Traumatology and Orthopaedics of Kazakhstan
ISSN - e2789-9640

Original article

Development of a Lightweight Adjustable Knee Exoskeleton for Rehabilitation

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Received: 04 August 2025
Revised: 12 September 2025
Accepted: 23 September 2025
Published: 30 October 2025

Citation: Kassymbek Ozhikenov, Ussen Shylmyrza, Assylbek Ozhiken, Akhmadiya Asset, Madina Karasheva, Damira Mussina. Development of a lightweight adjustable knee exoskeleton for rehabilitation. Trauma & Ortho Kaz, 2025, 76 (5), jto019
https://doi.org/10.52889/1684-9280-2025-76-jto019

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Abstract

Knee injuries and mobility impairments often require long-term rehabilitation, for which robotic exoskeletons have shown clinical potential. However, many existing devices are limited by high weight, poor adjustability, and insufficient torque generation, which restrict their usability in real-world clinical settings. This study aimed to design and evaluate a lightweight, adjustable knee exoskeleton with enhanced ergonomics and functional performance for rehabilitation. The exoskeleton was developed using CAD-based structural optimization to balance strength and weight. Materials were selected based on load-bearing requirements, combining acrylonitrile butadiene styrene plastic for lightweight construction with reinforced steel components for critical joints. A brushless direct current motor was employed for actuation, and the system was designed to provide three-axis alignment adjustability. Simulation studies assessed torque capacity, weight distribution, and biomechanical feasibility. The optimized design achieved a projected weight of less than 7 kg, representing a significant reduction compared to conventional devices. The actuation system generated torques up to 120 Nm, sufficient to support common rehabilitation activities. Biomechanical simulations demonstrated that the exoskeleton was feasible for walking, sit-to-stand, and stair-climbing movements. The adjustable alignment mechanism improved ergonomics, accommodating different body types and reducing the risk of joint misalignment during use. The proposed knee exoskeleton, with its lightweight structure, high torque capacity offers a promising solution for clinical rehabilitation. Compared to existing designs, it provides improved safety, comfort, and adaptability, making it suitable for diverse rehabilitation scenarios. Future work will involve prototype fabrication, experimental validation, and pilot clinical testing.

Keywords: exoskeleton device, rehabilitation, knee joint, gait, walking, postural balance.

1. Introduction

Knee joint disorders represent one of the leading causes of disability worldwide. Injuries to the anterior cruciate ligament (ACL), meniscus damage, post-traumatic arthritis, and neurological conditions such as stroke or spinal cord injury often result in impaired mobility and reduced quality of life [1,2]. According to the Global Burden of Disease Study, musculoskeletal and neurological disorders collectively affect more than one billion people [3].

Rehabilitation is the cornerstone of functional recovery in these patients. Traditional methods, such as manual therapy and repetitive exercise, are effective but limited. They require intensive therapist involvement, often lead to inconsistent exercise quality, and are difficult to maintain long-term [4]. These challenges underscore the need for technological solutions that can provide consistent, intensive, and patient-tailored rehabilitation.

Robotic exoskeletons have emerged as promising devices to complement or even replace conventional therapy. Exoskeletons are wearable electromechanical systems designed to align with the human body and assist or augment movement. Clinical studies have demonstrated that powered exoskeleton-assisted rehabilitation can improve gait speed, endurance, and lower-limb activation [5–8]. However, limitations remain: current exoskeletons are often heavy (>12–15 kg), lack anthropometric adjustability, and risk misalignment that causes discomfort or injury [9-11]. Furthermore, achieving sufficient torque output without compromising portability is a major engineering challenge [12].

Recent advances emphasize lightweight materials, ergonomic alignment, and modularity [13]. Brushless direct current (BLDC) motors provide compact, high-torque solutions, and ankle modules have been shown to improve gait symmetry [14]. Therefore, this study aimed to design and evaluate a lightweight, adjustable knee exoskeleton that addresses these limitations, with emphasis on clinical applicability and rehabilitation outcomes.

Therefore, the aim of this study was to design and evaluate a lightweight, adjustable knee exoskeleton that addresses limitations of existing systems. The proposed device incorporates a three-axis adjustable mechanism to ensure accurate alignment with the knee joint, employs acrylonitrile butadiene styrene (ABS) plastic and reinforced steel for a balance of strength and weight, and integrates a high-torque BLDC motor to meet clinical torque requirements. This work contributes to the growing field of rehabilitation robotics by presenting a design tailored for clinical applicability, patient comfort, and therapeutic effectiveness.

