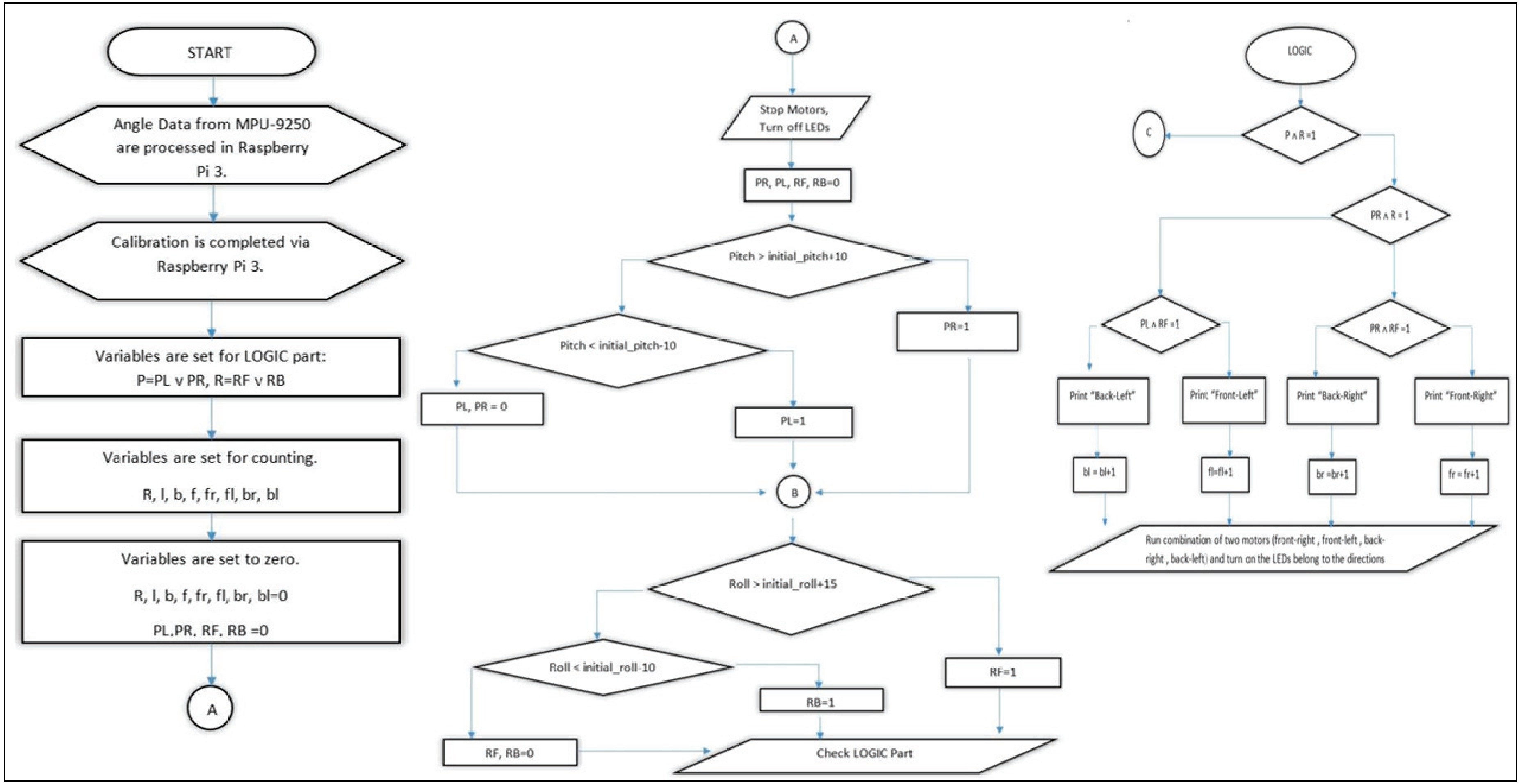

Fig. 4. Tactile biofeedback device Logic Chart and Control Algorithm

cause it is both tactilely sensitive and open to stimuli, and it also makes it simple for the user to wear it beneath clothing while using the sensor (Fig. 3). At the start of data collection, the participant stood still in an anatomical position for 3 seconds while the sensor was calibrated. The body's initial orientation was set using measured Euler angles, which were also referred to as the origin coordinates. Following the calibration procedure, threshold values were determined and entered into the sensor algorithm in order to pinpoint the area where the body can move in cardinal and/or quadrantal directions during walking. The sensor assumed the axial body as a pendulum, the sternum being the bob, when the pendulum bob swayed outside the allowed region, the corresponding vibration unit(s) were activated, and the tactile stimulus was given to the user simultaneously until the balance is regained (Fig. 4). The sensor's logic charts, and control algorithm can be found in the supplementary files.

