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Original article

Knee Joint Optimization for Medical Exoskeletons: Enhancing Biomechanical Efficiency in Gait Rehabilitation

Shyngys Dauletbayev [1*], Saule Karibzhanova [2]

[1] Researcher, Robotics and Artificial Intelligence, Nazarbayev University, Astana, Kazakhstan.
E-mail: shyngys.dauletbayev@alumni.nu.edu.kz
[2] Researcher, School of Medicine, Nazarbayev University, Astana, Kazakhstan. E-mail: saule.karibzhanova@nu.edu.kz

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Abstract

Lower limb dysfunction resulting from neurological or musculoskeletal disorders often leads to impaired gait and reduced mobility. Robotic exoskeletons are increasingly used in medical rehabilitation to support gait retraining, reduce therapist workload, and improve patient outcomes. However, conventional knee joint mechanisms in exoskeletons fail to fully replicate the complex biomechanics of the human knee, causing misalignment and patient discomfort during therapy. This study aims to design and optimize a bioinspired knee joint mechanism for a medical exoskeleton to improve biomechanical efficiency, enhance alignment with natural knee motion, and increase patient safety and comfort during gait rehabilitation. The proposed design is based on anatomical data obtained from magnetic resonance imaging of a healthy adult knee. Two mechanical configurations were developed using computer-aided design (CAD) modeling: a noncircular spur gear mechanism and a bearing-guided curved surface mechanism. Simulations were performed to evaluate joint kinematics, torque distribution, and mechanical stability under realistic gait conditions. The curvature profile of the femoral condyle was used to replicate the natural flexion–extension trajectory of the human knee. Simulation results demonstrated that the bioinspired knee mechanism achieved smoother motion and improved torque distribution compared to the conventional single-degree-of-freedom design. The proposed configuration minimized lateral misalignment, reduced parasitic forces at the exoskeleton–limb interface, and improved mechanical stability throughout the gait cycle. The study confirms that a bioinspired knee joint mechanism can significantly enhance gait rehabilitation performance. The findings provide a foundation for developing next-generation exoskeletons that are biomechanically consistent, energy-efficient, and safe for clinical use.

Keywords: Exoskeleton, Knee joint, Optimization, Biomechanics, Rehabilitation.

1. Introduction

Lower limb dysfunction is a common medical condition that may result from stroke, physical trauma, or other injuries. Many patients affected by such impairments have the potential to regain partial or full mobility through proper rehabilitation. Gait rehabilitation exoskeletons have been developed to enhance the effectiveness of physiotherapy for semi-paralyzed patients by performing repetitive movements with gradually reduced robotic assistance during recovery [1-3]. According to survey studies [4,5], robotic exoskeletons have demonstrated strong potential to improve rehabilitation efficiency and significantly reduce the physical workload of therapists.

The successful development of lower limb exoskeletons requires an in-depth understanding of human anatomy, particularly the complex biomechanics of the joints. The knee joint, in particular, exhibits multi-degree-of-freedom (DOF) kinematics that include rotation and translation components Figure 2 [6]. However, to simplify design and control, most orthoses, prostheses, and exoskeletons implement only a single-DOF revolute joint. While this simplification may suffice for non-actuated orthoses, it introduces alignment issues and undesired orthogonal forces in actuated systems. Clinical tests conducted under the supervision of rehabilitation specialists revealed that one-DOF knee mechanisms cause instability in the lower leg and frequent loosening of fixation belts during physiotherapy sessions. As a result, patients were unable to complete even short 10-minute sessions without repeated readjustment. These findings highlight the limitations of existing designs and the need for improved knee joint mechanisms that can better replicate natural human motion.

