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Soft Actuators in Cerebral Palsy Psychomotor Rehabilitation: Literature Review and Innovations

Ilham Saputra [1*], Efrem Olivio Gomes [2], Adhan Efendi [3], Aulia Fajrin [4], Ulfi Sartika Lubis [5], Andika Widiyanto [6]

ABSTRACT

This study investigates the application of soft actuator technology in psychomotor rehabilitation for cerebral palsy (CP), focusing on actuator types, features, applications, challenges, and innovation opportunities. After reviewing 290 articles related to motor rehabilitation, 12 relevant studies specifically on soft actuators in CP rehabilitation were selected. The findings highlight three main types of soft actuators used in CP therapy: pneumatic actuators, Twisted and Coiled Polymer (TCP), and Dielectric Elastomer Actuators (DEA). Each type offers distinct benefits and presents technical challenges. Soft actuators demonstrate enhanced adaptability, supporting natural body movements in the rehabilitation of the hand, ankle, knee, and neck. Despite their promise, the technology faces challenges such as motion precision, response speed, high production costs, and material durability. Innovations, including the integration of artificial intelligence (AI), the development of more efficient materials, and ergonomic modular designs, present opportunities to address these issues and improve accessibility. With advancements in temperature control, compact design, and adaptive sensors, soft actuators are expected to become more effective, affordable, and widely available. This study concludes that soft actuator technology holds substantial long-term potential to offer an affordable, efficient, and customizable solution for CP rehabilitation, significantly improving patients' quality of life.

Keywords: soft actuators, soft robotics, psychomotor rehabilitation, cerebral palsy

1. INTRODUCTION

Psychomotor rehabilitation plays a crucial role in improving motor function and quality of life for patients with neurological disorders, particularly those with Cerebral Palsy (CP). Psychomotor refers to the intricate relationship between cognitive processes and physical movement, focusing on how the brain controls and coordinates body movements. In CP, a neurological disorder caused by damage or abnormalities in brain development during the prenatal period or early life, these processes are disrupted, leading to difficulties with movement control, balance, and motor coordination. [1]. While the initial search included conditions like stroke and Parkinson's, this review focuses specifically on CP due to its unique rehabilitation needs. CP requires early intervention and tailored therapeutic approaches to address specific motor patterns, such as spasticity and ataxia, which are distinct from those seen in stroke or Parkinson's rehabilitation. The rehabilitation process for cerebral palsy patients requires intensive and continuous therapeutic interventions that can stimulate improvements in gross and fine motor functions effectively and safely [2].

In recent decades, the development of rehabilitation technology, particularly soft actuator technology, has contributed significantly to increasing the effectiveness of psychomotor rehabilitation therapy [3], [4], [5]. Soft actuators use elastic and flexible materials such as silicone, thermoplastic polymers, and electroactive materials, which can mimic the natural movements of the human body adaptively and safely [6], [7], [8]. Unlike conventional actuators, which tend to be rigid, soft actuators are able to adapt to changes in body shape and various movement patterns of the patient, thus providing comfort and reducing the risk of injury during the rehabilitation process [9]. The application of soft actuators in cerebral palsy rehabilitation includes a variety of innovative devices such as soft exoskeletons, adaptive wearable devices, and soft prosthetics specifically designed to support and facilitate the patient's natural movements [10]. Recent research trends show a significant increase in the number of scientific publications exploring the use of soft actuators in the medical field, reflecting the high interest in the potential of this technology as seen in Fig. 1.

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[1*] Ph.D. Student (corresponding author), Department of Mechanical Engineering, National Yunlin University of Science and Technology, Taiwan Lecturer, Department of Mechanical Engineering, Vocational College, Universitas Gadjah Mada, Indonesia

[2] Ph.D. Student, Department of Mechanical Engineering, National Yunlin University of Science and Technology, Taiwan

[3] Ph.D. Student, Graduate of Precision Manufacturing, National Chin-Yi University of Technology, Taiwan Lecturer, Department of Mechanical Engineering Education, Universitas Negeri Surabaya, Indonesia

[4] Assistant Professor, Department of Mechanical Engineering, Politeknik Negeri Batam, Kepulauan Riau, Indonesia

[5] Student, Master of Economic Science Study Program, Faculty of Economics, State University of Malang, Malang, Indonesia

[6] Student, Faculty of Science and Technology, UIN SUSKA RIAU, Pekanbaru, Indonesia