2.3. Experimental design and procedure

A standard testing protocol was developed and the same method was followed for each participant. Before the experiment, children with CP and typically developed children were introduced to the sensor, informed about the purpose of the study, trained about the safety features and asked to stop the procedure anytime whenever they felt uncomfortable. Enough time was given to each participant to get familiar with the sensor.

The lower extremity kinematic data and center of mass (T8 segment orientation) were collected with Xsens MVN Awinda (Xsens Technologies BV® (Netherlands)). Continuous balance monitoring and tactile biofeedback guidance were done by the sensor. The threshold value for postural control was set to 10 degrees in four cardinal and four quadrantal directions for children with CP and typically developed children. This threshold value was determined by the physical therapist and encircled the acceptable circular path that the sternum could sway during ambulation. As the sway region exceeded 10 degrees in any cardinal and/or quadrantal direction, then the corresponding vibration unit(s) was activated, and tactile biofeedback was provided to the participant.

Lower extremity kinematic data and change in center of mass were collected during a 10-meter walk test at a self-selected speed while the participants were (with biofeedback condition) and were not (without biofeedback condition) guided with real-time biofeedback. Kinematic data were recorded for 2 minutes and 5 consecutive strides were analyzed for each participant during "with" biofeedback and "without" biofeedback conditions. Data collection was done in a fully equipped gait analysis laboratory under doctor and physical therapist supervision. Data for "with" and "without" biofeedback conditions were collected consecutively and on the same day for each participant.

2.4. Data processing and outcome measures

The lower extremity movement trajectories and ROM data were collected at 60 Hz with Xsens MVN. All continuous variables were presented as mean ± SD. The Kolmogorov–Smirnov normality test was conducted to examine the distribution of the continuous variables. One-way repeated measures ANOVA was established to compare the mean differences between the "with" and "without" biofeedback conditions of the two groups. All tests were 2-tailed, and the significance level ($p < 0.05$) was considered statistically significant. The statistical analysis was performed using SPSS (version 12, Chicago, IL). For the bivariate analyses, Pearson Correlation Coefficient and Root Mean Square Difference techniques were used to evaluate the difference between lower extremity joints' movements. the error is calculated with the equation given below:

$$\text{Error}_{\text{(with BF/ without BF)}} = \sqrt{(X_{\text{with BF}} - X_{\text{without BF}})^2 - (Y_{\text{with BF}} - Y_{\text{without BF}})^2}\,, \quad (1)$$

$$\text{Error}_{\text{(with BF CP / with BF control group)}} = \sqrt{(X_{\text{with BF control group}} - X_{\text{without BF CP group}})^2 - (Y_{\text{with BF control group}} - Y_{\text{without BF CP group}})^2}\,. \quad (2)$$

3. Results

Twelve children with CP and 12 typically developed children completed the data collection without any complications. Spatial-temporal parameters and lower extremity kinematic data were collected and compared

Table 2. Mean (standard deviation) values of spatiotemporal parameters for CP and control groups

Spatial-temporal parameters	CP group		Control group	
	without biofeedback	with biofeedback	without biofeedback	with biofeedback
Stance [%]	73.91 ± 10.42	63.53 ± 2.99	60.32 ± 2.38	62.26 ± 3.45
Cadence [steps/min]	59.25 ± 40.91	63.63 ± 18.78	114.80 ± 15.49	110.62 ± 18.44
Walking Speed [m/s]	0.52 ± 0.37	0.61 ± 0.19	1.04 ± 0.12	1.24 ± 0.68
Step length [m]	0.41 ± 0.11	0.49 ± 0.07	0.54 ± 0.07	0.52 ± 0.14
Step width [m]	0.20 ± 0.05	0.18 ± 0.07	0.16 ± 0.04	0.15 ± 0.12
Step time [s]	1.55 ± 1.07	0.73 ± 0.14	0.53 ± 0.06	0.59 ± 0.03