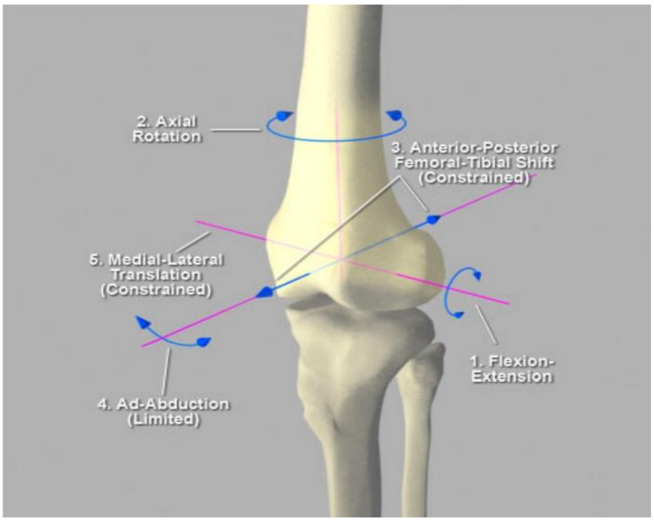

Figure 1- Natural human knee DOF-s [6]

This study aims to develop and evaluate improved conceptual designs for an exoskeleton knee joint mechanism that align more accurately with human knee kinematics. Several design concepts were identified through a literature review and assessed for compatibility with the AK80-64 motor and alignment with the anatomical joint. Selected designs were modeled using SolidWorks CAD software and virtually simulated. The design validation was carried out through ergonomic testing on a human leg to identify potential improvements and ensure proper alignment with human movement.

2. Materials and methods

Research Design

This study employed an experimental design approach to develop and evaluate bioinspired knee joint mechanisms for a lower limb rehabilitation exoskeleton. Several existing knee joint designs were reviewed to identify models capable of achieving close alignment between human knee kinematics and robotic motion. Among the concepts considered, bioinspired mechanisms were selected for further development due to their superior alignment accuracy Figure 2.

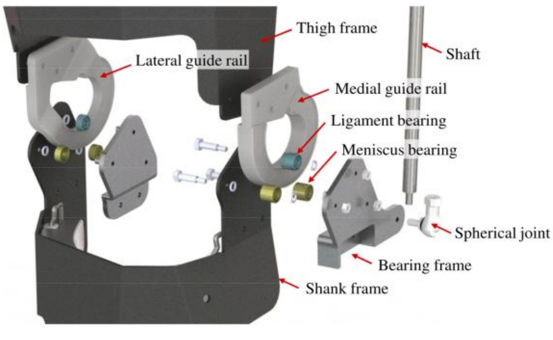

Figure 2 - Bio inspired knee joint [12]

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Materials and Data Sources

The proposed knee joint concepts were modeled using SolidWorks CAD software and simulated virtually. The bioinspired design was based on the curvature of the femur bone derived from sagittal plane magnetic resonance imaging (MRI) scans of a healthy 25-year-old female subject, obtained from the publicly available dataset of Tim Luijkx [7]. The MRI images were used to extract the curvature profiles of the femoral condyles and to design the trajectory for the instantaneous center of rotation (ICR) of the knee joint.

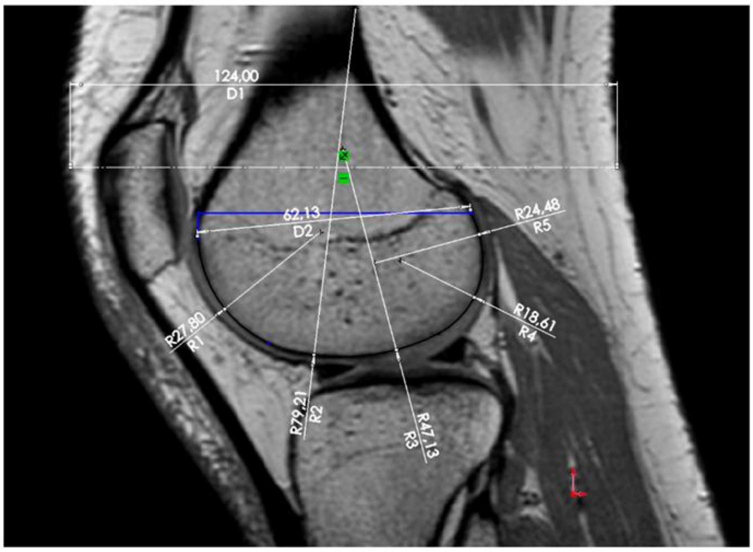

Figure 3: Curvature profile drawing on a lateral condyle MRI picture's projection

Design and Prototyping Procedure

Three main knee joint configurations from previous studies were analyzed, including four-bar linkages [8,9], multi-revolute planar mechanisms [10,11], and bioinspired designs [12]. Based on comparative assessment, two bioinspired models were developed in this work:

- Gear-based knee joint concept – incorporating a non-circular gear profile that replicates the femoral condyle curvature, improving motion stability and mechanical reliability.
- Bearing-based knee joint concept – employing ball bearings rolling along a curved surface of the femur analog, connected via springs and metal bars to allow smooth flexion and extension.