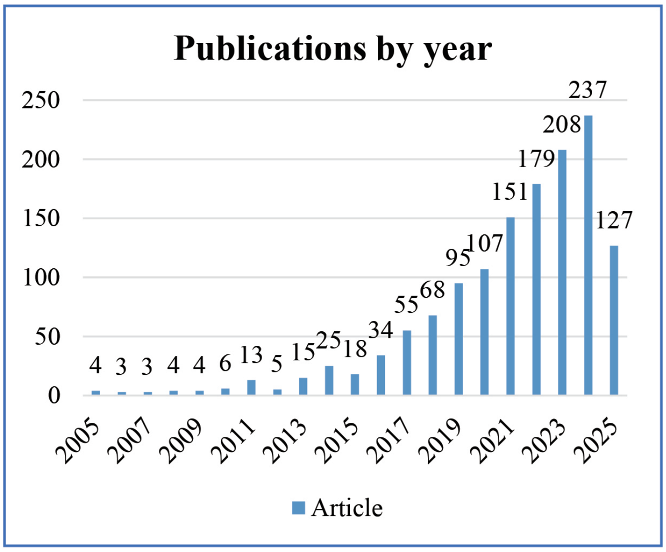

Fig. 1 Number of Articles Published Annually on Soft Actuators

Despite this technology's significant potential, the implementation of soft actuators in cerebral palsy rehabilitation still faces several challenges. Key challenges include the need for actuators with high movement precision, responsiveness to varying patient conditions, and ergonomic design for long-term use [11]. In addition to these technical challenges, high production costs and limited medical infrastructure in various regions also pose significant obstacles, particularly in developing countries [12], [13], [14]. Against this background, this article aims to conduct a systematic literature review on the application of soft actuators in cerebral palsy psychomotor rehabilitation and explore opportunities for innovation in the design, materials, and implementation of this technology. This review will specifically discuss the advantages, challenges, and potential innovations that can improve the effectiveness and accessibility of rehabilitation therapy for cerebral palsy patients. By providing a comprehensive overview of the current state of the art and future research directions, it is hoped that the results of this study will encourage further innovation in the development of soft actuator technology that is more affordable, efficient, and accessible to patients and healthcare facilities at all levels.

2. EXPERIMENTS

This literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. On July 20, 2025, a search was conducted in the Web of Science database using the following keywords: "ALL=("soft actuator" OR "soft robotics") AND (ALL=("rehabilitation" OR "therapy") AND ALL= psychomotor ("stroke" OR "Parkinson's disease" OR "cerebral palsy" OR "spinal cord injury" OR "multiple sclerosis")). The "ALL" tag allows for a keyword search across articles defined by the authors. The keyword selection reflects the eligibility criteria described below. This search yielded 290 articles.

a.Identifying Research Questions (RQ)

This literature review is guided by three primary research questions that focus on the technical aspects, applications, and challenges of soft actuator technology in psychomotor rehabilitation:

1. RQ1: What are the types and characteristics of soft actuators used in psychomotor rehabilitation, specifically for Cerebral Palsy?
2. RQ2: How are soft actuators implemented in Cerebral Palsy psychomotor rehabilitation systems, and what evaluation methods are used to measure their effectiveness?
3. RQ3: What are the challenges and opportunities for innovation in the development and implementation of soft actuator technology for Cerebral Palsy psychomotor rehabilitation?

These questions served as the basis for the search, selection, and analysis of data from the reviewed literature and served as a framework for structuring the results and discussion.

b.Inclusion and Exclusion Criteria

Inclusion Criteria:

1. Discusses the use of soft actuators/soft robots in the context of medical rehabilitation.
2. Focuses on psychomotor rehabilitation, specifically for patients with Cerebral Palsy or neurological conditions.
3. Presents primary data covering the design, integration, or implementation of soft actuators in rehabilitation devices.

Exclusion Criteria:

1. The article does not discuss the use of soft actuators or soft robots in the context of medical rehabilitation.
2. The article does not have a clear focus on psychomotor rehabilitation or motor therapy.
3. The article is a review study, meta-analysis, editorial, or does not present primary data from experiments.

These criteria were specifically designed to ensure that the review only includes relevant articles that directly contribute to the understanding of the application of soft actuator technology in psychomotor rehabilitation for Cerebral Palsy. [15] added that the PRISMA method is well-suited for analyzing review papers in the field of robotics. The PRISMA Process Flowchart for Article Selection is shown in Figure 2.

c.Search Strategy

The article search process for this literature review was conducted by identifying articles registered in the Web of Science database, resulting in a selection of 290 articles as initial data. During this initial identification stage, articles that did not meet the initial eligibility criteria were screened, including duplicates (n=3) and articles identified as corrections (n=2). This screening resulted in 285 articles for further processing. In the next screening stage, articles were assessed based on their titles and abstracts, applying predetermined inclusion and exclusion criteria. At this stage, 67 articles did not meet the criteria because they did not discuss soft actuators, were not related to psychomotor rehabilitation, lacked primary data, were review articles, book chapters, journal letters, or contained only abstracts. This left 218 articles for further processing.

In the next stage, the articles were further screened based on their specific relevance to the topic of cerebral palsy. Of these 218 articles, 202 were excluded because they did not specifically address psychomotor rehabilitation in patients with cerebral palsy. A total of 16 articles were deemed suitable for full analysis based on the relevance of their content. Next, a final evaluation of the remaining 16 articles was conducted by reading the full text to ensure that each article met all strict inclusion criteria. At this stage, 2 articles were identified as having only abstracts without complete data, and 2 articles were found to be review papers; therefore, they were excluded from the final analysis. The complete process is shown in Fig. 2.

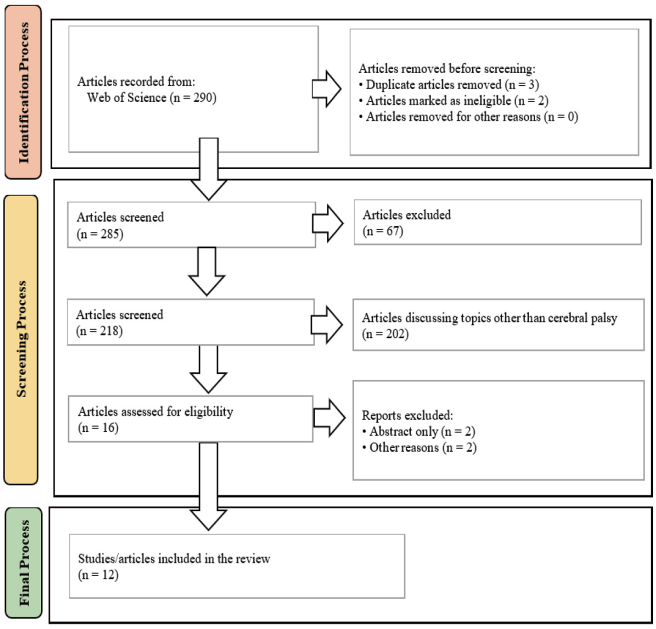

Fig. 2 PRISMA Process Flowchart for Article Selection

Table 1 Final articles reviewed (Author, year of publication, number of citations, and publishing journal)