Table 3. Pairwise comparisons for children with CP: (1) without BF, (2) with BF

One-way repeated measures ANOVA results for "with" and "without" biofeedback conditions							
	Conditions	*N*	Mean	Std. dev.	Std. error	95% confidence interval for mean	
						lower bound	upper bound
Ankle ROM	without BF	12	61.3	18.9	3.7	58.9	65.2
	with BF	12	51.6	16.7	1.3	45.6	59.4
	total	24	55.5	9.4	1.3	52.1	68.5
Knee ROM	without BF	12	23.5	10.5	1.9	16.3	27.2
	with BF	12	34.8	5.8	1.1	17.6	36.9
	total	24	37.1	9.2	1.2	28.6	43.4
Hip ROM	without BF	12	31.7	7.5	1.4	25.5	34.5
	with BF	12	36.7	7.9	1.5	18.7	44.7
	total	24	35.7	7.7	0.9	29.7	43.7
Pelvic tilt	without BF	12	4.2	9.4	2.1	1.8	2.8
	with BF	12	2.9	4.9	1.1	2.4	3.9
	total	24	2.4	11.1	1.5	1.5	3.3
Pelvis obliquity	without BF	12	13.1	16.2	2.4	6.2	12.0
	with BF	12	9.2	12.9	2.4	7.4	10.9
	total	24	11.7	14.0	1.8	9.8	15.3
Pelvis rotation	without BF	12	17.5	17.7	6.5	12.8	24.2
	with BF	12	11.2	8.8	1.9	8.0	16.0
	total	24	15.6	21.7	3.5	7.5	27.6

for "without" and "with" biofeedback conditions for both groups (Table 2). The CP group was characterized by a longer stance percentage, lower cadence, shorter step length, and longer stride time when compared to the control group. Spatial-temporal parameters of control group participants were not significantly different for "with" and "without" biofeedback conditions.

In Table 3, the one-way repeated measures ANOVA results for "with" and "without" biofeedback conditions are presented. The lower extremity joints' movement trajectories are depicted in Fig. 5. In Figure 6, the violin plots show the active range of motion with median, minimum and maximum scores of "with" and "without" biofeedback conditions of lower extremity joints. The whiskers are based on the interquartile range (IQR). The change in the center of mass for "with" and "without" biofeedback conditions of both groups is shown in Fig. 7.

Pearson Correlation Coefficient (PCC) and Root Mean Square Error (RMSE) techniques were used to evaluate the trajectory similarity of lower extremity joint trajectories of "with" and "without" biofeedback conditions Eqs. (1) and (2). Larger differences in RMSE indicated a poor regression fit and a larger gap between the movement trajectories of conditions. Contrarily, smaller differences in RMSE indicated strong regression fit and similar movement trajectories.

The CP group participants had higher pelvic tilt and abnormal range of motion on pelvis rotation (with biofeedback CP – Control Group RMSE:14.25 and without biofeedback CP – Control Group RMSE: 17.44)