The curvature of the lateral femoral condyle was chosen for trajectory modeling, as it exhibited a larger curvature profile. MRI images were scaled to match the average male knee dimensions (ages 23–25). Curvature profiles were constructed using uniform radius arcs with radii values of R_1 = 27.8 mm, R_2 = 79.21 mm, R_3 = 47.13 mm, R_4 = 18.61 mm, and R_5 = 24.48 mm Figure 3. The models were scaled to accommodate the AK80-64 BLDC motor (Figure 4) ensuring mechanical compatibility and maintaining natural knee motion kinematics.

Figure 4 - AK80-64 BLDC motor

Kinematic Analysis

Kinematic evaluation was conducted by applying the Denavit–Hartenberg (DH) convention using parameters derived from the mechanical design (Table 1). Although each prototype includes a single actuated joint, the curvature profile of the upper segment induced a secondary translational motion along the connecting bars, resulting in effective two-degree-of-freedom (revolute and prismatic) kinematics.

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Table 1 - Denavit-Hartenberg parameters

i	α_{i-1}	a_{i-1}	d_{i-1}	θ_i
1	0	0	0	θ_1
	90^o	D_x	0	0

Design Validation

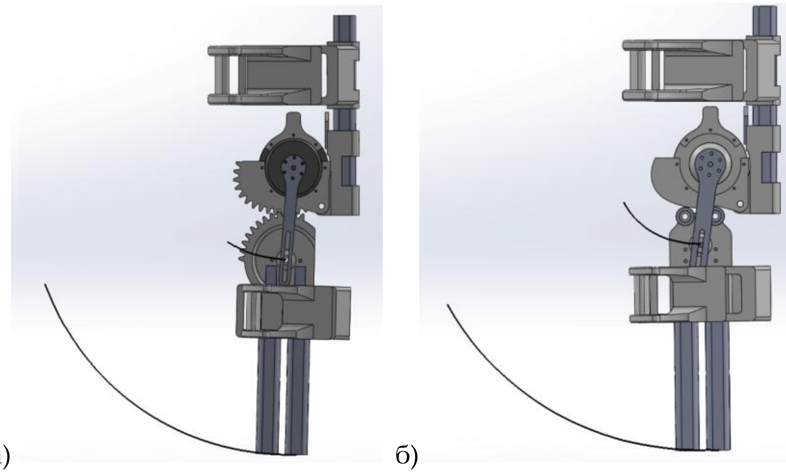
Prototype testing was performed to assess ergonomic performance and alignment accuracy. 3D-printed prototypes were fitted on a human leg to verify comfort, joint motion smoothness, and potential interference with exoskeleton belts or braces. Observations were recorded to identify design flaws and guide refinements.

Ethical Considerations

This research complies with the basic ethical principles of human subject research as outlined in the Declaration of Helsinki. No direct patient involvement or personal data collection was conducted. The MRI data used in this study were obtained from open-access medical imaging databases and contained no identifiable personal information.

3. Results

To evaluate the developed prototypes, the SolidWorks motion analysis tool was first employed. This tool enables simulation of the assembly by incorporating physical interactions between components and allows tracking of point trajectories (Figure 5). Subsequently, practical experiments were performed to assess the ergonomics of the knee joint and to identify any design shortcomings.



a) б)

Figure 5 -Trajectory graphs Assembled model: (a) Geared concept. (b) Ball bearing

Software design validation concept

SolidWorks-based design evaluation is particularly advantageous in the initial development stages, as it provides detailed insights into assembly kinematics and enables comparison with existing human knee motion data. Prior studies have characterized knee joint trajectories, making such comparisons feasible [12]. Data from published experimental plots were digitally extracted, and analogous data from the assembly model were gathered using the same method to ensure consistency.

