



Robotic Shoulder Rehabilitation After Stroke: Development and Validation of a Hybrid Cable-Driven Exoskeleton System

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Abstract

Every year, stroke-induced upper limb impairment impacts millions of people worldwide, necessitating intensive rehabilitation to regain motor control. While conventional physical therapy and end-effector-based robots have been utilized, they often face limitations such as high labor costs, therapist fatigue, and an inability to control the redundancy of the human arm, which can lead to nonphysiologic compensatory movements. To address these challenges, this paper presents the development of the hybrid shoulder rehabilitation exoskeleton, an advanced iteration of the previous HYBRID-1 prototype. The hybrid shoulder exoskeleton introduces two major design modifications based on performance evaluations and cable tension issues identified in the initial version. First, the shoulder girdle mechanism was redesigned by replacing the inverted slider-crank linkage with a planar crank-rocker four-bar linkage consisting of four revolute joints to better align with human anatomy. Second, a novel pretension mechanism was integrated into the Cable-Driven Parallel Mechanism to prevent cable derailment and maintain consistent tension using a system of rods, rollers, and compression springs. The design was first validated through a 3D-printed miniature model and CAD simulations, which confirmed the accuracy of the forward and inverse kinematic models. Subsequently, a real-scale prototype was manufactured featuring an adjustable shoulder cuff and additional base support to enhance structural stability for clinical applications. Initial assembly and preliminary testing indicate that these modifications provide a robust platform for intensive, task-specific rehabilitation. Future work will focus on performance testing with healthy subjects to evaluate the system's adaptability to various body parameters such as height and arm diameter.

Keywords: Stroke Rehabilitation, Shoulder Exoskeleton, Shoulder Girdle Mechanism, Passive Pretension Mechanism, Crank-Rocker Four-Bar Linkage.

1. Introduction

Every year, strokes cause significant disabilities for millions of people worldwide, often impairing upper limb function and severely impacting quality of life [1]. Weakness and loss of motor control in the upper limbs are common consequences of stroke, affecting a substantial portion of survivors [2]. Rehabilitation for stroke patients typically requires specific training with a dedicated physical therapist to regain functional mobility. However, conventional physical therapies are often exhausting, laborious, and expensive. The quality of manually assisted training heavily depends on the therapist's experience and judgment, which can vary widely and sometimes be ineffective [3]. Additionally, training sessions are often short due to therapist fatigue and a lack of standardized methods for recording patient progress and recovery. Moreover, it is estimated that the incidence of strokes will increase from 3.29 million in 2019 to nearly 4.90 million in 2030—a 49 % rise [4].

These statistics, coupled with a global shortage of medical personnel, underscore the urgent need for innovative rehabilitation methods. The growing demand for rehabilitation services, coupled with a shortage of qualified therapists, led researchers and engineers to develop end-effector-based rehabilitation robots as an initial solution [5–8]. Although these devices have been developed and used for more than 2 decades, scientists continue to refine and create new end-effector-based technologies to better meet evolving rehabilitation needs [9]. Such devices can be beneficial in supporting activities of daily living (ADL) training. While end-effector-based devices can facilitate the hand's 6-DOF movements and are beneficial for ADL execution, their primary limitation is the inability to control the redundancy of the human arm. This can often lead to nonphysiologic synergies and compensatory movements in both, severely and mildly affected patients. Nonphysiologic synergies can be often accepted in severely affected patients, however, they can be highly undesired in mildly affected patients. Furthermore, severely affected patients require full support on all joints for passive limb mobilization, but end-effector devices transmit all assistance through the hand, potentially

overloading intermediate joints and causing irritations.

Exoskeleton-based devices, in contrast, can provide full control over each joint, thereby enabling a more physiologic training experience [10]. Since the human upper limb has nine relevant degrees of freedom—encompassing shoulder, elbow, forearm, and wrist motions—exoskeletons that support all DOF can better accommodate both severely and mildly affected individuals [11]. This comprehensive control helps reduce detrimental compensatory strategies while also facilitating more natural ADL performance, highlighting the need for exoskeleton architectures in advanced rehabilitation systems.