2. Materials and Methods

Design Concept: The exoskeleton was designed using Autodesk Fusion CAD software, incorporating adjustable mechanisms across three axes (X, Y, Z) to accommodate anthropometric variations. This ensures accurate alignment of the device with the user's anatomical knee axis. Actuation System: The CubeMars AK80-64 BLDC motor was employed to provide high torque output with compact design (Table 1, Figure 1-3). Nominal torque of 48 Nm and peak torque of 120 Nm ensured safe operation above the therapeutic requirement range of 20–35 Nm [11].

Figure 1 – Image of the AK 80-64 Cubemars BLDC motor

https://doi.org/10.52889/1684-9280-2025-76-jto019

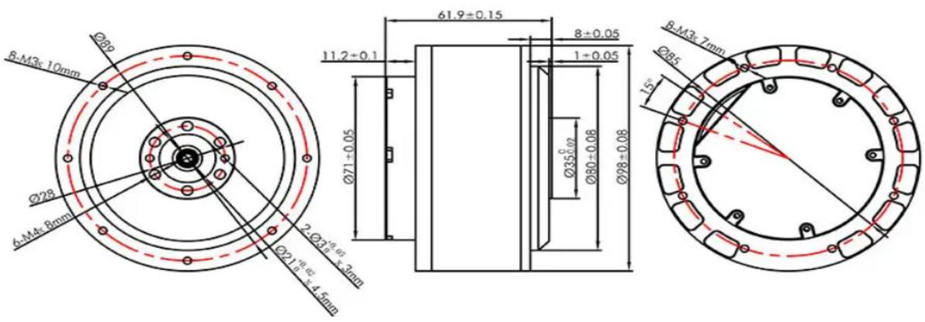


Figure 2 – Engineering drawing of the AK 80-64 engine from Cubemars

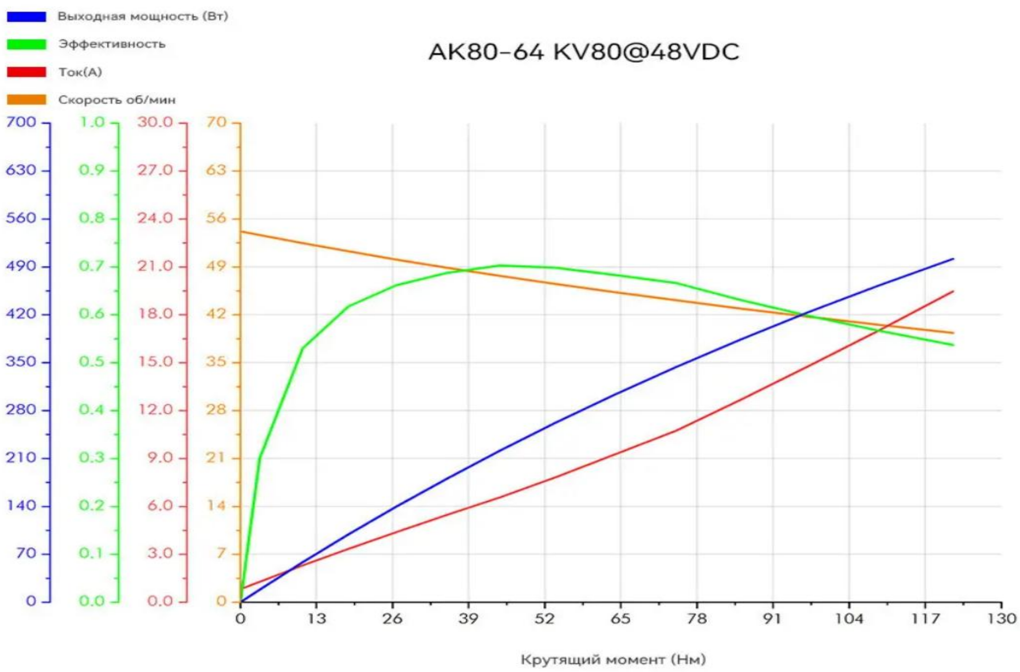


Figure 3 – Analytical diagram of the AK 80-64 electric motor

Materials. Lightweight ABS plastic was selected for adjustable components, providing tensile strength between 30–50 MPa and impact resistance suitable for rehabilitation. Structural reinforcements and motor supports were fabricated in steel to enhance stability.

