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Original article

Kinematic Performance Assessment of a Cable-Driven Elbow–Wrist Exoskeleton for Upper Limb Rehabilitation

Sharafatdin Yesirkepov [1*], Adilet Toleshev [2], Shylmyrza Ussen [3], Igembay Yerbolat [4], Serik Didar [5], Murat Alibek [6]

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[1] Research Assistant, Nazarbayev University, Astana, Kazakhstan. E-mail: sharafatdin.yessirkepov@nu.edu.kz
[2] Research Assistant, Nazarbayev University, Astana, Kazakhstan. E-mail: adilet.toleshev@nu.edu.kz
[3] PhD Student, Satbayev University, Almaty, Kazakhstan. E-mail: u.shylmyrza@satbayev.university
[4] PhD Student, Satbayev University, Almaty, Kazakhstan. E-mail: y.igembay@satbayev.university
[5] Junior researcher, Satbayev University, Almaty, Kazakhstan. E-mail: d.serik@satbayev.university
[6] Senior-lecturer, Astana IT University, Astana, Kazakhstan. E-mail: murat.alibek@astanait.edu.kz

***Corresponding author**: sharafatdin.yessirkepov@nu.edu.kz

Abstract

The aim: To evaluate the kinematic performance of a cable-driven elbow-wrist exoskeleton intended for upper limb rehabilitation in orthopaedic and post-traumatic conditions.

Methods. A four-degree-of-freedom cable-driven exoskeleton was designed to assist elbow flexion-extension and multi-axis wrist motion. To reduce distal inertia and minimize joint misalignment commonly associated with rigid transmission systems, a cable-based actuation architecture was implemented. The elbow mechanism was configured as a single-degree-of-freedom joint powered by two antagonistic motors enabling bidirectional torque generation and modulation of joint stiffness through co-contraction principles. The wrist module provided three rotational degrees of freedom actuated by four tendons, where three cables-controlled roll and pitch motions and a diagonally oriented cable enabled yaw rotation. Kinematic modeling was performed using homogeneous transformation matrices to establish forward and inverse kinematic relationships from the proximal fixation point to the distal platform. Numerical simulations were conducted in MATLAB, followed by experimental validation on a scaled prototype. Cable displacement responses were compared with theoretical inverse kinematic predictions throughout the operational workspace.

Results. The developed system demonstrated consistent agreement between theoretical modeling and experimental measurements. The elbow module achieved controlled flexion and extension within a range from minus sixty to sixty degrees, with stable bidirectional motion and predictable cable displacement patterns. The wrist mechanism preserved smooth multi-axis rotation and maintained mechanical transparency across roll, pitch, and yaw movements without evidence of kinematic singularities within the tested workspace. Experimental results confirmed accurate mapping between joint angles and cable actuation lengths, supporting the validity of the proposed kinematic model.

Conclusion. The proposed cable-driven elbow–wrist exoskeleton demonstrates reliable kinematic performance and reduced mechanical inertia compared to rigid transmission systems. The validated modeling framework establishes a foundation for the future implementation of hybrid position and torque control strategies in orthopaedic upper limb rehabilitation technologies.

Keywords: exoskeleton devices, upper extremity, rehabilitation, biomechanics, kinematics, robotics.

1. Introduction

Upper limb dysfunction is a frequent consequence of orthopaedic trauma, postoperative immobilization, peripheral nerve injury, and degenerative joint disorders. Restoration of elbow and wrist mobility is essential for recovering functional independence, as these joints play a central role in positioning and stabilizing the forearm during daily activities. In recent years, upper-limb exoskeletons have gained increasing attention in rehabilitation, assistive, and human augmentation applications due to their ability to provide controlled and repetitive motion while operating in close physical interaction with the user. Clinical research have reported that robot-assisted rehabilitation can improve motor function recovery of the upper limb after stroke. Early clinical studies using robotic therapy systems such as MIT-MANUS demonstrated measurable improvements in motor function of the affected arm following repetitive robot-mediated training [1]. A systematic review and analysis which includes several randomized controlled trials presented that robot-assisted training positively influence arm motor function in comparison with traditional therapy [2]. Unlike industrial robotic systems, wearable elbow devices must function under uncertain and variable human dynamics, which places significant demands on both mechanical design and control strategies.

Control strategies for upper-limb and elbow exoskeletons have traditionally relied on either position-based or torque-based approaches [3]. Position control is widely adopted because of its simplicity and its capacity to ensure accurate trajectory tracking; however, when applied to wearable systems, it may result in stiff interaction and reduced adaptability to the user's natural motion [4]. To address these limitations, torque-based, impedance, and admittance control methods have been introduced to enhance compliance and safety during human–robot interaction [5]. Although these approaches improve interaction quality, they may compromise positional accuracy or stability when precise motion guidance is required [5]. Consequently, several studies have emphasized the limitations of exclusively position- or torque-based control, motivating the development of hybrid strategies that integrate the advantages of both paradigms [6].

