

## БАЛАЛАРДЫҢ ЦЕРЕБРАЛЬДЫ САЛ АУРУЫНА АРНАЛҒАН РОБОТТЫ ОҢАЛТУ

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**Түйіндеме:** Церебральды сал ауруы (ЦСА) бар балалар жоғарғы және төменгі аяқ-қолдарының моторикасының айтарлықтай бұзылуына тап болады. Бұл олардың күнделікті әрекеттерді орындау қабілетін айтарлықтай шектейді. Роботты экзоскелеттер оңалтуды қолдаудың және осы популяциядағы қозғалыс функцияларын жақсартудың құралы ретінде пайда болды. Бұл жұмыста біз екі роботтық жүйені ұсынамыз, олардың бірі жүру параметрлерін жақсартуға, екіншісі ЦС бар балалардағы жалпы тепе-теңдікті жақсартуға арналған. Роботтың көмегімен жүру жаттығулары кеңістіктік-уақыттық жүру параметрлерін жақсартады, ал роботтық бұзылуларға негізделген жаттығулар жалпы тепе-теңдікті (статикалық, динамикалық және функционалды/ постуральды) және ЦС балаларындағы проприоцепцияны жақсартады деген болжам бар. Үздіксіз зерттеулеріміздің бір бөлігі ретінде біз жүгіру жолында кедергісіз табиғи жүруді қамтамасыз ететін дизайнға қол жеткізу үшін жаңа гибридік белсенді-пассивті механизмге GEAR (Gait Exoskeleton-Assisted Rehabilitation) роботын әзірледік. Біз сондай-ақ балалар ЦС-мен оқыту үшін Роботты Пертурбация Жүйесін (RPS) жасадық. Біз осы екі роботтық жүйені пайдалана отырып, алғашқы клиникалық сынақтарды ЦС бар балалармен жүргіздік және әсер ету мөлшері 20% - дан асатын нәтижелерді байқадық.

**Түйін сөздер:** церебральды сал ауруы, роботты оңалту, пертурбация жаттығулары, тепе-теңдікті бақылау, бұлшықеттерді белсендіру, салмақ орталығы.

## РОБОТИЗИРОВАННАЯ РЕАБИЛИТАЦИЯ ПРИ ДЕТСКОМ ЦЕРЕБРАЛЬНОМ ПАРАЛИЧЕ

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**Резюме:** Дети с церебральным параличом (ДЦП) сталкиваются со значительными нарушениями моторики как верхних, так и нижних конечностей, что серьезно ограничивает их способность выполнять повседневные действия. Роботизированные экзоскелеты стали многообещающим инструментом для поддержки реабилитации и улучшения двигательных функций у этой группы населения. В этой статье мы представляем две роботизированные системы, одна из которых предназначена для улучшения параметров походки, а другая - для улучшения общего равновесия у детей с ДЦП. Предполагается, что роботизированная тренировка походки улучшит пространственно-временные параметры походки, а роботизированная тренировка на основе возмущений улучшит общее равновесие (статическое, динамическое и функциональное/ постуральное) и проприоцепцию у детей с ДЦП. Благодаря нашим постоянным исследованиям мы разработали нового гибридного робота GEAR (Gait Exoskeleton-Assisted Rehabilitation), основанного на активно-пассивном механизме, конструкция которого близка к прозрачной и обеспечивает непринужденную естественную ходьбу по беговой дорожке. Мы также разработали роботизированную систему возмущения (RPS) для обучения детей с ДЦП. Мы провели первоначальные клинические испытания с использованием обеих

этих роботизированных систем у детей с ДЦП и получили значительные результаты, достигшие более 20% эффекта.

**Ключевые слова:** детский церебральный паралич, роботизированная реабилитация, тренировка движений, контроль равновесия, активация мышц, центр масс.

## ROBOT-ASSISTED REHABILITATION IN PEDIATRIC CEREBRAL PALSY

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**Abstract:** Children with cerebral palsy (CP) face significant motor impairments in both their upper and lower limbs, severely limiting their ability to perform daily activities. Robotic exoskeletons have emerged as a promising tool to support rehabilitation and enhance motor functions in this population. In this paper, we present two robotic systems, one for enhancing gait parameters and the other one for improving the overall balance in children with CP. It is hypothesized that the robot-assisted gait training will improve spatio-temporal gait parameters and robotic perturbation-based training will improve overall balance (static, dynamic, and functional/ stural) and proprioception in CP children. Through our continuing research, we have developed a new hybrid active-passive mechanism-based GEAR (Gait Exoskeleton-Assisted Rehabilitation) robot to achieve a close-to-transparent design to provide unconstrained natural walking on a treadmill. We have also developed a Robotic Perturbation System (RPS) to train Children with CP. We have carried out initial clinical trials using both these robotic systems with CP Children and have observed significant results with effect sizes of more than 20%.