Robotic exoskeletons, designed to align with human anatomical joints, offer a promising solution to these challenges [12–14]. These devices provide intensive, repetitive, and task-specific exercises, potentially increasing the effectiveness of rehabilitation [15,16]. The shoulder, being one of the most biomechanically complex joints in the human body, requires special considerations in exoskeleton design [17]. Existing shoulder robots often focus on the three rotational degrees of freedom (DOF) in the glenohumeral joint (GH), the main shoulder joint (see Fig. 1). However, the integrated motion between the GH joint and the shoulder girdle leads to translations of the GH joint's center of rotation, which many robots fail to accommodate, causing misalignments and discomfort during training sessions [18].

The remainder of this paper is organized as follows: Section II details the design and development of the shoulder rehabilitation exoskeleton, focusing on the mechanical transition from the HYBRID-1 to the hybrid shoulder exoskeleton iteration. Section III presents the experimental results obtained from the 3D-printed miniature model and the current assembly status of the real-scale prototype. Finally, Section IV provides a discussion of the system's performance, and Section V concludes the paper with an overview of future research directions.

2. Design and development of shoulder rehabilitation exoskeleton

A. First Iteration of the Exoskeleton

The design of the shoulder exoskeleton builds upon the author's previous exoskeleton developments [19,20], which were originally inspired by the CAREX exoskeleton [14]. As in the previous iteration, the exoskeleton consists of three main components: the base support, which is fixed to the ground; the shoulder girdle mechanism, which actuates

the shoulder cuff; and the Cable-Driven Parallel Mechanism (CDPM) mechanism, which actuates the upper arm cuff. These elements were also present in the earlier real-scale prototype [21], developed at the University of Wollongong and named the HYBRID-Shoulder Rehabilitation Exoskeleton (HYBRID-SRE), hereafter referred to as HYBRID-1. The schematic kinematic model of the HYBRID-1 exoskeleton is illustrated in Fig. 1b.

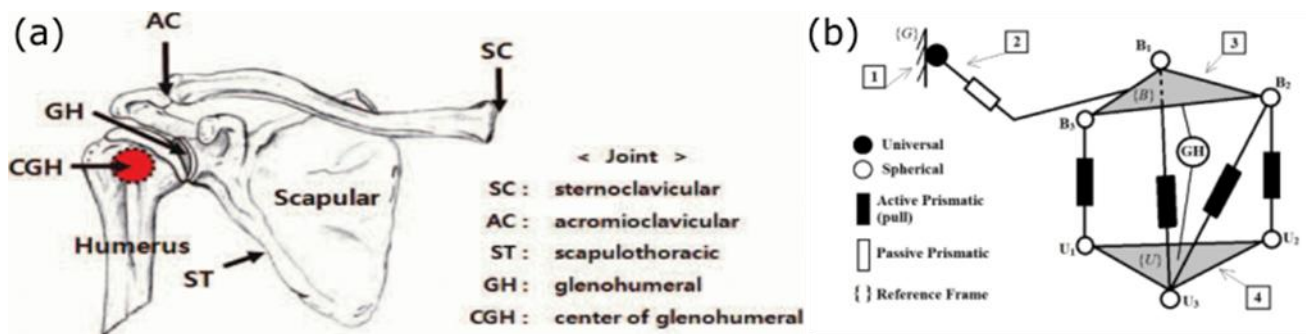


Figure 1 - Shoulder joint structure: (a) Bones and joints of the human shoulder [16]; (b) Kinematic model of the HYBRID-1 exoskeleton: (1) – fixed base, (2) – shoulder girdle mechanism, (3) – shoulder cuff, (4) – upper arm cuff [19]

The base support (or fixed base) is used to align the robot's joint axes along vertical and horizontal planes. Additionally, to reduce the exoskeleton's overall weight, all actuation units are mounted on the base support behind the user's back. A detailed description of the actuators' setup can be found in Section III. Figure 3 shows that the shoulder girdle mechanism is connected in series with the fixed base. This mechanism includes two rotational drives responsible for protraction/retraction and elevation/depression of the shoulder girdle. A detailed kinematic analysis of the HYBRID-1 exoskeleton is provided in [20]. It consists of two active Revolute (R) joints and one passive Prismatic (P) joint.