No.	Author	Year of Publication	Citation	Journal	Ref
1.	Ozlem, K et al.	2025	0	Advanced Intelligent Systems	[16]
2.	Mares, Sarah et al	2025	1	MDPI In Technologies	[17]
3.	Hui, ZC et al.	2024	2	Brain Sciences	[18]
4.	McCall, JV et al	2024	1	Journal of Neuro engineering and Rehabilitation	[19]
5.	Gonzalez-Vazquez, A et al.	2024	3	Smart Materials and Structures	[20]
6.	Mohammadi, V et al.	2024	7	Sensors	[21]
7.	Greco, C et al.	2023	10	Robotics	[22]
8.	Kuroda, MM et al.	2022	3	Pediatric Reports	[23]
9.	Bützer, T et al.	2021	157	Soft Robotics	[24]
10.	Park, EJ et al.	2020	75	IEEE Transactions on Medical Robotics and Bionics	[25]
11.	Zhang, HH et al.	2019	15	IEEE Robotics and Automation Letters	[26]
12.	Jarrett, C & McDaid, AJ	2017	50	IEEE Transactions on Neural Systems and Rehabilitation Engineering	[27]

*Data from July 2025

Therefore, a total of 12 articles were included in this final literature review, all of which were relevant and met the established criteria, as shown in Table 1. While the sample size is relatively small, it was carefully selected to provide a focused and in-depth understanding of the role of soft actuators in psychomotor rehabilitation for patients with cerebral palsy. The studies cover a variety of actuator types, applications, and evaluation methods, ensuring a comprehensive analysis of the technology’s benefits and challenges. Although the limited sample size may limit the ability to generalize findings across all CP populations, the selected studies offer valuable insights into the effectiveness and potential of soft actuators. These insights provide a strong foundation for future research, which can expand upon these findings and explore the broader applicability of soft actuator technology in CP rehabilitation and other neurological conditions.

d.Data Extraction and Analysis Process

The data extraction stage in this review was conducted systematically using a pre-prepared extraction form. The extraction form included several key pieces of information from each article, including article identity (title, author, year of publication), actuator type, materials used, function, advantages, challenges, implementation method, evaluation results, and innovation opportunities, as well as significant findings relevant to the use of soft actuator technology in cerebral palsy rehabilitation. After the extraction process was completed, the obtained data were analyzed descriptively and thematically. Descriptive analysis was conducted to describe the general characteristics of the included articles, such as the distribution of publication years, research methods, types of actuators frequently used, and patient populations in the studies. Meanwhile, thematic analysis was conducted to identify key patterns or themes from the data related to the effectiveness, advantages, disadvantages, technical challenges, and innovation opportunities in the application of soft actuators for cerebral palsy rehabilitation. The results of this data analysis were then presented in narrative form, supported by tables or diagrams, thus facilitating readers to understand a comprehensive overview of the use of soft actuators in cerebral palsy psychomotor rehabilitation.

While this review focuses specifically on soft actuator applications in CP rehabilitation, it's important to note that many of the excluded articles primarily centered on stroke rehabilitation. These studies often explored the use of soft actuators in recovering motor function, balance, and mobility post-stroke, which share similarities with CP rehabilitation in terms of the need for motor recovery. However, stroke rehabilitation typically focuses on recovery after an acquired brain injury, whereas CP involves early-onset motor impairments that require different rehabilitation strategies, including early intervention and long-term management. This distinction underscores the unique rehabilitation needs of CP patients, which this review aims to address.

e.Related Review Articles

Two relevant review articles were found during our search. Rodríguez-Fernández et al. [28] provided a systematic review of wearable exoskeletons for gait rehabilitation in individuals with neuromuscular disorders. Their focus was on the state of the technology, clinical validation, and benefits of exoskeletons for gait recovery, but they emphasized challenges such as bulky devices and limited clinical effectiveness. In contrast, our review focused on soft actuators in psychomotor rehabilitation for cerebral palsy, encompassing broader rehabilitation goals beyond just walking. Meanwhile, Jing et al. [29] reviewed soft wearable rehabilitation robots driven by artificial muscles using smart materials. Their work addressed the biomechanical challenges and material limitations of wearable robots, with a focus on non-clinical applications. In contrast to their review, our study specifically examined soft actuators for psychomotor rehabilitation in cerebral palsy, highlighting innovations in material design and patient-centered approaches. These reviews provide important context, but differ in their focus on patient populations, rehabilitation goals, and technology specifics.

3. RESULTS AND DISCUSSION

This chapter analyzes 12 articles selected from the systematic literature review described in the previous chapter. The analysis focuses on several key dimensions: the type of soft actuator used, its application in psychomotor rehabilitation, the evaluation methods employed, and the innovations and challenges faced in developing this technology.

a.Types And Characteristics of Soft Actuators in Cerebral Palsy Psychomotor Rehabilitation (RQ1)

Soft actuators are a rapidly developing technology in medical rehabilitation due to their ability to mimic the mechanical behavior of human muscles in a safe, flexible, and adaptable manner to the patient's body shape. In the context of psychomotor rehabilitation for cerebral palsy (CP) patients, the use of soft actuators is crucial to support the recovery process of impaired motor function. Based on the analysis of 12 selected articles, it is known that there are various types of soft actuators used in CP rehabilitation. Each type of actuator has unique characteristics, both in terms of basic materials, working mechanisms, main functions, and technical challenges. Table 2 summarizes these types of actuators and their characteristics.