Table 1 – Technical characteristics of the CubeMars AK80-64 BLDC motor

Characteristic	**Meaning/Type**	**Characteristic**	**Meaning/Type**
Drive type	FOC	Peak Current (DC, A	19
Operating ambient temperature	-20℃~50℃	KV (rpm)	80
Winding connection diagram	Delta	KT (Nm/A)	0.136
Insulation class	H	Ke (V/1000 rpm)	13.7
Insulation breakdown voltage	1000V 5mA/2s	Interphase resistance (mΩ)	220

https://doi.org/10.52889/1684-9280-2025-76-jto019

Continuation table 1

Insulation resistance	1000V10MΩ	Interphase inductance (μH)	133.5
Phase	3	Inertia (gsm²)	564.5
Pairs of poles	21	Torque constant (Nm/√W)	0.29
Gear reduction ratio	64:1	Mechanical time constant (ms)	0.67
Reverse torque (Nm)	4.7	Electrical time constant (ms)	0.61
Backlash (°)	0.18	Weight (g)	850
Temperature sensor	NTC MF51B 103F3950	Maximum torque to weight ratio (Nm/kg)	141.2
Noise in dB at a distance of 65 cm from the motor	60	CAN port	A1257WR-S-4P
Max. axial load (dynamic) N	2000	UART port	A1257WR-S-3P
Max. axle load (static) N	2520	Power port	XT30PW-M
Nominal voltage (V)	24/48	Nominal speed (rpm)	23/48
Nominal torque (Nm)	48	Rated current (DC, A)	7

Additionally, it is planned to engrave a ruler on the surface and along the length of all steel guide pipes. Later, it is planned to use anodized aluminum profiles to build more precise and adjustable joints (Table 2).

Table 2 – ABS plastic properties

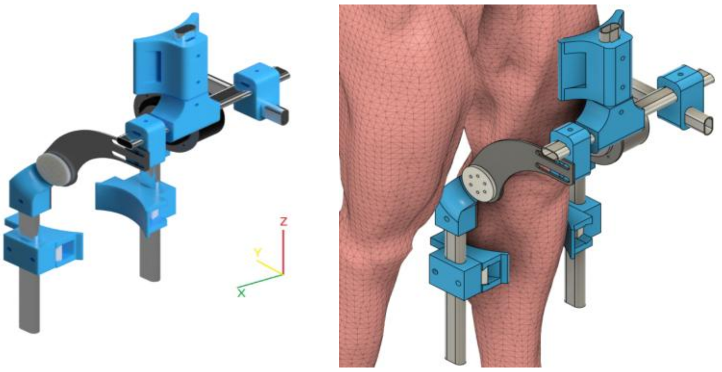
Indicator	**Meaning**
Limit strength on stretching	30–50 MPa
Limit strength on bend	45–80 MPa
Module elasticity (bending)	1.5–2.4 GPa
Impact strength (IZOD , notched)	10–15 kJ /m²
Temperature softening (Vicat)	95–110 °C

3. Results

3.1 Structural Design and Adjustability

The CAD prototype achieved full three-axis adjustability, enabling precise alignment with anatomical knee axes. This reduces misalignment-related torques and enhances user comfort [10].

The design shown in Figure 4 allows for adjustment of the exoskeleton dimensions along three axes (X,Y,Z). The main adjustments are located on the upper part of the exoskeleton (Figure 5), where the device is attached to the thigh with a wide belt. As for the lower part of the exoskeleton (Figure 5), where the structure is attached to the leg at the tibia and calf muscles, rigid adjustment is possible only in depth along the Y axis. At the bottom, along the Z axis there is a free play to achieve passive alignment of the exoskeleton during movement to match the natural biomechanics and trajectory of the knee joint during flexion and extension.



A B

Figure 4 – Isometric views of the knee joint exoskeleton prototype. A – render; B – screenshot from Autodesk software. Fusion with an exoskeleton and a life-size human mannequin