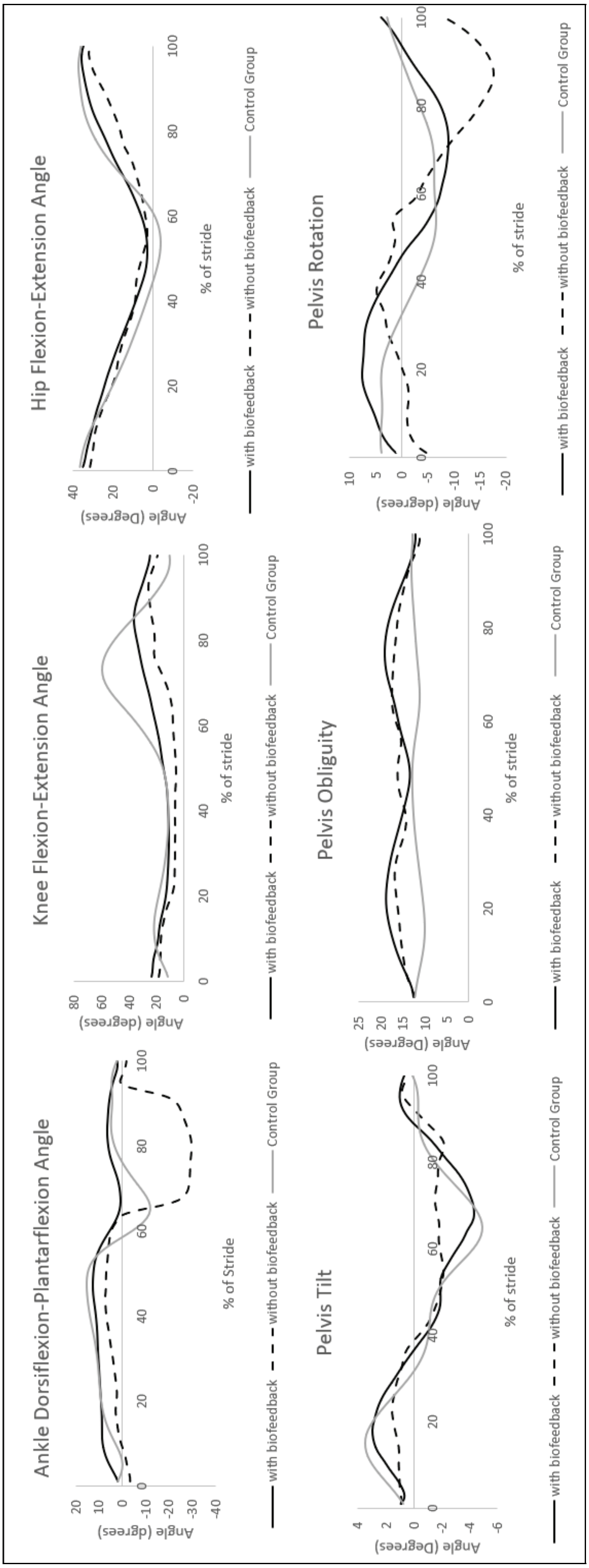

Fig. 5. Comparison of the lower extremity joints kinematics for children with CP (with-without biofeedback conditions)

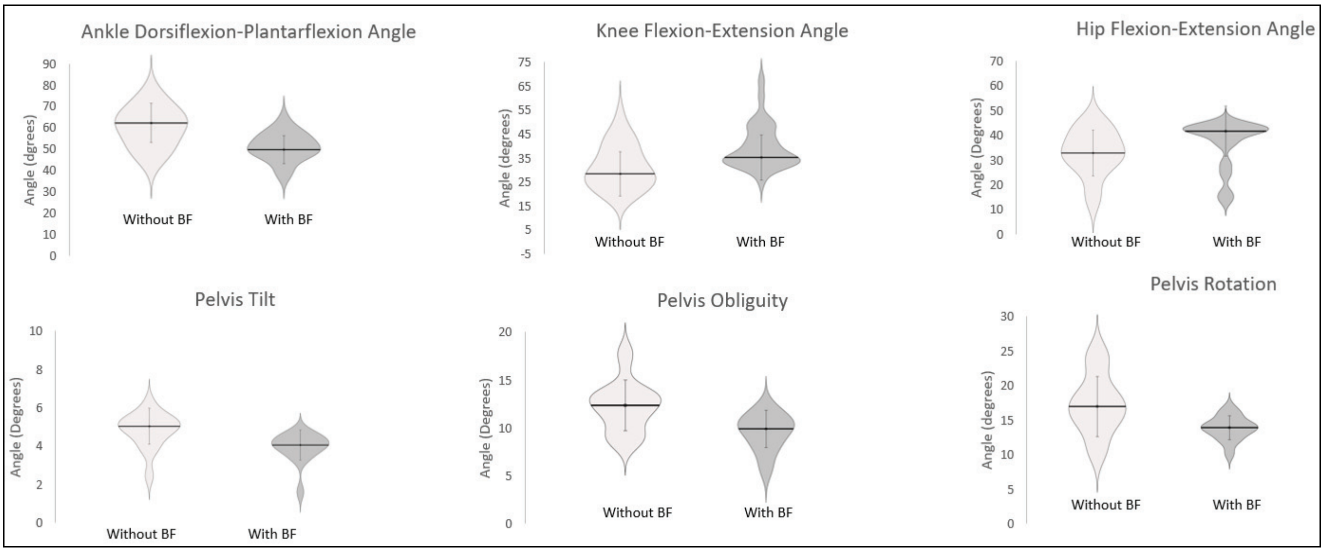

Fig. 6. Range of motion presented as violin plot for lower extremity kinematics of children with CP for "with" and "without" biofeedback conditions