In the studies reviewed, differences in clinical outcomes were observed between the various actuator types, including pneumatic actuators, TCP, and DEA. Pneumatic actuators, for example, were primarily used in hand rehabilitation and showed promising results in improving finger extension and grip strength, though challenges remain in motion precision and response time. Twisted and Coiled Polymer (TCP) actuators, often employed in lower body rehabilitation, demonstrated strong performance in producing high torque but were limited by low operating frequency, affecting their ability to support dynamic movement tasks like gait training. Furthermore, Dielectric Elastomer Actuators (DEA), with their rapid response and high precision, proved particularly effective in ankle orthotic devices, where they could generate the necessary assistive force during walking. Despite these variations, the discussion in the review largely highlights the descriptive analysis of actuator types, with the need for further studies to directly compare clinical outcomes across different actuator technologies.

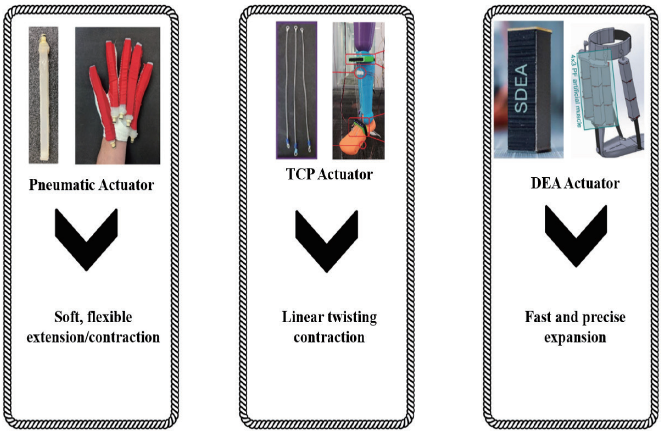

Fig. 3 Comparison of Three Types of Soft Actuators for Cerebral Palsy Rehabilitation [19], [20], [21]

Table 2 Types and Characteristics of Soft Actuators in Psychomotor Rehabilitation

No	Ref	Types of Actuators	Materials Used	Main Functions	Advantages	Challenges
1	[16]	Textile-Based IoT Gloves	Capacitive Sensor	Hand detection and manipulation	Adaptive, lightweight, connected to IoT	Movement accuracy is limited to hand movements
2	[17]	Pneumatic Actuator	Elastomer	Neck Rehabilitation	Safer, more responsive, and more flexible	Control accuracy

No	Ref	Types of Actuators	Materials Used	Main Functions	Advantages	Challenges
3	[18]	Soft Robotic Exoskeleton	RGB-D Camera, Force Sensor	Motor rehabilitation of the legs	Portable, lightweight, improves foot mobility	Requires long-term testing
4	[19]	Manual Pneumatic Actuator	Elastomer	Helping finger extension	Fast, responsive, suitable for smooth movements	Limitations in high frequencies
5	[20]	Twisted and Rolled Polymer Actuators	Spun Polymer	Helps ankle mobility	Lightweight, durable, high torque	Often affected by temperature and frequency
6	[21]	Elastomer Dielectric Orthosis	Elastomer Dielectric	Ankle movement assistance	Compact, lightweight, safe for natural movement	Temperature and durability limitations
7	[22]	Soft Exoskeleton with TCAM	Carbon Fiber, Force Sensor	Wrist rehabilitation	Flexible, adaptive, lightweight	Limitations in material durability
8	[23]	Limb Hybrid Assistive	Position Sensor, Force Sensor	Assisting movement after surgery	Adaptive, aids post-operative mobility	Limited duration of use
9	[24]	Soft Hand Exoskeleton	Electric Gripper, Force Sensor	Improving grip strength	Easy to use, comfortable, flexible	Prototype, still under development
10	[25]	Hinge-less Exosuit	Vision Sensor, Force Sensor	Assists knee extension when walking	Lightweight, effective in confined spaces	Further clinical trials are needed
11	[26]	Robotic Neck Support	Force/Pressure Sensor	Assists head and neck movement	Reducing head movement errors	No long-term impact
12	[27]	Cable-based exoskeleton	Force Sensor, Torque Sensor	Assisting arm movements	Improving arm mobility	Limited to patients with severe CP

From the 12 articles analyzed in this study, it was found that various types of soft actuators have been successfully implemented, with characteristics and functions that vary greatly depending on the body part targeted for rehabilitation. The most commonly used types of actuators are pneumatic actuators, twisted and coiled polymer (TCP), and dielectric elastomer actuators (DEA) as shown in Fig. 3. These three types offer their own functional advantages, while also facing different technical challenges. Pneumatic actuators are widely used in rehabilitation devices for the hand and fingers. Research by McCall et al. [19] showed that the use of a pneumatic actuator attached to the palmar side of the finger can propel the finger into extension more comfortably and safely compared to pulling through the dorsal side. The results indicate that this system is able to provide sufficient propulsive force to address mild to moderate spasticity. This technology was expanded by Ozlem et al. [16], who integrated a pneumatic actuator glove with cloud-based control and capacitive sensors, creating a telerehabilitation system that allows therapists to remotely control a patient's hand movements. The advantages of pneumatic actuators lie in their flexibility, light weight, and ability to adapt to body contours, but challenges remain in terms of limited precision, response time, and the need for a stable air pressure source.

The next type of actuator that is widely developed is twisted and coiled polymer (TCP). This technology is widely used in lower-body rehabilitation, especially the ankle and wrist. Gonzalez-Vazquez et al. [20] implemented TCP in a children's wearable device to improve ankle dorsiflexion movement, while Greco et al. [22] utilized a carbon fiber TCP to support wrist movement. TCP is known for its advantages in producing large torque in a small size, as well as low power consumption. However, its disadvantages include low operating frequency and temperature sensitivity, which can affect performance and comfort when worn for long periods.