The remaining two components of the device—the shoulder cuff and the upper arm cuff—are connected via cables, as shown in Fig. 1, forming the CDPM. The cables are designed so that their ends function as spherical (S) joints, while a prismatic (P) joint in the middle allows actuation in only one direction (pull). The shoulder cuff serves as the base platform (BP), while the upper arm cuff acts as the moving platform (MP), enabling three rotational DOFs

for the spherical GH joint. These cables pass through the cuffs and connect to the actuators on the fixed base.

Several experiments were conducted using the HYBRID-1 exoskeleton with a healthy participant wearing an Xsens suit equipped with motion trackers [21]. The participant performed predefined motion patterns while attached to the HYBRID-1 exoskeleton, which was tested without actuation to assess its Range of Motion (ROM). The positions of the right forearm and upper arm trackers were recorded to capture shoulder and shoulder girdle movements. Xsens technology was used to evaluate the workspace of the HYBRID-1 and compare its ROM to that of a healthy human shoulder.

Basic control experiments were conducted to evaluate the performance of HYBRID-1's position controllers. These experiments included standard shoulder movements as well as complex trajectories involving both independent and coordinated motions of the exoskeleton's sub-mechanisms.

One of the most challenging tasks was maintaining tension in the exoskeleton's cables. Additional cable tension tuning was performed for each cable independently. Despite these efforts, some difficulties persisted during the experiments. In the initial position-control trials, some cable tensions dropped below zero because of purely position-based control and insufficient initial pretensioning. This issue emphasized the difficulty of maintaining proper tension without a dedicated control mechanism. Consequently, a new version of the CDPM has been

developed in the subsequent iteration of the exoskeleton.

As a result, based on this initial design, a new iteration of the exoskeleton has been developed at Nazarbayev University, referred to as hybrid shoulder exoskeleton, with two major modifications discussed in the following subsections. First, a 3D-printed miniature model of hybrid shoulder exoskeleton was created to evaluate the impact of these changes (Fig. 2). Insights from this model were then used to manufacture a real-scale prototype of the hybrid shoulder exoskeleton shoulder robotic exoskeleton.

3. Experimental results

A. 3D-Printed Miniature Model of the Hybrid Shoulder Exoskeleton

The new iteration of the shoulder rehabilitation exoskeleton includes modifications to the shoulder

girdle mechanism and the CDPM. As described in [22], a miniature 3D-printed model has been designed to study the coupling mechanisms between a robotic exoskeleton and human anatomy (Fig. 2a).