**Keywords:** cerebral palsy, robotic rehabilitation, perturbation training, balance control, muscle activation, center of mass.

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### Introduction

Musculoskeletal & Neurological Disorders in children due to diseases of the nervous system, sense organ, and osteoarticular system are on the rise in Kazakhstan [1] and the rest of the world [2, 3]. Cerebral palsy and other neurological diseases adversely affect the use of muscles that control movement, coordination, and communication. Reported incidences of these diseases such as cerebral palsy (CP) in children aged 0–17 years are increasing in Kazakhstan, and this may be accredited to the rising awareness in the urban healthcare system. During the period 2006–2016, the reported CP case at the national level increased by 84.6% while the average increase in urban CP population over rural CP population during 2010–19 was also recorded as 84.5% [4]. These Children require therapeutic interventions to enhance their gait stability, postural balance, and social skills. However, due to inadequate infrastructure, only a small fraction (less than 25%) of these children have access to clinics for such services in Kazakhstan. [4, 5]. The common challenges in Kazakhstan and the rest of the world include the lack of therapists and the labor-intensive, time-consuming nature of therapeutic sessions. The rehabilitation process, therefore, requires technology-driven interventions to achieve clinical effectiveness, accessibility, capacity building, and long-term socio-economic benefits. It is hypothesized that the robot-assisted gait training will improve their spatio-temporal gait parameters and robotic perturbation-based training will improve their overall balance (static, dynamic, and functional/ postural) and proprioception. Cognitive function can be improved through the development of appropriate VR systems. Research efforts should also focus on improving social skills and communication. Researchers previously proposed a combined gait asymmetry metric (CGAM) by merging spatial, temporal, kinematic, and kinetic gait parameters and later comparing it with the clinical measures. [6]. Another indices proposed in the literature are, Gait Posture Index

(GPI) [7], Gait Abnormality Index (GAI) [8], Gillette Gait Index (GGI), Gait Deviation Index (GDI), Gait Profile Score (GPS), and Gait Quality Index (GQI) [9]. The Gait Profile Score can also be merged with the GDI and a GDI\* resulting from these covering almost all the aspects of gait. [10]. To evaluate balance in children with MMD, researchers widely use instrumental measures of center of mass (COM) & center of pressure (COP) and clinical tools such as Berg Balance Scale (BBS), Timed Up and Go test, and Paediatric Balance Scale (PBS) [11, 12].

Currently, motor functions in children with MMD are quantified using the Gross Motor Function Classification System (GMFCS) [13-15], Fine Motor Function Assessment (Box and Block Test, Nine-Hole Peg Test) [16-18], Functional Mobility Scale (FMS) [19], and 3D motion analysis [20, 21]. Cognitive abilities, on the other hand, are assessed using the Wechsler Intelligence Scale for Children (WISC) [22, 23], Cognitive and Neuropsychological Testing (e.g., NEPSY-II) [24], and Behavior Rating Inventory of Executive Function (BRIEF) [25]. However, there is no consensus on preferred assessment instruments, and they all have limitations in providing a comprehensive assessment of disabilities. [26-28]. There is an urgent need to devise new metrics combining clinical and instrumental (EMG, IMU, etc.) measures using AI for evidence-based evaluations of children with MMD. Such metrics will help in identifying patterns, biomarkers, or specific parameters indicating functional levels. To impart gait training to Children with MMD, exoskeleton-type robots [29, 30] can be used. However, to benefit from robots, patients must actively participate and not become dependent on the robots [31]. Patient participation can be increased by designing robots that provide a natural walking experience, in other words, robots should have haptic transparency [32-38] to avoid/minimize residual forces at interface points, potentially causing discomfort or long-term complications. However, achieving transparency poses challenges due to the complex kinematics of human joints [39]. The LOKOMAT represents the most prevalent commercially available gait rehabilitation robotic orthosis [40, 41]. Subsequently, many research prototypes such as LOPES & ALEX, etc. have been proposed [42-45] improving transparency through design [46] and control methods [47]. We, the investigators, have been conducting active research in gait rehabilitation and have previously developed a few prototypes [48-56]. Through our continuing research, we have developed a new hybrid active-passive mechanism-based GEAR (Gait Exoskeleton-Assisted Rehabilitation) robot (Figure 1) to achieve a close-to-transparent design to provide unconstrained natural walking on a treadmill. The GEAR robot, which has a body weight support system and the necessary sensors, is being used by children with cerebral palsy and has been found safe for use by children. It is planned to improve its design and the controller to impart gait training to Children with various MMDs.