A third important type of actuator is the dielectric elastomer actuator (DEA), which was used in the DE-AFO by Mohammadi et al. [21]. DEA works by the principle of contraction of an elastic polymer layer when subjected to high tension, producing movements resembling natural human muscles. DEA can contract quickly and with high precision, making it very suitable for ankle orthotic devices in children with CP. In this study, the device was able to generate up to 100% of the required assist force during the swing phase of walking. However, technical challenges that need to be overcome are the need for high tension and temperature management during use. To provide a clearer comparison of the key performance metrics of these actuators, Table 3 summarizes their pressure ranges, voltage requirements, efficiency, and response times. This comparative overview highlights the distinct advantages and challenges of pneumatic actuators, TCP, and DEA in CP rehabilitation.

Several other studies also highlight innovations in form and materials. Jarrett & McDaid [27] developed a cable-based exoskeleton system that utilizes torque control and the natural elasticity of the material to support elbow movement in CP patients. Although flexible, this system requires precise torque calibration to ensure user safety. Zhang et al. [26] introduced a soft neck brace based on pressure sensors and passive actuation to assist head-neck movement training in patients with postural disorders, while Park, EJ et al. [25] designed a hinge-less knee exosuit to assist extension during walking; this suit is designed to be lightweight and follows the user's movements without inhibiting natural movement. Meanwhile, systems such as neck rehabilitation using pneumatic actuators [17], make new discoveries to utilize actuators in neck rehabilitation, although they have not been directly tested in CP patients. Soft hand exoskeletons such as those developed by Bützer, T et al. [24] also demonstrated the ability to assist patients in grasping objects for daily activities, while the HAL system (Kuroda et al., [23]) combined soft actuators and sensors to detect movement intentions after tendon lengthening surgery in children with CP.

From these findings, it can be concluded that pneumatic actuators remain the primary choice due to their ease of integration and flexible nature. However, TCP and DEA are increasingly emerging as more precise and efficient solutions in certain applications. TCP excels in its power-to-size ratio, while DEA offers smoother and faster motion control. All of these actuator types have specific roles in assisting different body parts, such as the hand, ankle, knee, and neck. With the development of smart materials and new control techniques, it is hoped that soft actuator technology will become increasingly adaptable to the individual needs of CP patients, both for intensive rehabilitation in clinics and long-term use at home. These findings demonstrate the great potential of soft actuator technology in providing more humane, adaptive, and personalized therapeutic interventions for patients with psychomotor impairments due to cerebral palsy.

Table 3 Comparison of Soft Actuators for Cerebral Palsy Rehabilitation

Actuator Type	Pressure Range	Voltage Requirements	Efficiency	Response Time	Ref
Pneumatic Actuators	6.9 – 48.3 kpa	Low	40-60%	1000-1500 ms	[16], [19]
Twisted and Coiled Polymer (TCP)	N/A (Mechanical deformation)	Mid	~80%	200-600 ms	[20], [22]
Dielectric Elastomer Actuators (DEA)	Up to 1 MPa (10 bar)	High	70-90%	~500 ms	[21]

While soft actuators such as pneumatic actuators, TCP, and DEA have shown significant promise in CP rehabilitation, their comparison to conventional rigid exoskeletons raises important questions regarding clinical efficacy and long-term outcomes. Rigid exoskeletons generally provide more precise control over movement, making them beneficial for tasks that require high stability and high torque. These exoskeletons are often used for more intensive rehabilitation, such as gait training, but they can be bulky and less adaptable over time, potentially limiting long-term use in CP rehabilitation. However, both soft actuators and rigid exoskeletons show clinical efficacy, soft actuators have the advantage of comfort and adaptability, which may lead to better long-term outcomes in terms of sustained use and patient compliance. However, further research is needed to directly compare the long-term effects of both technologies, especially in terms of maintenance of motor function and quality of life over extended periods.

b.Application of Soft Actuators in Cerebral Palsy Psychomotor Rehabilitation System (RQ2)

The application of soft actuator technology in CP rehabilitation has been introduced in various forms, ranging from hand and ankle exoskeletons to simpler yet more effective wearable devices. Evaluation of the success of soft actuator therapy is generally conducted using methods that can measure gross and fine motor function, as well as balance and grip strength, as shown in Table 4.

A review of 12 relevant articles shows that soft actuator technology is capable of providing adaptive, flexible, and safe interventions for various motor needs of CP patients, both in clinical settings and in home therapy contexts. One of the most dominant forms of application is in the development of hand exoskeletons. McCall et al. [19] developed a pneumatic actuator-based hand exoskeleton system designed to propel fingers into extension, assisting CP patients with spasticity.

Table 4 Application of Soft Actuators in Psychomotor Rehabilitation Systems and Evaluation Methods

No	Ref	Application Method	Evaluations Used	Evaluation Results
1	[16]	Hand telerehabilitation with IoT gloves	Evaluation of system accuracy and transmission quality	Evaluation of system accuracy and transmission quality 48.4 ms
2	[17]	Passive mobilization of the cervical spine	Computational simulation	Effective in creating movement at physiological limits
3	[18]	Soft exoskeleton for walking training	10MWT, 6MWT, GMFM-88	Significant improvement in walking speed (+6.78 m/min), distance covered (+34.42 m)
4	[19]	Pneumatic actuator on the hand	Evaluation of finger extension strength	Significant improvement in finger extension movement with optimal strength
5	[20]	Ankle rehabilitation system	Torque, range of motion	Achieves 1.4 Nm of torque and a 10-degree range of motion
6	[21]	Foot orthosis with artificial muscles	Evaluation of strength and comfort	Provides sufficient torque to assist ankle movement
7	[22]	Wrist exoskeleton	Mechanical testing and EMG	Improving mobility and providing support during wrist exercises
8	[23]	Hybrid Assistive Limb for walking training	GMFM, Canadian Occupational Performance Measure	5.93% increase in GMFM, increased satisfaction and performance
9	[24]	Hand exoskeleton for daily activities	Functionality test of grip	Enables up to 80% improvement in grip strength
10	[25]	Exosuit for knee extension assistance	Biomechanical analysis	Reduces average knee biological force by up to 23.2% when walking uphill
11	[26]	Neck brace for neck movement training	Measurement of movement errors	Significantly reduces rotational movement errors