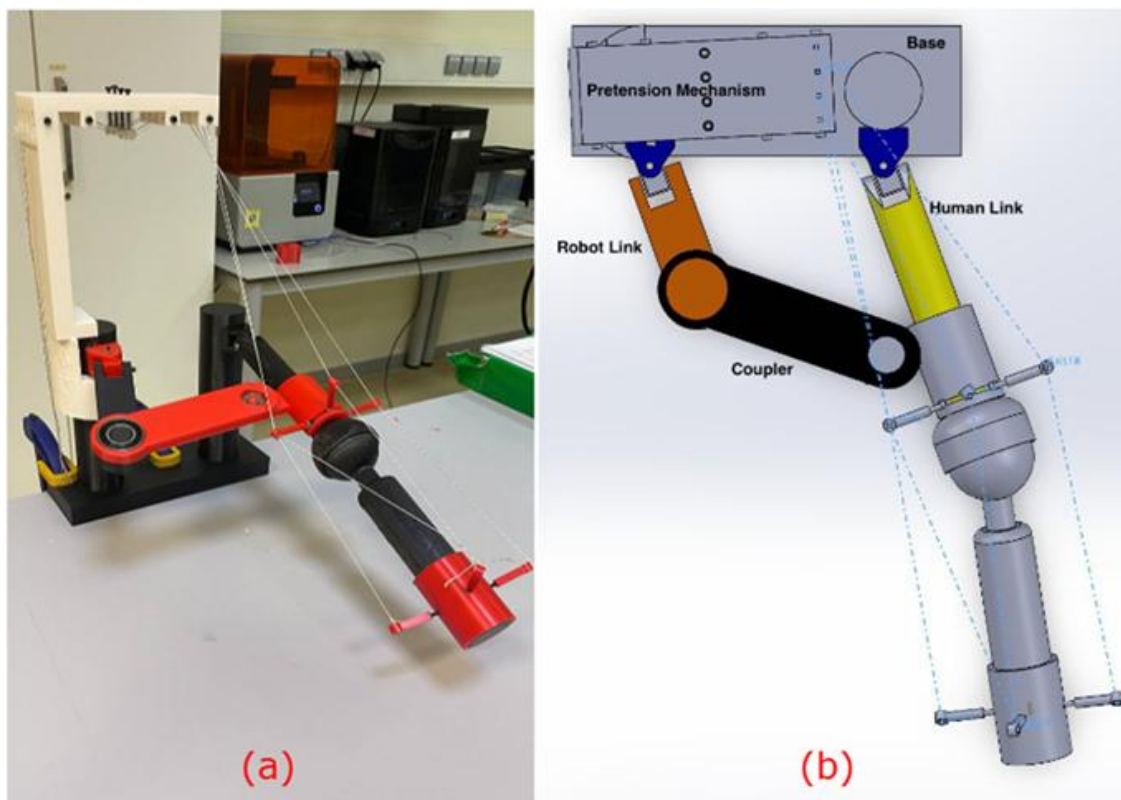


Figure 2 - 3D Printed Mini-prototype and Cad model of hybrid shoulder exoskeleton [22]

To begin with, a CAD design was created to visualize and understand the interaction between the robotic exoskeleton and human shoulder biomechanics. The design incorporates a hybrid 5-degree-of-freedom (DOF) shoulder mechanism, combining a 2-DOF four-bar linkage for the shoulder

girdle with a 3-DOF CDPM for the spherical human shoulder joint. The mechanical design of the hybrid shoulder exoskeleton is shown in Fig. 2b, where key components such as the base, universal joints, revolute joints (bearings), shoulder joint, pretension mechanism, rigid robot links, human links, shoulder

cuff, upper arm cuff, and cable links can be seen. One of the crucial objectives of developing the miniature model is to validate the kinematic models by comparing mathematical predictions with practical CAD simulations. Both forward and inverse kinematics for the four-bar mechanism, as well as inverse kinematics for the CDPM, were tested, showing close alignment between theoretical predictions and simulated outcomes. This confirmed the accuracy of the mechanism's design.

The first significant modification in the new iteration is the redesign of the shoulder girdle mechanism. The inverted slider-crank linkage, which was a key part of the shoulder girdle mechanism in HYBRID-1, has been replaced with a planar crank-rocker four-bar linkage consisting of four revolute (R) joints.

The second modification is the addition of a novel pretension mechanism for the CDPM. This mechanism includes adjustable straps or cables that can be fixed to specific parts of the robot link and connected to either springs, pneumatic/hydraulic actuators, or motors [23, 24]. These straps/cables help maintain tension in the driven cables, preventing derailment and interference while also providing assistive force to support the patient's movement.