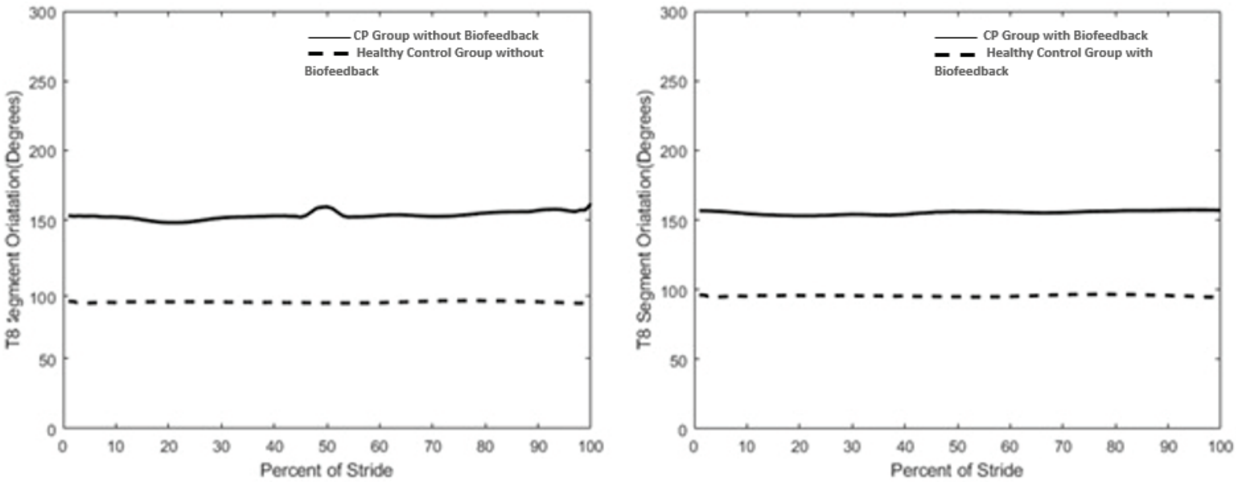

Fig. 7. Sternum IMU Orientation (T8 segment of the trunk) while participants (a) were not and (b) were guided with biofeedback

Table 4. Gait Parameters: Quantification of error of lower extremity joints

Gait Parameters: Quantification of error		
	Walking at Self-Selected Speed	
	Without biofeedback CP group – with biofeedback CP group	With biofeedback CP group – with biofeedback Control Group
Ankle Angle (Dorsiflexion-Plantarflexion)	R^2: 0.3948 RMSE: 16.99	R^2: 0.519 RMSE: 15.24
Knee Angle (Flexion-extension)	$R^2 = 0.5631$ RMSE: 18.41	$R^2 = 0.5025$ RMSE: 12.70
Hip Angle (Flexion-extension)	$R^2 = 0.7065$ RMSE: 36.01	$R^2 = 0.7082$ RMSE: 26.68
Pelvis Angle (Pelvic tilt)	$R^2 = 0.533$ RMSE: 17.44	$R^2 = 0.4964$ RMSE:14.25

in the sagittal plane during with and without biofeedback conditions. Balance control through tactile biofeedback guidance improved pelvic biomechanics and relatively higher symmetry was obtained with the control group. The pelvic obliquity of CP participants was significantly higher compared to the control group during both with and without biofeedback conditions. In the absence of biofeedback, CP group participants presented a middle peak during late stance. Pelvic tilt and pelvis rotation revealed similar outcomes in CP group participants during “with” and “without” biofeedback conditions. Hip flexion and extension angle revealed similar trajectories for children with CP for “with” and “without” biofeedback conditions and characterized with lower swing phase extension and longer stance phase, therefore increased double support percentage. The children with CP reached lower knee flexion during “with” and “without” biofeedback conditions (Table 4).

Analysis of ankle kinematics of CP participants showed that biofeedback reduced the excessive plantarflexion at initial contact observed during “without” biofeedback condition when participants were guided with tactile biofeedback. Similarly, tactile biofeedback helped CP group participants to improve their dorsiflexion during the stance and swing phases.

4. Discussion

Biofeedback is a method of providing real-time biological information to the patient by using auditory, visual and tactile stimuli. Additionally, physicians and physiotherapists can utilize biofeedback mechanisms to regulate the gait pattern, correct balance/posture and thus create personalized physical therapy and rehabilitation programs for the patients while regulating the physiological, kinetic and kinematic variables. The primary aim of this study was to develop a tactile biofeedback device, which tracks balance continuously and provides haptic biofeedback to its user through real-time vibration stimulus. The efficacy of this device was investigated on the balance and postural control of children with CP during ambulation.