In [12], the researchers recorded the swing phase of gait using reflective markers placed on the thigh (T1, T2) and shank (S1, S2). Because the thigh remained fixed and only the lower leg moved, the analysis focused on the shank markers, with thigh markers serving as the reference. This process yielded the trajectory diagram shown in Figure 6. The marker spacing on the human leg was 250 mm, whereas the spacing in the assembly model was 230 mm, producing an observable offset between the respective trajectories.

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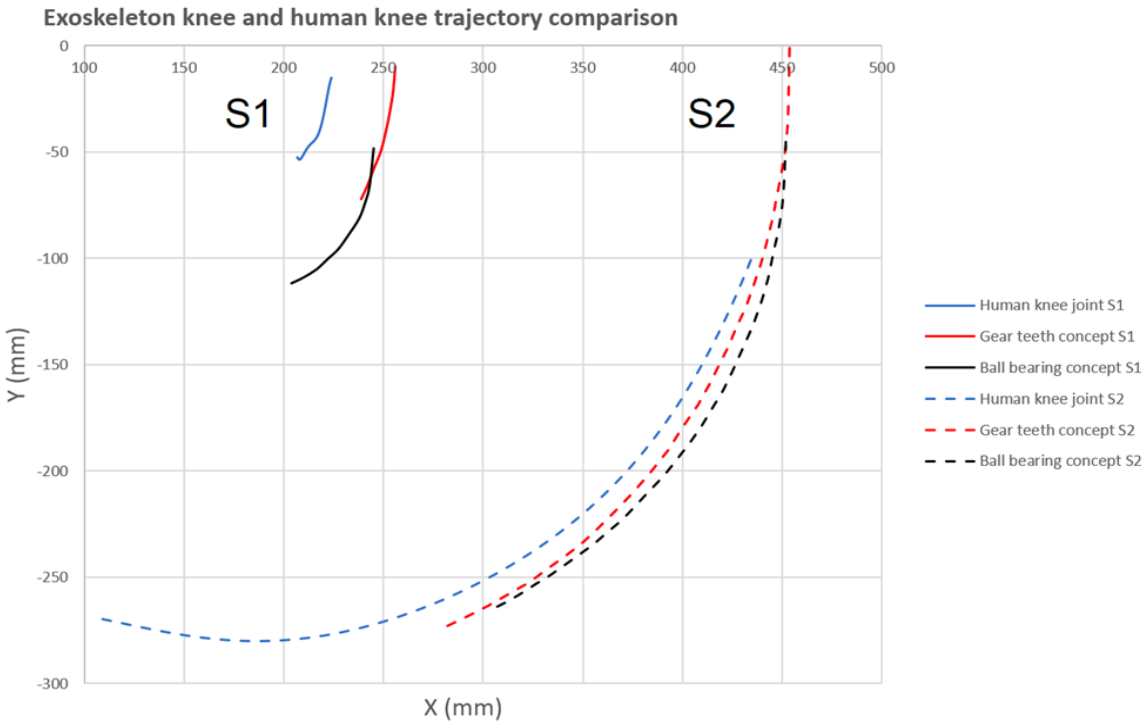


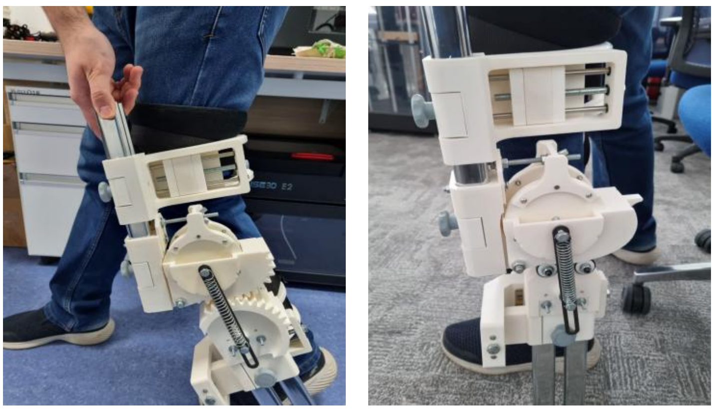
Figure 6- Diagram with trajectories of markers on a human leg and knee joint concept

Practical design validation

Following software-based validation of both concepts, a physical prototype was developed, enabling practical experiments for final design verification. The braces of the prototype were fabricated from solid plastic; therefore, soft pads were added between the braces and the straps to improve user comfort. The straps were secured using plastic fastex buckles, which, in some cases, introduced minor inconveniences. Each prototype model was tested individually to determine the more suitable design (Figure 7).