The prototype serves as a functional tool for exploring different optimization scenarios in the exoskeleton's design for practical use. It allows for adjustments in joint angles, ROM, and force feedback, tailoring the therapy to individual needs. This level of customization enables precise control over rehabilitation processes, potentially enhancing recovery outcomes for patients with shoulder impairments. Such a detailed approach in designing and verifying the 3D-printed prototype highlights its potential for clinical applications, providing a robust platform for further research and development in robotic-assisted rehabilitation. The creation of this miniature model has not only validated the applied modifications but has also initiated the design and development process of a new version of the exoskeleton.

B. Current Status of Hybrid Shoulder Rehabilitation Exoskeleton

Based on the previous version of the exoskeleton (HYBRID-1) [20] and the modifications demonstrated in the miniature model, work on the new iteration has begun with the implementation of these changes in a CAD model of the exoskeleton. The updated version of the CAD model of the exoskeleton

is represented in Fig. 2. With these changes, the exoskeleton has been modified as a novel pretension mechanism is now adapted into the base. Also, instead of the inverted slider-crank mechanism, the subsystem of the shoulder girdle mechanism, the crank-rocker four-bar linkage has been proposed and integrated. Furthermore, additional support at the base of the exoskeleton has been added to improve the overall stability of the structure.

The shoulder cuff, which is serially connected to the crank-rocker four-bar linkage, is depicted in Fig. 3b. It is designed to be adjustable for different users. Additionally, the cable connection points for the CDPM, located on the shoulder cuff, can be repositioned, which will be useful for future research.

The article by [23] discusses the development of a novel mechanical system designed to address tension management issues in cable-driven continuum manipulators. These manipulators are commonly used in biomechanical and medical robotics due to their flexibility and their ability to transmit force over a distance without requiring motors at each joint. The paper highlights the challenges of tension and friction in cable-driven manipulators, particularly in multi-section actuated systems, where cable derailment and interference are significant concerns. As stated by [24], a pretension mechanism can stabilize cable-driven systems by preventing cable derailment from pulley grooves and reducing interference between cables. We adapted this mechanism to our exoskeleton and placed it on top of the main exoskeleton.

The pretension mechanism consists of eight rods placed at the top of the exoskeleton, along with the roller holders that are placed onto these rods. The roller holder consists of linear bearings (with the help of which the roller holder can slide up and down avoiding excessive friction), rollers for cable movement, and pins to secure the rollers [23]. Additionally, compression springs are placed along and at the bottom of all rods to provide the necessary tension force. For initial experiments, the roller holders are 3D printed. In later experiments, the materials may be changed to enhance durability due to the high tension forces generated during actuation.

Instead of the octagon-shaped pretension mechanism presented in [23], the mechanism's structure has been adapted to suit the directions of cables in the developed exoskeleton. The concept of pretension still works, as compression springs keep tension across the cables. The roller holders are pulled down due to the load (the weight of a hand) and the

springs counteracting the downward force generate a pretension force. The upper arm cuff is in the final stage of assembly. This component consists of an orthotic brace and a metallic cuff with cable connection points for the CDPM.

4. Discussion

The development of the hybrid shoulder exoskeleton shoulder rehabilitation exoskeleton addresses critical limitations identified during the evaluation of its predecessor, HYBRID-1. A primary challenge in the initial prototype was the instability of the cable-driven parallel mechanism (CDPM), where cable tensions frequently dropped below zero during position-control trials. This lack of consistent tension not only risked cable derailment but also compromised the accuracy of the assistance provided to the patient. The integration of a novel pretension mechanism in hybrid exoskeleton, featuring eight rods and spring-loaded roller holders, provides a passive yet effective solution to maintain tension and prevent interference. By adapting this mechanism from continuum manipulator research to an exoskeleton framework, the system can now better manage the gravitational loads of the human arm while ensuring the cables remain securely within their paths.