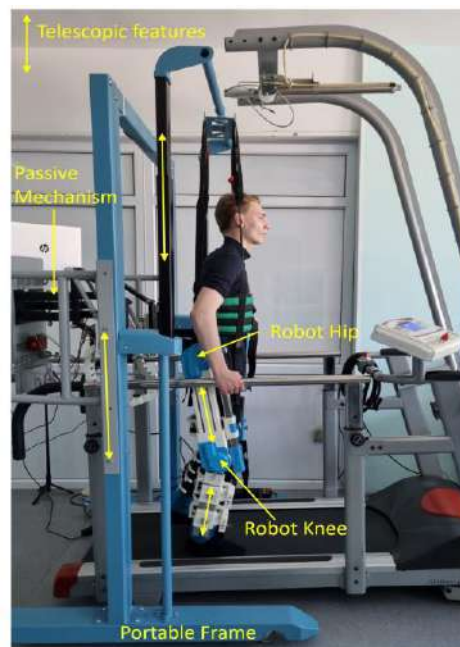


Figure 1: GEAR Robot for Gait Rehabilitation

Balance in Children with MMD can be improved through perturbation-based training which is mostly delivered using passive equipment in clinics. [57]. An active perturbation system has been developed for improving balance and cognition in the elderly. [58] We have also developed a Robotic Perturbation System (RPS) to train Children with MMD (Figure 2). We have carried out initial clinical trials with Children with CP and have observed significant results (with effect sizes of more than 20%) that have motivated us to conduct such trials on a large group of subjects to get more insight into the mechanism of balance improvement in these children and also improve the initial design of our Robotic Perturbation System (RPS) through this proposed program.

Virtual Reality (VR) assisted programs have been designed previously. [59] And found effective in the rehabilitation of children with MMD. It is possible, therefore, to improve cognitive skills in these children by designing a VR system using a device that provides mixed reality experience (a hybrid of VR, and augmented reality).

#### Materials and methods

We have developed a Proof-of-Concept prototype of the gait rehabilitation robot (GEAR) to be used for the gait training of the children with CP (Figure 1). In order to work with CP children, we made certain design and control-related improvements in the robotic system. The hybrid active-passive mechanism-based GEAR (Gait Exoskeleton Assisted Rehabilitation) robot is developed to achieve a close-to-transparent design

in this research. The GEAR robot is designed with fewer actuated joints to provide unconstrained natural walking on a treadmill. The thigh and shank segments of the robot are telescopic and can be customized for different subjects. The entire robotic mechanism is mounted on a height-adjustable movable frame. The RCM-based passive mechanism of the robot supports torso and pelvic rotations in transverse and frontal planes. The robot hip joint is designed to provide actuated sagittal plane motions besides passive frontal and transverse plane motions. A new knee joint on the GEAR robot that mimics the human knee joint anatomy is proposed in this research. It is shown that the robot knee joint remains aligned with the human knee during gait while following the ICR of the human knee closely. The new knee joint has the potential for personalization. The upper part of the robot knee joint can be designed to match the subjects' femoral condyle by extracting its shape from an X-ray or MRI scan. This part can be replaced with the robot knee while making other structural adjustments (e.g., robot thigh and shank length adjustments) for customization.