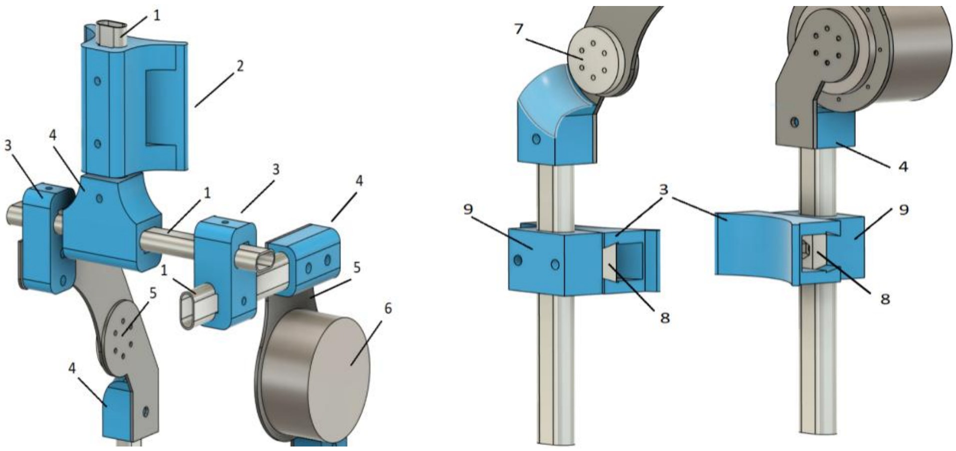


Figure 5 – Upper lower parts of the exoskeleton:1- Steel pipe, 2- Adjustable plastic block with mount, 3- Adjustable plastic block, 4- Non-adjustable plastic block, 5- Steel plate, 6-Electric moto; 7- Bearing/bushing for stabilization, 8- Plastic pressure block, 9- Plastic block with free play

Adjustment of the width of the lower part of the exoskeleton (along the X-axis) depends on the adjustment of the width of the upper part. In case of significant deviations from the proportions of a person, it is possible to change the width of the lower part by adding additional washers at the attachment points to the electric motor rotor and to the stabilizing bearing or bushing.

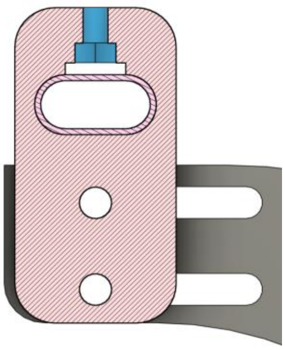


Figure 7 – Mechanism for adjusting the upper part of the exoskeleton along the X- and Y axes

https://doi.org/10.52889/1684-9280-2025-76-jto019

The figure 7 illustrates the mechanism for adjusting the upper part of the exoskeleton in width and depth. Inside the plastic block there will be a steel pipe, 30 mm wide, 15 mm high and with a wall thickness of 1 to 1.5 mm. On the side/top of the pipe there will be a steel plate 15 mm wide, 3 mm high and the length of the plastic block. The plastic block will be printed on a 3D printer from ABS plastic filament. This type of plastic has a more flexible and impact-resistant structure compared to other types.

To secure the block in place, an M6 nut and an M6x20 bolt will be inserted into a pre-designed groove. Tightening the nut will create pressure on the pressed steel plate, which will lead to a strong connection between the block and the steel pipe.

To regulate the position of the block along the Y axis , a mechanism similar to the one described above is used on the motor side. On the other side of the exoskeleton, it was decided to insert a steel plate with cut grooves (Figure 8).

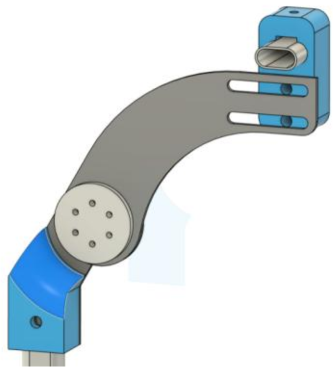


Figure 8 – Image of the exoskeleton from the bearing/bushing side for stabilization

The lower part of the exoskeleton is adjusted in depth (Y axis) using a plastic insert, which is pressed by a nut with a bolt of size M8 (Figure 9). This type of mechanism is easy to use and maintain.

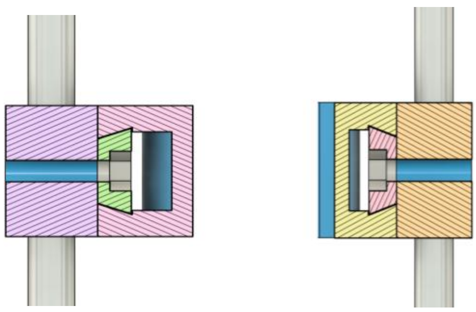


Figure 9 – Sectional view of the adjustment mechanism for the lower exoskeleton fastenings in depth