Furthermore, the transition from an inverted slider-crank to a planar crank-rocker four-bar linkage for the shoulder girdle represents a significant improvement in anatomical alignment. The shoulder is a biomechanically complex joint where the motion of the glenohumeral (GH) joint is inextricably linked

All actuators have been installed at the back of the exoskeleton. Before installing the actuation units, preliminary tests were conducted, with detailed information provided in the next section.

to the movement of the shoulder girdle. Traditional robots that focus solely on the three rotational degrees of freedom often cause discomfort due to misalignment with the shifting center of rotation. The modified four-bar linkage in hybrid shoulder exoskeleton is designed to better accommodate these translations, potentially reducing the nonphysiologic synergies and compensatory movements often seen in stroke survivors.

The successful validation of these changes through a 3D-printed miniature model and CAD simulations confirms that the theoretical kinematic models align closely with practical application. This iterative design approach allowed for optimization of joint angles and range of motion before committing to the full-scale manufacture. While the current prototype demonstrates improved structural stability through additional base support and adjustable components, the next critical phase involves assessing how these mechanical improvements translate to a clinical setting. Future performance testing with a diverse group of healthy subjects will be essential to determine how variations in body parameters, such as height and arm diameter, affect the system's ability to provide precise, task-specific therapy.

5. Conclusions

The development of the hybrid shoulder rehabilitation exoskeleton marks a significant advancement in robotic-assisted therapy by addressing the critical mechanical shortcomings of its predecessor. By replacing the previous inverted slider-crank mechanism with a planar crank-rocker four-bar linkage, the device achieves better alignment with the complex biomechanics of the human shoulder girdle. This modification, alongside the integration of a novel passive pretension mechanism, effectively mitigates the issues of cable derailment and tension loss that hindered the performance of the HYBRID-1 prototype.

The successful validation of these design changes through CAD simulations and a 3D-printed miniature model confirms the accuracy of the system's kinematic models. With the manufacturing of a real-scale prototype featuring an adjustable shoulder cuff

and enhanced structural stability, the project has established a robust platform for providing intensive, task-specific exercises. These improvements are essential for reducing nonphysiologic compensatory strategies and ensuring a safe, comfortable, and standardized rehabilitation experience for patients.

Moving forward, the focus will shift to preliminary performance testing through position control experiments involving 12 healthy subjects. These tests will evaluate how variations in individual body parameters—specifically height, width, and upper arm diameter—impact the system's physical performance. Ultimately, the hybrid exoskeleton aims to bridge the gap in current rehabilitation services, offering a scalable solution to the growing demand for stroke recovery interventions.

Conflict of interests. The authors declare no conflict of interest.

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Author contributions. Conceptualization – S.Y.; methodology – M.K.; examination – B.A. and A.O.; formal analysis – S.Y., Zh.S. and A.C.; writing (original draft preparation) – Z.A.; writing (review and edition) – S.Y.

All authors have read, agreed to release version of a manuscript and signed the Author's right transfer form.

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Инсульттан кейінгі иық буынын роботтандырылған оңалту: Гибридті аспалы-арқанды экзоқаңқа жүйесін әзірлеу және бағалау

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Түйіндеме

Жыл сайын инсульт салдарынан туындаған жоғарғы аяқ-қол қызметінің бұзылуы бүкіл әлем бойынша миллиондаған адамның өмір сапасына әсер етеді. Ал моторлық бақылауды қалпына келтіру үшін қарқынды оңалтуды қажет етеді. Дәстүрлі физиоом мен соңғы үлгідегі буынды роботтар қолданылғанымен, олар көбінесе жоғары еңбек шығындары, терапевттің шаршауы және адам қолының еркіндік дәрежесінің артықтығын бақылай алмау сияқты шектеулерге тап болады. Бұл бейфизиологиялық компенсаторлық қозғалыстарға әкелуі мүмкін. Мақалада HYBRID-1 алдыңғы прототипінің жетілдірілген нұсқасы болып табылатын гибриді иықты оңалту экзоскелетін әзірлеу жұмыстары ұсынылған.