We have also created a Proof-of-Concept prototype for the Robotic Perturbation System (RPS), it is shown in Figure 2. The RPS utilized in this study employs a planar cable-driven parallel mechanism with four active cables connected to a central ring (end-effector) encircling the waist of the patient. The driven cables are affixed to four connection points on the end-effector (EE), enabling diagonal pull motions. The controller for this mechanism is integral to delivering precise and controlled perturbations during treadmill walking sessions, enhancing the rehabilitation process for children with cerebral palsy (CP). The controller interfaces with the mechanical components of the perturbation mechanism, comprising motors (AK80-64 actuators) driving the active cables in a torque control mode. It operates based on predefined algorithms crafted to generate random perturbations within specified parameters, tailored to each patient's unique needs. At the initial position, all four motors apply a specified torque to preload the cables, establishing the initial tension. The controller incorporates safety measures to prevent excessive perturbation forces that could jeopardize patient safety. Limits on cable tension, velocity, and acceleration are enforced to ensure that perturbations remain within safe thresholds throughout the intervention. Seamless integration of the controller with the treadmill system ensures synchronization of perturbation delivery with the patient's walking gait. This synchronization optimizes the timing of perturbations to coincide with specific phases of the gait cycle, maximizing the therapeutic benefits while minimizing disruption to the natural walking pattern.

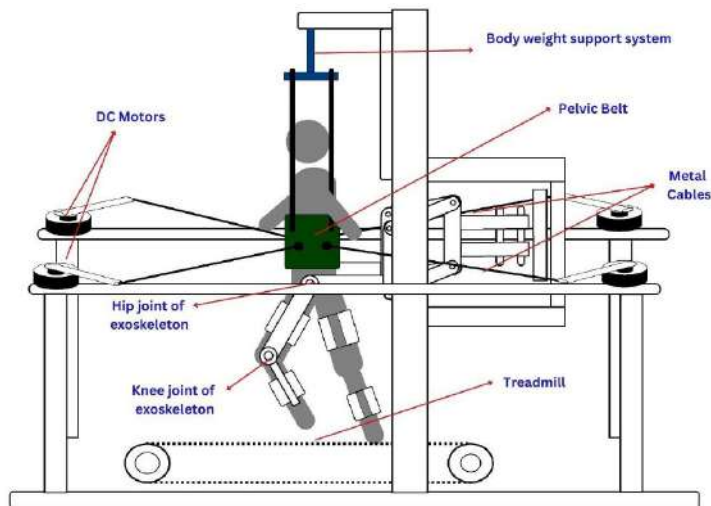


Figure 2: The proposed Robotic Perturbation System (RPS) together with the GEAR Robot

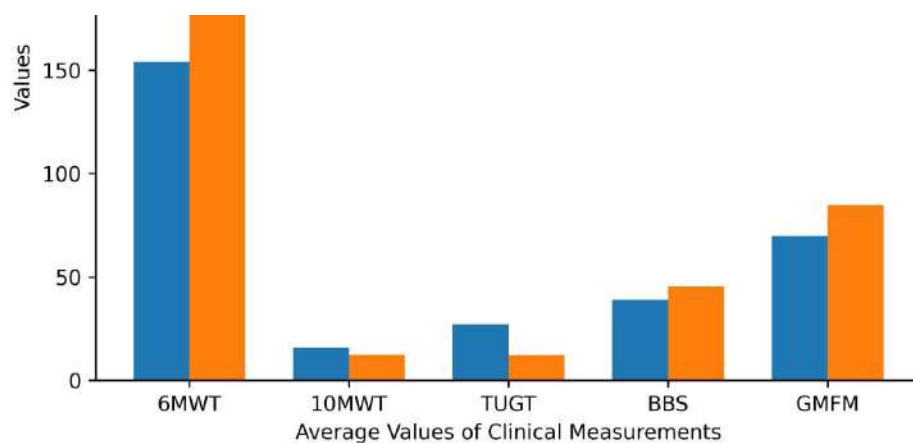


Figure 3: Overall improvement in the gait of the CP subjects as a results of four weeks of biweekly training on Robotic Perturbation System (RPS) together with the GEAR Robot.

A. Data Collection Tools

Informed Consent: After getting informed consent from the children’s parents and children. Subjects’ socio-demographic data will be collected.