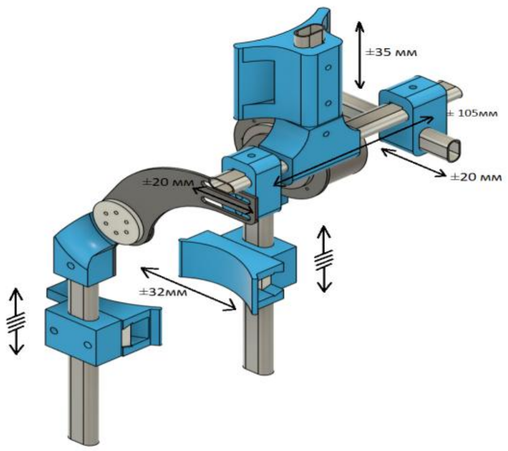


Figure 10 – Exoskeleton adjustment range

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3.2 Weight Optimization

Material selection lowered the projected device weight to <7 kg, substantially lighter than many existing systems (>12 kg) [9,11]. This supports longer rehabilitation sessions with reduced user fatigue.

3.3 Actuation and Torque

The CubeMars AK80-64 BLDC motor provided nominal torque of 48 Nm and peak torque of 120 Nm, surpassing the clinical requirements of 20–35 Nm for sit-to-stand and stair climbing tasks [12].

3.4 Biomechanical Feasibility

Simulations confirmed feasibility for walking gait cycles, sit-to-stand movements, and stair climbing. Knee flexion-extension support was effective up to 120°, with torque assistance reducing quadriceps load.

4. Discussion

The proposed exoskeleton addresses limitations of current devices by combining adjustability, torque sufficiency, and lightweight construction. Misalignment, a key barrier in exoskeleton comfort, is mitigated by adjustable multi-axis mechanisms [7]. The torque generated by the CubeMars motor exceeds clinical requirements, enabling assistance across rehabilitation stages from early supported ambulation to advanced functional training [11].

Compared to rigid commercial systems weighing over 12 kg, the use of ABS plastic and modular reinforcements improves portability and usability [6,9]. Clinically, robotic exoskeletons have demonstrated benefits in improving gait symmetry, reducing spasticity, and enhancing endurance [12-14]. The presented design holds potential to contribute to these outcomes while offering improved comfort and usability. Physical prototyping and clinical trials will be required to validate mechanical integrity, usability, and rehabilitation outcomes.

5. Conclusions

This study introduces a lightweight and adjustable knee exoskeleton specifically developed for rehabilitation purposes. The design emphasizes ergonomic three-axis adjustability, allowing precise alignment with the human knee joint and thereby reducing the risks associated with joint misalignment. Through material optimization and modular structural design, the overall device weight was substantially reduced, improving portability and patient usability compared with heavier existing systems.

These findings underscore the clinical relevance and applicability of the design, while also highlighting its potential to complement conventional rehabilitation approaches. Although current validation is limited to CAD modeling and simulation, the results lay a solid foundation for future work involving physical prototyping, biomechanical testing, and clinical trials with patients to confirm mechanical integrity, safety, and therapeutic effectiveness.

Conflicts of Interest. The authors declare no conflicts of interest.

Acknowledgements. The authors thank the Ministry of Science and Higher Education of the Republic of Kazakhstan for supporting this study.

Funding. This research was funded by the Ministry of Science and Higher Education of the Republic of Kazakhstan, grant number BR24992820.

Author contributions: Conceptualization, O.K.A.; Design, U.Sh. and A.O.; Writing—original draft preparation, M.K.; Writing—review and editing, A.A.; Supervision, O.K.A.

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Оңалтуға арналған жеңіл және реттелетін тізе экзоскелетін жасау