No	Ref	Application Method	Evaluations Used	Evaluation Results
12	[27]	Cable-based exoskeleton	Human-robot interaction test	Demonstrates good performance in performing daily activities

Evaluation was conducted by measuring finger extension strength and movement frequency, which showed significant improvements in the patient's grip function and finger flexibility after use of the system. A similar approach was used by Bützer, T et al. [24] with a soft exoskeleton system called RELab tenoexo, which allows users to perform up to 80% of daily gripping activities, verified through user functional testing. Meanwhile, Jarrett & McDaid [27] tested a cable-based soft exoskeleton with adaptive torque control for the arm, and in a case study on CP patients, this device demonstrated positive performance in supporting light motor activities.

In lower extremity rehabilitation, Hui et al. [18] used a soft exoskeleton equipped with force sensors for gait training in children with spastic CP. The device was evaluated using two key clinical measures: the 10 Meter Walk Test (10MWT) and the 6 Minute Walk Test (6MWT). The results showed significant improvements in walking speed (+6.78 m/min) and walking distance (+34.42 m), demonstrating the effectiveness of using soft actuators in improving patients' functional capacity. These functional improvements in walking speed and walking distance are highly significant for CP patients, as they directly influence daily activities. For CP patients, walking speed is a crucial measure of independence and mobility.

Even modest improvements in walking speed can lead to greater autonomy, reducing dependence on caregivers and enabling participation in everyday activities such as walking to school, shopping, or engaging in social activities. This can have profound psychosocial benefits, boosting self-esteem and social integration. In addition to the physical benefits, increased walking speed can also prevent the secondary complications of CP, such as musculoskeletal deformities and contractures, by encouraging more natural and frequent movement. As CP patients improve their walking speed, they experience enhanced overall mobility, better coordination, and increased comfort during daily tasks. This can result in a higher quality of life, reduced social isolation, and improved mental well-being, making rehabilitation technologies like soft actuators highly relevant for long-term therapeutic interventions.

Another study by Kuroda, MM et al. [23] added the context of using the Hybrid Assistive Limb (HAL) after tendon lengthening surgery. Evaluations using the GMFM and the Canadian Occupational Performance Measure showed improvements in performance and patient satisfaction with their mobility abilities. TCP technology also made an important contribution. Gonzalez-Vazquez et al. [20] developed a twisted and coiled polymer (TCP)-based pediatric ankle rehabilitation system that produced a torque of 1.4 Nm and a range of motion of 10 degrees. Its effectiveness was demonstrated through torque and biomechanical measurements, which showed improved ankle control. Similar findings were found in the study of Greco et al. [22], who used TCAM for EMG-assisted wrist rehabilitation, showing positive results in supporting wrist flexion and deviation movements.

Mohammadi et al. [21] designed the DE-AFO, an ankle-foot orthosis with dielectric elastomer actuators (DEA) technology. Theoretical and experimental evaluations showed that this system can provide up to 100% of the force required for the swing phase of the gait cycle, with higher comfort compared to conventional orthoses. Meanwhile, Park et al. [25] used a flexible exosuit without hinges to support knee extension during walking. Biomechanical results showed a decrease in knee biological forces by up to 23.2% during uphill walking, indicating that this soft system effectively supports the user's muscle work.

Not only that, sensor-based technology and AI are also being introduced for the early detection of motor development delays. Sarah et al [17] developed rehabilitation equipment for neck joints by utilizing actuators from Festo. In the future, by using machine learning models, this system is able to detect interaction patterns such as touch and grip with high accuracy. Zhang et al. [26] developed a soft robotic neck brace that assists in head-neck movement training for patients with CP. Evaluation showed a significant reduction in head rotation errors during training, demonstrating the potential of this system in improving posture and head control. Meanwhile, an internet-based approach was carried out by Ozlem et al. [16] through an IoT-based pneumatic glove. This system enables remote telerehabilitation with a response time of only 48.4 ms. Evaluation of movement accuracy and data transmission quality showed excellent results, enabling the use of this system outside the clinic.

In general, the evaluation methods used in these studies varied significantly depending on the body part being rehabilitated and the therapy's goals. Measures such as the 10MWT and 6MWT were used to evaluate gait ability, GMFM and COPM for general motor performance, and biomechanics and EMG for specific movements. These results consistently demonstrated significant functional improvements following intervention with soft actuators.

Fig 4 Diagram of the human body showing the areas assisted using various soft actuators as per the reference article.