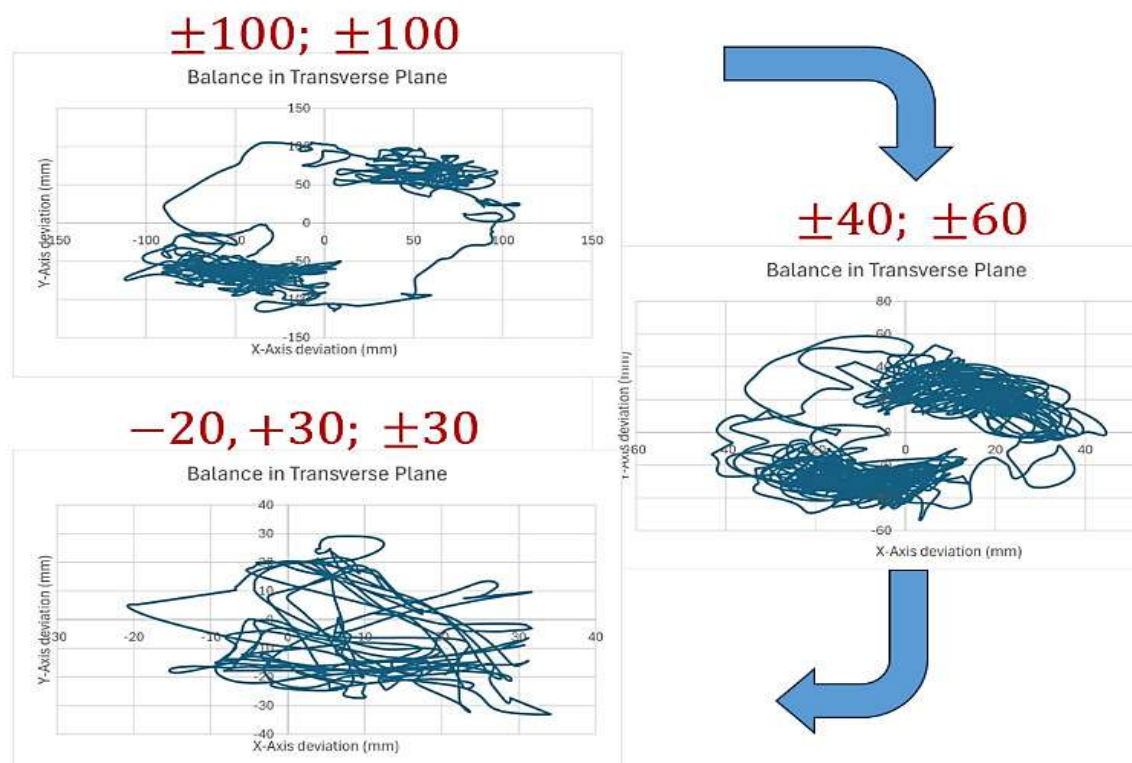


Figure 4: Overall improvement in the balance in subjects while standing is illustrated using the trajectories of their Center of Mass (CoM) as a results of four weeks of biweekly training on Robotic Pert

WHODAS assessment: Subjects' disability scores would be established using WHO disability assessment schedule 2.0 (WHODAS 2.0). This instrument provided insights into six domains: Cognition, Mobility, Self-care, Getting Along, Life activities, and Participation.

Fatigue Severity Scale: FSS is a self-reported questionnaire measuring the severity of fatigue and its impact on functioning in daily life. It provides quantitative information about the severity of fatigue and how it affects their quality of life.

Short Form-36 Health Survey: SF-36 assesses health-related quality of life across multiple domains. It covers various aspects of physical and mental health, including physical functioning, role limitations due to physical health problems, bodily pain, general health perception, vitality, social functioning, role limitations due to emotional problems, and mental health.

*Clinical Assessment:* Pre- and post-assessment of Children with Cerebral Palsy would include the following:

- 1) Anthropometric Measurements of the lower limb
- 2) 6-Minute Walking Test: To measure the level of endurance and exercise capacity over a long duration.
- 3) 10 Meter Walk test: To assess the mobility and functional ambulation for a short duration.
- 4) Gross Motor Function Measure: The GMFM is a standard and validated tool that measures gross motor functional changes over time in CP children. It has a 4-point scale divided into five dimensions, section A contains tasks related to "Lying (supine and prone) and Rolling" " Section B contains "Sitting" " Section C contains "Crawling and Kneeling" " Section D contains "Standing" and section E contains "Walking, Running and Jumping" related activities.
- 5) Berg Balance Scale (BBS): The Berg Balance Scale was used to assess the functional balance of children, which consists of both static and dynamic balance [47]. It consists of 14 items that correspond to activities of daily living children able to perform [48].

Before starting the experiment, each participant's guardian or parents were guided about the clothes and proper athletic shoes to easily access the assessment area and insert deep soles, respectively. Various sizes in the Whole number for deep soles are available, and the snug fit was ensured by the proper selection of size and lacing of footwear.