During these trials, several plastic components were damaged, prompting minor redesigns of the CAD models to enhance durability without altering the kinematics. In the ball-bearing concept, misalignment between the upper and lower components was observed, leading to the addition of guiding tracks to improve stability.

Midway through the practical validation, it was found that the gear-based concept caused overbending of the lower brace beyond a certain flexion angle. Nevertheless, for slow gait motion involving low flexion angles, alignment remained adequate and did not lead to discomfort. For the ball-bearing design, insufficient support at the ankle resulted in slight twisting of the exoskeleton during the gait cycle.



(a) (b)

Figure 7 - Practical test pictures: (a) Geared concept, (b) Ball bearing concept

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4. Discussion

The software-based evaluation demonstrated that designing the curvature profile to match the lateral condyle of the femur enables proper alignment between the human knee and the exoskeleton joint. Although further experiments with the actual exoskeleton are required for definitive verification, the current analysis already incorporates the real system's kinematic constraints.

Practical testing helped identify several structural design issues, most of which were resolved through iterative CAD modifications. However, the overbending observed in the geared design requires more detailed investigation. It is suspected that this issue results from the unequal number of gear teeth on the upper and lower components. Attempts to address the problem revealed that increasing the number of teeth on the lower component would substantially enlarge its overall diameter, which is not desirable for the final design.

5. Conclusions

Misalignment between the human knee and the exoskeleton joint often results in noticeable discomfort. Although many exoskeleton manufacturers adopt simplified single-revolute-joint mechanisms, medical and rehabilitation applications require highly accurate alignment. In this study, several approaches were explored to develop a knee joint mechanism capable of achieving proper alignment while remaining compatible with an existing gait rehabilitation robot. Taking into account the biomechanical constraints of the human knee and the design requirements of rehabilitation exoskeletons, two concepts were proposed, prototyped, and evaluated through both simulation and practical testing.

The results indicated that the ball-bearing concept achieved more accurate alignment across all flexion angles. The geared design also demonstrated potential, though further refinement of the gear tooth configuration is likely needed. The ball-bearing mechanism similarly requires additional adjustments to reach optimal performance; however, based on the current kinematic assessment and preliminary validation, this design provides alignment that closely matches that of the human knee.

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

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Author Contributions. Conceptualisation, methodology and experimentation – Sh.D., Writing, revising, analysis – S.K.

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Медициналық экзоскелеттерге арналған тізе буындарын оңтайландыру: Жүруді қалпына келтірудегі биомеханикалық тиімділікті арттыру

Даулетбаев Ш. [1*], Карибжанова С. [2]

[1] Ғылыми қызметкер, Робототехника және жасанды интеллект, Назарбаев Университеті, Астана, Казахстан. E-mail: shyngys.dauletbayev@alumni.nu.edu.kz

[2] Ғылыми қызметкер, Медицина мектебі, Назарбаев Университеті, Астана, Казахстан. E-mail: saule.karibzhanova@nu.edu.kz