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Түйіндеме

Тізе буынының жарақаттары мен қозғалыс бұзылыстары жиі ұзақ мерзімді оңалтуды қажет етеді, осы мақсатта роботтандырылған экзоскелеттер клиникалық әлеуетін көрсетті. Алайда, қазіргі құрылғылардың көпшілігі жоғары салмақпен, жеткілікті түрде реттелмеуімен және төмен айналу моментімен шектелген, бұл олардың клиникалық ортада қолданылуын шектейді. Зерттеудің мақсаты: эргономикасы мен функционалдық сипаттамалары жетілдірілген жеңіл әрі реттелетін тізе экзоскелетін жасау және бағалау. Экзоскелет беріктік пен масса арасындағы тепе-теңдікті сақтау үшін компьютерлік модельдеуге негізделген құрылымдық оңтайландыруды қолдана отырып жасалды. Материалдар жүктемелік талаптарға сәйкес таңдалды: жеңіл құрылымдық элементтер үшін акрилонитрил-бутадиен-стирол, ал жоғары жүктемеге ұшырайтын тораптар үшін арматураланған болат қолданылды. Қозғалысты қамтамасыз ету үшін түкшесіз тұрақты ток қозғалтқышы пайдаланылды, ал жүйе үш өс бойынша туралау мүмкіндігімен жобаланды. Симуляциялық зерттеулер айналу моментін, салмақ үлестірімін және биомеханикалық сәйкестігін бағалау үшін жүргізілді. Оптимизацияланған құрылымның болжамды салмағы 7 килограммнан аз болып шықты, бұл дәстүрлі құрылғыларға қарағанда айтарлықтай төмен.

https://doi.org/10.52889/1684-9280-2025-76-jto019

Жетек жүйесі 120 ньютон-метрге дейінгі айналу моментін жасады, ол кең таралған оңалту жаттығуларын қолдауға жеткілікті. Биомеханикалық модельдеу экзоскелеттің жүру, отырып-тұру және баспалдақпен көтерілу қозғалыстары үшін қолдануға жарамды екенін көрсетті. Реттелетін туралау механизмі эргономикалық тиімділікті арттырып, әртүрлі дене бітіміне бейімделуге және буын осінің сәйкес келмеуі қаупін азайтуға мүмкіндік берді. Ұсынылған тізе экзоскелеті жеңіл құрылымымен және жоғары қуаттылығымен клиникалық оңалту үшін тиімді шешім болып табылады. Қолданыстағы құрылғылармен салыстырғанда ол қауіпсіздік, жайлылық және бейімделу тұрғысынан жақсартылған қасиеттерге ие, бұл оны әртүрлі оңалту жағдайларына бейім етеді. Болашақ зерттеу кезеңдеріне прототипті жасау, тәжірибелік тексеру және клиникалық пилоттық сынақтар кіреді.

Түйін сөздер: экзоскелет құрылғысы, оңалту, тізе буыны, жүру, жүру үлгісі, тұрақтылық тепе-теңдігі.

Разработка легкого регулируемого коленного экзоскелета для реабилитации

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Резюме

Травмы коленного сустава и нарушения подвижности часто требуют длительной реабилитации, для которой роботизированные экзоскелеты показали клинический потенциал. Однако многие существующие устройства ограничены высокой массой, недостаточной возможностью регулировки и низким уровнем создаваемого крутящего момента, что снижает их применимость в реальных клинических условиях. Цель данного исследования заключается в разработке и оценке легкого регулируемого коленного экзоскелета с улучшенной эргономикой и функциональными характеристиками для реабилитации. Экзоскелет разработан с использованием структурной оптимизации на основе компьютерного моделирования для достижения баланса между прочностью и массой. Материалы подбирались с учетом нагрузочных требований: для легких конструктивных элементов использовался акрилонитрил-бутадиен-стирол, а для критически нагруженных узлов армированная сталь. В качестве привода применялся бесщеточный двигатель постоянного тока, а система была спроектирована с возможностью трехосевой регулировки выравнивания. Симуляционные исследования проводились для оценки крутящего момента, распределения массы и биомеханической целесообразности. Оптимизированная конструкция имеет расчетную массу менее 7 килограммов, что представляет собой значительное снижение по сравнению с традиционными устройствами. Приводная система обеспечивала крутящий момент до 120 ньютон-метров, что достаточно для выполнения распространенных реабилитационных задач. Биомеханические симуляции показали, что экзоскелет может применяться для ходьбы, перехода из положения сидя в положение стоя и подъема по лестнице. Механизм регулируемого выравнивания повысил эргономичность, позволив адаптировать устройство к различным типам телосложения и снизить риск несоосности суставов во время эксплуатации. Предложенный коленный экзоскелет с легкой конструкцией и высокой мощностью привода является перспективным решением для клинической реабилитации. По сравнению с существующими разработками он обеспечивает более высокий уровень безопасности, комфорта и адаптивности, что делает его применимым для различных реабилитационных сценариев. В дальнейшие этапы работы войдут изготовление прототипа, экспериментальная валидация и пилотные клинические испытания.

Ключевые слова: экзоскелет, реабилитация, коленный сустав, ходьба, походка, постуральное равновесие.