Thus, it can be concluded that the application of soft actuators in the psychomotor rehabilitation of CP patients has demonstrated high effectiveness across various movement domains. Various exoskeleton and wearable systems based on soft actuators are not only able to improve muscle strength and flexibility, but also provide better comfort and freedom of movement compared to conventional technologies. Evaluations conducted through clinical and mechanical methods reinforce the findings that this technology has great potential for integration into long-term rehabilitation programs and personalized therapy for CP patients. Figure 4 can complement the visual understanding of the distribution of soft actuators based on the targeted body areas, such as the hand (pneumatic), neck, ankle (TCP and DEA), and knee and hip (HAL).

c. Challenges and Opportunities for Innovation in the Development and Implementation of Soft Actuators for Cerebral Palsy Psychomotor Rehabilitation (RQ3)

Although soft actuator technology provides many therapeutic benefits in CP rehabilitation, several challenges and innovation opportunities need to be considered to improve the efficiency and accessibility of these devices, as seen in Table 5. The main challenges faced in the development of soft actuators are movement precision, high cost, and difficulty in adaptation in patients with more severe motor impairments. Although this technology has many advantages, several major challenges still need to be overcome to improve the effectiveness and accessibility of these devices. The first challenge is motion precision. Actuators such as pneumatic actuators, although effective in providing flexible motion, still struggle in providing motion precision, especially in fine motor tasks such as grasping small objects. McCall et al. [19] revealed that although pneumatic actuator systems can provide responsive motion, precise control in more complex motions remains a major challenge.

Furthermore, response speed is also a barrier [30], especially in TCP-based devices, which are widely used in ankle rehabilitation. Gonzalez-Vazquez et al. [20] explained that although TCP is effective for the high torques required in ankle movements, the low operating frequency limits the device's ability to respond to dynamic movements. This is crucial in therapies that require high response speeds such as walking and rapid mobility training. Developing technologies that can overcome the response speed issue is one of the major innovation opportunities in improving soft actuator technology for CP rehabilitation.

In addition to these technical challenges, high production costs are also a major obstacle. Soft actuator technologies often use advanced materials that require complex manufacturing processes, leading to high costs and reducing accessibility for patients, especially in developing countries. Gonzalez-Vazquez et al. [20] noted that although TCP technology has proven effective, the high cost and complexity of the manufacturing process make these devices inaccessible to many patients. Therefore, innovation in more affordable and efficient materials presents a significant opportunity to increase the accessibility of this technology.

Another challenge is related to temperature control in DEAs (Dielectric Elastomer Actuators) used in ankle-foot orthoses. Mohammadi et al. [21] noted that although DEAs provide fast and precise movements, issues with temperature control and long-term material durability can reduce device reliability.

Table 5 Application of Soft Actuators in Psychomotor Rehabilitation Systems and Evaluation Methods

No	Ref	Challenges	Opportunities for Innovation
1	[16]	Limitations in movement precision	Smart sensor integration for higher accuracy
2	[17]	Limited response and movement precision	AI integration for automatic adjustment and smart sensors for real-time movement
3	[18]	Limitations of long-term testing	Use of AI for training optimization
4	[19]	High frequency limitations	Development of more responsive actuators
5	[20]	Limitations on operating frequency	Use of new materials that are lighter and stronger
6	[21]	Temperature and durability limitations	Material innovations for longer durability
7	[22]	Material durability challenges	Use of bio-inspired materials for improved durability
8	[23]	Limitations on long-term use	Development of a more compact and ergonomic design
9	[24]	Challenges in modularity	Automatic adjustment for user comfort
10	[25]	Limitations on further clinical trials	Development of a hingeless exosuit for high comfort
11	[26]	Limitations in testing CP patients	Use of sensor systems for automatic adaptation
12	[27]	Limitations for users with severe CP	More flexible and adaptive joint design

Addressing these issues by developing more durable materials and improving temperature control is an innovation opportunity that can improve device sustainability.

Given these challenges, the greatest opportunity lies in integrating artificial intelligence (AI) and smart sensors. AI can be used to automatically adjust devices based on a patient's previous movements, allowing the device to learn and adapt to the patient's specific needs, increasing the device's precision and responsiveness (Ozlem et al., [16]). The use of new, more efficient materials and the development of modular designs can also reduce production costs, making devices more affordable and accessible to a wider range of patients. These innovations will enable soft actuator technology to become more affordable, responsive, and effective in CP rehabilitation.

4. CHALLENGES, OPPORTUNITIES, AND FUTURE DIRECTIONS OF SOFT ACTUATOR TECHNOLOGY IN PSYCHOMOTORIC REHABILITATION OF CEREBRAL PALSY

In this part, we will discuss the challenges faced in the use of soft actuators for psychomotor rehabilitation in patients with cerebral palsy (CP), as well as opportunities for innovation and future development of this technology. Although soft actuator technology has shown promising results in rehabilitation, several shortcomings remain that need to be addressed to maximize its benefits. On the other hand, advances in materials, artificial intelligence (AI), and modular design offer significant opportunities to improve the effectiveness, efficiency, and accessibility of soft actuator devices in the future. One of the primary challenges facing soft actuator technology is achieving precise movement. While actuators such as pneumatic and twisted and coiled polymer (TCP) offer exceptional flexibility, they often struggle to provide highly precise movement control, particularly for fine motor tasks like grasping small objects. This issue is particularly pronounced in hand and finger rehabilitation applications, where precision is crucial. Response speed is also a significant constraint, particularly with TCP-type actuators, which have a low operating frequency. This limits the device's ability to support therapies that require dynamic and rapid movement, such as gait training. Slow response speed can reduce the effectiveness of therapy in patients requiring rapid movement improvement, particularly in larger body parts like the feet and knees.

In the process of review, no significant adverse effects or risks were identified with the use of soft actuators in CP rehabilitation. However, potential risks include over-assistance leading to muscle fatigue or joint strain, especially in patients with spasticity. Additionally, temperature regulation in DEA actuators and material degradation over time are concerns. Long-term clinical trials are necessary to fully assess these risks and ensure the safety of soft actuators for patients with CP.