Түйіндеме

Жүйке немесе тірек-қимыл жүйесінің бұзылыстары төменгі аяқ-қол қызметінің әлсіреуіне және жүру қабілетінің төмендеуіне әкеледі. Медициналық экзоскелеттер жүруді қалпына келтіру емінде кеңінен қолданылады. Себебі олар науқастардың қозғалысын қолдап, физиотерапевттердің жүктемесін азайтып, оңалтудың тиімділігін арттырады. Дегенмен, дәстүрлі бір айналу осі бар тізе буыны механизмдері адамның табиғи буын биомеханикасын толық қайталай алмайды. Нәтижесінде буын сәйкессіздігі мен науқастың жайсыздығы туындайды. Бұл зерттеудің мақсаты – жүруді оңалтуға арналған медициналық экзоскелетке биомиметикалық тізе буыны механизмін жобалау және оңтайландыру арқылы биомеханикалық тиімділікті арттыру, табиғи қозғалыс траекториясымен сәйкестікті күшейту және науқастың қауіпсіздігі мен жайлылығын қамтамасыз ету. Ұсынылған механизм сау ересек адамның тізе буынының магниттік-резонанстық томографиясы деректеріне негізделді. Екі механикалық конфигурация жасалды: бейдөңгелек тісті беріліс механизмі және доғал бетпен айналатын мойынтіректі жүйе. Компьютерлік модельдеу (CAD) арқылы буынның кинематикасы, моменттің таралуы және тұрақтылығы нақты жүру жағдайларында талданды. Фемордың (сан сүйегінің) латералды айдаршығының қисық пішіні адамның табиғи тізе қозғалысын имитациялау үшін пайдаланылды. Модельдеу нәтижелері биомиметикалық тізе буыны дәстүрлі бір еркіндік дәрежелі механизммен салыстырғанда қозғалыстың бірқалыптылығын және айналу сәтін жақсартқанын көрсетті. Ұсынылған конфигурация экзоскелет пен аяқ арасындағы көлденең сәйкессіздікті азайтып, артық күштердің әсерін төмендетті және жүру циклінің барлық кезеңінде тұрақтылықты арттырды. Зерттеу нәтижелері биомиметикалық тізе буыны механизмі жүруді оңалту тиімділігін едәуір арттыра алатынын көрсетті. Бұл жұмыс клиникалық қолдануға арналған, биомеханикалық тұрғыда дәл және энергия үнемдейтін жаңа буын экзоскелеттерін әзірлеуге негіз қалайды.

Түйін сөздер: экзоскелет, тізе буыны, оңтайландыру, биомеханика, оңалту.

Оптимизация коленного сустава для медицинских экзоскелетов: Повышение биомеханической эффективности при реабилитации походки

Даулетбаев Ш. [1*], Карибжанова С. [2]

[1] Научный сотрудник, Робототехника и искусственный интеллект, Назарбаев Университет, Астана, Казахстан. E-mail: shyngys.dauletbayev@alumni.nu.edu.kz

[2] Научный сотрудник, Школа Медицины, Назарбаев Университет, Астана, Казахстан. E-mail: saule.karibzhanova@nu.edu.kz

Резюме

Нарушения функций нижних конечностей, вызванные неврологическими или опорно-двигательными заболеваниями, часто приводят к ограничению подвижности и нарушению походки. Медицинские экзоскелеты все чаще применяются в реабилитации для поддержки пациентов во время восстановления походки, снижения нагрузки на физиотерапевтов и повышения эффективности терапии. Однако традиционные механизмы коленного сустава с одной осью вращения не способны точно воспроизводить сложную биомеханику человеческого колена, что вызывает к смещению суставов и дискомфорт у пациента во время занятий. Целью данного исследования является разработка и оптимизация биоинспирированного механизма коленного сустава для медицинского экзоскелета с целью повышения биомеханической эффективности, улучшения соответствия траектории естественного движения и обеспечения безопасности и комфорта пациента во время реабилитации. Предложенная конструкция основана на данных магнитно-резонансной томографии коленного сустава здорового взрослого человека. Были разработаны две механические конфигурации: механизм с некруглой зубчатой передачей и механизм с подшипниками, перемещающимися по изогнутой поверхности. С помощью CAD-моделирования проведены симуляции для оценки кинематики сустава, распределения крутящего момента и механической устойчивости при реалистичных условиях шага. Профиль кривизны латерального мыщелка бедренной кости использовался для воспроизведения естественной траектории сгибания и разгибания колена. Результаты моделирования показали, что предложенный биоинспирированный механизм коленного сустава обеспечивает более плавное движение и равномерное распределение крутящего момента по сравнению с традиционной конструкцией с одной степенью свободы. Конфигурация уменьшает боковое смещение, снижает паразитные силы в местах контакта экзоскелета с конечностью и повышает механическую устойчивость на протяжении всего цикла шага. Проведенное исследование подтверждает, что использование биоинспирированного механизма коленного сустава может значительно повысить эффективность реабилитации походки. Полученные результаты служат основой для разработки нового поколения экзоскелетов, отличающихся биомеханической точностью, энергоэффективностью и безопасностью при клиническом применении.

Ключевые слова: экзоскелет, коленный сустав, оптимизация, биомеханика, реабилитация.

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