Participants in the control group were able to maintain their postural control with or without biofeedback guidance and the sternum orientation did not alter when biofeedback was given. The gait pattern of children with CP, on the other hand, showed a peak at the late stance phase of the stride when biofeedback was not present. Balance control through tactile biofeedback guidance improved pelvic biomechanics and relatively higher symmetry was obtained with the control group. The pelvic obliquity of CP participants was significantly higher compared to the control group during both with and without biofeedback conditions. In the absence of biofeedback CP group participants presented a middle peak during late stance. Pelvic tilt and pelvis rotation revealed similar outcomes in CP group participants during “with” and “without” biofeedback conditions. Hip flexion and extension angle revealed similar trajectories for children with CP for “with” and “without” biofeedback conditions and characterized with lower swing phase extension and longer stance phase, therefore increased double support percentage. Analysis of ankle kinematics of CP participants showed that biofeedback reduced the excessive plantarflexion at initial contact observed during “without” biofeedback condition when participants were guided with tactile biofeedback. Similarly, tactile biofeedback helped CP group participants to improve their dorsiflexion during the stance and swing phases.

The findings of this study are in accordance with the literature [13] which states that physical activity adaptation can be supported continuously with biofeedback for maintaining postural control/balance and regulating gait. Recent studies converge that biofeedback is a tool useful for maintaining participation, motivation and global motor function domains of the participant [7], [13], [22]. For this purpose, tactile biofeedback has been integrated into physical therapy and rehabilitation programs of children and adult patients previously, hence, its effects on balance control and minimizing sway have been reported. The proposed device, which serves both aims, promoted physical activity adaptation of the patient and regulated gait through continuous and real-time balance control and reduced the region where the body swayed. Contrarily, tactile biofeedback did not change or disturb the balance control of the typically developed children.

The ability to maintain stability and balance is critical for neurological and orthopedic rehabilitation, as the goal is to achieve functional independence during ambulation. CP patients experience psychomotor problems and altered motor functions. The absence of gait symmetry, which is the ratio of kinetic and kinematic parameters between the right and left extremities, results in differences in muscle contraction, balance, and biomechanical parameters during mobilization. Accurate awareness of static and dynamic proprioception is essential to maintain balance and sustain safe ambulation. Postural control and balance, which require complex synchronization of muscles and ligaments, are essential for optimal mobilization. In this study, it has been shown that haptic biofeedback could be used as a tool to continuously guide the patient to facilitate balance and postural control during ambulation and the proposed wearable device could be integrated into the physical therapy and rehabilitation process of patients, who have balance and postural control impairments.

The main limitation of this study is the short adaptation period of the participants to the device and real-time tactile biofeedback guidance. Each participant was given the needed time to use the device and get familiar with the balance control mechanism through real-time tactile biofeedback. However, this procedure was not integrated into their conventional physical therapy routines for a certain amount of time to test the motor learning capabilities of the children with CP. Therefore, the effects of the device on long-term motor learning and motor adaptation abilities were not investigated. The trunk stability and sagittal spinal alignment have been investigated through the T8 segment orientation of the axial body. This parameter showed the changes in the center of mass pattern as the participants performed walking activity with and without biofeedback guidance. Further aims are (1) to investigate the long-term efficacy of the device on the motor learning and motor adaptation of the patients and (2) to develop a wireless and compact version of device, which provides more comfortable and practical balance control and biofeedback guidance.

5. Conclusions

This study hypothesized that real-time balance biofeedback would improve postural control and gait parameters of patients with neuromuscular diseases. The findings verified the hypothesis of the investigation. The novel balance control device did not disturb healthy gait and helped children with CP to regulate their lower extremity joints' ROM, the center of mass and spatial-temporal parameters during walking at a self-selected speed. Trunk stability and sagittal spinal alignment of children with CP have been regulated with real-time biofeedback. Physical activity adaptation, which is the optimal motor control response of the body to deliver performance, is a complicated process that involves various physiological systems, thus tactile biofeedback can optimize gait parameters during ambulation through sensory and proprioceptive guidance. The findings of this study indicated that physical activity adaptation can be supported continuously for maintaining postural control and balance to sustain optimal energy consumption and kinematic parameters.

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