Furthermore, high production costs are another barrier. Soft actuator technology often involves advanced materials that necessitate complex manufacturing processes, leading to high production costs. This makes soft actuator devices unaffordable for patients in developing countries or those with limited financial resources. Limitations in temperature control and material durability are also concerns, particularly for dielectric elastomer actuators (DEA). DEAs require high voltages to function properly, but suboptimal material durability and temperature control can impact device reliability over long-term use.

Despite these challenges, there are various innovation opportunities that can address these issues. One of the biggest opportunities is the integration of artificial intelligence (AI) for dynamic device adjustment. By incorporating AI, soft actuator devices can learn from patient interactions and automatically adapt to the patient's movements and therapeutic needs. This will not only improve the device's precision and responsiveness but also enable it to deliver more personalized and efficient therapy, reducing the need for manual intervention from therapists. Thus, AI can serve to optimize rehabilitation outcomes by providing immediate, customizable feedback based on the patient's progress. For real-time assistance, the device can implement adaptive impedance control and model predictive control (MPC), which adjust the force/torque of actuators based on information from the IMU, EMG, and force sensors at each movement step. These algorithms estimate the patient's status (gait phase, spasticity level, fatigue) every 10-50 ms, and update the set-point accordingly to ensure safety while optimizing assistance. For hand tasks, an assist-as-needed scheme maintains the motion actively (without over-assisting) by reducing assistance as performance improves.

Another opportunity that could support the development of soft actuator technology is the development of more efficient and affordable materials. Innovations in materials could lower the production costs of devices, thereby increasing their accessibility to more patients. The use of lighter, stronger, and more durable materials would reduce maintenance costs and improve patient comfort, thereby increasing the effectiveness of therapy. Furthermore, modular designs that allow devices to be tailored to different body parts and levels of motor limitations are also a promising area. With a modular design, devices can be used for rehabilitation of various body parts, from the hands to the lower extremities, and tailored to the patient's specific needs. Personalizing therapy through this modular design would improve the quality of rehabilitation, ensuring that each patient receives the therapy most appropriate for their condition.

Advances in monitoring technology also hold significant potential for improving rehabilitation. The use of smart sensors and the Internet of Things (IoT) enables remote monitoring during therapy. With these systems, soft actuator devices can transmit real-time data to therapists, enabling faster and more precise therapy adjustments. Remote monitoring systems also provide greater flexibility for patients, who can continue their therapy outside the clinic without losing necessary supervision. This is particularly useful for patients requiring long-term rehabilitation and allows for more flexible and sustainable therapy delivery. For low latency, AI inference runs on edge devices (microcontrollers/SoC on the actuator device), while cloud synchronization is used for longitudinal analytics and tele-rehabilitation. Target latency is <100 ms from sensor input to control decision, ensuring actuator output feels natural. The therapist dashboard displays key metrics (walking speed, step symmetry, ROM, and assistance level) and allows remote adjustments of protocol parameters. Data security is ensured with end-to-end encryption and patient data anonymization.

Furthermore, developing more efficient and adaptive devices for patients with severe CP is an important step in broadening the benefits of this technology. Many current devices are more effective for patients with mild to moderate CP, but they do not provide sufficient support for patients with severe CP, who may have more severe motor limitations. More flexible designs that adapt to limited muscle strength will allow patients with more severe conditions to benefit from soft actuator therapy. With devices that can be adjusted to provide more power and support, therapy for patients with severe CP could become more effective and lead to significant improvements in quality of life. A reinforcement learning model with constraints or learning from demonstration can personalize the assistance profile for each patient (age, GMFCS level) without violating safety boundaries. A safety supervisor based on rule-based or observer models enforces ROM, speed, and actuator current/voltage limits; if anomalies (e.g., fall pattern, sudden spasm) are detected, the system switches to a fail-safe mode (releases assistance, locks to a safe position, and notifies the therapist).

The future direction of soft actuator technology will depend heavily on the integration of these innovations. The application of artificial intelligence, the development of new materials, and modular designs will bring this technology to a more efficient and accessible level. These developments will not only enhance the effectiveness of therapy but also make these devices more accessible to a wider range of patients worldwide, particularly in developing countries. With more innovations addressing current shortcomings, soft actuator technology has great potential to become a key solution in psychomotor rehabilitation for cerebral palsy. Overall, while there are still some challenges to overcome, the future of soft actuator technology in CP rehabilitation is very promising. With advances in artificial intelligence, materials, and more adaptive designs, these devices will become increasingly effective, affordable, and adaptable, meeting specific patient needs. Hopefully, this technology will continue to evolve into better, more efficient, and more accessible solutions for CP patients worldwide.

5. CONCLUSION

Soft actuator technology has demonstrated significant potential in enhancing psychomotor rehabilitation for patients with cerebral palsy (CP). An analysis of 12 relevant articles concluded that soft actuators offer a more adaptive, flexible, and natural-motion-focused solution compared to conventional exoskeleton technology. Various types of soft actuators, such as pneumatic actuators, TCP actuators, and DEA actuators, have been applied to the rehabilitation of different body parts, from the hand and ankle to the knee and neck. Each type of actuator has its own advantages and technical challenges that need to be overcome to improve effectiveness and accessibility. However, several key challenges, such as movement precision, response speed, high production costs, and material durability, still hinder the full potential of this technology. Therefore, innovations in new, more efficient materials, the integration of artificial intelligence (AI) for automatic adjustment, and more compact and ergonomic designs are crucial for the future. These innovations can improve the precision, responsiveness, and accessibility of devices, making them more affordable and widely accessible to patients with motor disorders such as CP. Overall, despite the technical and economic challenges, the potential for innovation in soft actuator technology offers a long-term solution that is more widely accessible, has a significant positive impact on psychomotor rehabilitation for patients with cerebral palsy, and is expected to improve the quality of life for patients in the future.

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