*Biomechanical Assessments:* Biomechanical Assessments of the subject are conducted through Noraxon Ultium Portable Lab. By utilizing the following sensors:

- 1) Electromyography: The multi-modal Ultium® EMG sensor system from Noraxon provides high-fidelity data and versatile measuring choices. Ultium EMG sensors have low baseline noise (1 V RMS) with little natural artifacts, sample up to 4,000 times per second, and synchronize in real-time. The electrodes will be placed on pelvis muscles, such as gluteal muscles.
- 2) 3-D Motion Capture System: From Noraxon, a 3D motion Capture System that used IMU to measure parameters such as anatomical joint angle, orientation angles, linear acceleration, and synchronizing with EMG.
- 3) Smart Insoles: Smart Insoles from Ultium Lab provided information regarding the static and dynamic loading asymmetry and spatiotemporal gait analysis parameters.
- 4) Intervention: Before starting the experiment, each participant's guardian or parents were guided about the clothes and proper athletic shoes to easily access the assessment area and insert deep soles, respectively.

Various sizes in the Whole number for deep soles are available, and the snug fit was ensured by the proper selection of size and lacing of footwear.

### **Discussion of the results**

Children with cerebral palsy exhibit poor functional balance and gait impairments that result from a lack of adequate muscle activation of pelvis muscles. The present study aims to find that delivery of a combination of robot-assisted gait therapy and perturbation training leads to the activation of pelvic muscles especially, the gluteal maximus and medius, as reported. [60] That perturbation training improves the gluteal medius activation as a result it leads to improved pelvic obliquity in stroke, however, no such research has been reported about pelvic muscle activation as a result of perturbation training in literature.

Nevertheless, our research experiments with CP children suggest improvements in their gait parameters and also in their overall balance as illustrated in Figures 3 & 4. The balance was measured as the hovering motion of the center of mass (CoM) of the CP children when they stood on the ground with their eyes closed. It was observed that after four weeks of biweekly training on the Robotic Perturbation System (RPS) together with the GEAR Robot, the balance in CP children was improved from  $\pm 100$  mm deviation to  $\pm 30$  mm Deviation.

There were improvements observed in 6MWT (Six Minute Walk Test), 10MWT (Ten Meter Walk Test), TUGT (Time Up and Go Test), BBS (Berg Balance Scale), and GMFM (Gross Motor Functional Measure) scores as illustrated in Figure 4. The current study shows that robot-assisted rehabilitation can significantly improve balance in multiple planes which contributes towards postural stability and gait parameters in children with cerebral palsy. The results of this study are consistent with previous studies [57, 58] and show that robot-assisted therapy enhances functional recovery by promoting repetitive, task-specific training. However, the improvements in muscle activation patterns were more pronounced in the previous trials [60], likely due to the integration of the feedback mechanisms. These improvements in the context of motor control are attributed to neuroplasticity facilitated by repetitive movement training, which aligns with motor learning theories that suggest that task-specific, robotic interventions can enhance cortical reorganization in children with CP. [61]. The results suggested that robot-assisted interventions could be particularly beneficial to children with moderate spasticity, offering alternative or adjunct to conventional physical therapy by delivering more precise, intensive, and consistent motor training. One limitation of the study was the small sample size, which limits the generalizability of the findings. Future direction with larger cohorts with multiple CP types is needed to analyze the obtained trends and provide stronger evidence for the efficacy of these interventions. Along with these further research should be conducted to observe the long-term impacts of such training as well as personalized approach should be taken into account due to various motor levels, functional status, and specific subtypes of CP.

### **Conclusion**

In conclusion, robot-assisted rehabilitation presents a promising avenue for improving motor functions and the overall quality of life of these children. As technology continues to improve and evolve over the period of time, its role in the case of pediatric rehabilitation is likely to expand, offering new opportunities for tailored, personalized, and efficient interventions.

### **Conflict of Interest**

The authors declare that there was no conflict of interest regarding the publication of this article.

### **Authors' Contribution**

Lead Author: Dr. Prashant K Jamwal contributed to study's conceptualization, design, and drafting of manuscript.

Co-authors: Amna Khawaja contributed towards data collection, signal processing and analysis of the data and contributed towards drafting and revision of manuscript.

Dilnoza Karibzhanova contributed to recruitment of study participants, conducted clinical assessment and revision of manuscript.

All authors provided intellectual inputs and approval of final manuscript for submission, ensuring integrity and accuracy in the study's finding and discussion

#### **Acknowledgement**

This work was funded by grant BR24992820 from the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

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