Өнімділікті бағалау және бастапқы нұсқада анықталған арқан керілуі мәселелеріне негізделі отырып, гибриді экзоскелет дизайнына екі негізгі өзгеріс енгізілді. Біріншіден, иық белдеуінің механизмі адам анатомиясына жақсырақ сәйкестендіру үшін төрт айналмалы шарнирден тұратын жазық төрт буынды иінді-белдік (кривошип-коромысло) механизміне ауыстырылды. Екіншіден, арқандардың шығып кетуін болдырмау және стерженьдер, роликтер мен сығу серіппелері жүйесін пайдалана отырып, тұрақты керілуі сақтау үшін арқанды параллель механизмге (CDPM) жаңа алдын ала керілу механизмі біріктірілді.

Дизайн алдымен 3D-басып шығарылған миниатюралық модель және САД симуляциялары арқылы тексерілді, бұл тура және кері кинематикалық модельдердің дәлдігін растады. Кейіннен клиникалық қолдану үшін құрылымдық тұрақтылықты арттыру мақсатында реттелетін иық манжеті және қосымша негізгі тірегі бар толық ауқымды прототип дайындалды. Бастапқы құрастыру және алдын ала сынақтар бұл модификациялар қарқынды, арнайы тапсырмаларға бағытталған оңалту үшін сенімді платформаны қамтамасыз ететінін көрсетеді. Болашақ жұмыс жүйенің бой биіктігі мен иық диаметрі сияқты әртүрлі дене параметрлеріне бейімделуін бағалау үшін сау адамдармен өнімділікті сынауға бағытталады.

Түйін сөздер: инсульттен кейінгі оңалту, иық экзоскелеті, иық белдеуінің механизмі, пассивті алдын ала керілу механизмі, төрт буынды иінді-белдік механизмі.

Роботизированная реабилитация плечевого сустава после инсульта: Разработка и валидация гибридной тросовой системы экзоскелета

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Резюме

Ежегодно нарушения функций верхних конечностей, вызванные инсультом, затрагивают миллионы людей во всем мире, что требует интенсивной реабилитации для восстановления моторного контроля. Хотя традиционная физиотерапия и роботы с концевыми эффекторами уже находят применение, они часто сталкиваются с такими ограничениями, как высокие трудозатраты, утомляемость терапевта и невозможность контролировать избыточность степеней свободы человеческой руки, что может приводить к нефизиологичным компенсаторным движениям. Для решения этих задач в данной работе представлена разработка гибридного плечевого реабилитационного экзоскелета, являющегося усовершенствованной итерацией предыдущего прототипа HYBRID-1.

В гибридном экзоскелете внедрены два основных конструктивных изменения, основанных на оценке производительности и проблемах с натяжением тросов, выявленных в первой версии. Во-первых, был переработан механизм плечевого пояса: инвертированная ползунно-шатунная передача была заменена на плоский четырехзвенный шарнирно-рычажный механизм (кривошип-коромысло), состоящий из четырех вращательных шарниров для лучшего соответствия анатомии человека. Во-вторых, в тросовый параллельный механизм (CDPM) был интегрирован инновационный механизм предварительного натяжения, предназначенный для предотвращения соскакивания тросов и поддержания постоянного натяжения с помощью системы стержней, роликов и пружин сжатия.

Конструкция была предварительно валидирована на напечатанной на 3D-принтере миниатюрной модели и в среде CAD-моделирования, что подтвердило точность моделей прямой и обратной кинематики. Впоследствии был изготовлен полномасштабный прототип с регулируемой плечевой манжетой и дополнительной опорой основания для повышения структурной устойчивости в клинических условиях. Первичная сборка и предварительные испытания показывают, что данные модификации обеспечивают надежную платформу для интенсивной целенаправленной реабилитации. Будущая работа будет сосредоточена на тестировании производительности с участием здоровых испытуемых для оценки адаптивности системы к различным антропометрическим параметрам, таким как рост и диаметр плеча.

Ключевые слова: реабилитация после инсульта, плечевой экзоскелет, механизм плечевого пояса, механизм пассивного предварительного натяжения, четырехзвенный шарнирно-рычажный механизм.