To bridge the gap between clinical settings and home use, recent research has prioritized the development of low-cost exoskeleton arms specifically tailored for rehabilitation, ensuring that financial constraints do not limit patient recovery [7]. Beyond mere affordability, the effectiveness of these devices relies heavily on their mechanical alignment with the user's physiology. Recent implementations have emphasized using specific anthropometric data to customize robot dimensions, which ensures a better ergonomic fit and safer joint alignment during repetitive exercises [9].

The evolution of these systems also involves the integration of sophisticated control and actuation strategies. Modern devices are increasingly incorporating intention detection techniques to foster active patient participation, allowing the exoskeleton to respond dynamically to the user's motor volitions rather than providing purely passive movement [8]. Furthermore, there is a growing interest in alternative hardware configurations, such as cable-driven designs, which offer a lightweight and flexible alternative for assistive tasks, though they require rigorous experimental evaluation to validate their performance in real-world scenarios [10]. By integrating these diverse approaches—ranging from cost-effective hardware to intent-based control—the next generation of upper-limb exoskeletons aims to provide more effective and inclusive rehabilitation solutions.

Beyond control methodology, the mechanical actuation architecture plays a critical role in elbow exoskeleton performance, particularly in systems involving close physical human–robot interaction. Conventional rigid transmission mechanisms, such as geared electric drives, increase reflected inertia and sensitivity to joint misalignment, potentially reducing mechanical transparency and user comfort [11]. As an alternative, cable-driven actuation has been widely adopted in upper-limb exoskeletons because it enables remote actuator placement, reduces distal mass, and introduces inherent mechanical compliance [12].

Within cable-driven systems, antagonistic actuation where two cables generate opposing torques about the same joint allows bidirectional torque generation and supports joint stiffness modulation through co-contraction [13,14]. These characteristics make antagonistic cable-driven mechanisms particularly suitable for elbow exoskeletons that aim to combine accurate motion control with safe and compliant physical interaction.

Despite these advancements, comprehensive kinematic modeling and experimental validation of multi-degree-of-freedom cable-driven elbow–wrist exoskeletons remain limited. In particular, the integration of an antagonistic elbow mechanism with a tendon-based multi-axis wrist module requires rigorous kinematic analysis to ensure predictable motion transmission and coordinated joint behavior.

Therefore, the aim of this study was to develop a laboratory-scale four-degree-of-freedom cable-driven elbow–wrist exoskeleton and to evaluate its kinematic performance through mathematical modeling and experimental validation.

2. Materials and methods

Study design

This study was an experimental laboratory-based engineering validation of a four-degree-of-freedom cable-driven elbow–wrist exoskeleton. The investigation focused on mechanical design and kinematic modeling, followed by prototype-based validation. No human participants were involved.

Mechanical Design of the Exoskeleton

The proposed mechanism is a laboratory-developed miniature prototype of a four-degree-of-freedom exoskeleton robot designed for preliminary mechanical testing and kinematic assessment. The prototype was modeled using SolidWorks software to ensure precise geometric alignment of structural components.

The system consists of:

- a one-degree-of-freedom elbow joint;
- a three-degree-of-freedom wrist joint.

Figure 1 provides a direct comparison between the mechanical design of the exoskeleton and the human arm it is intended to assist.

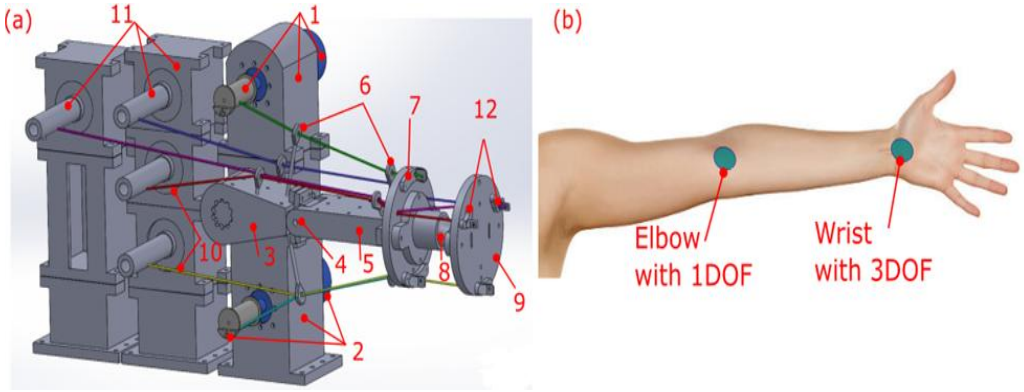

Figure 1 - Comparison between the modeled robotic arm and a human arm: a) 3D assembly designed in SolidWorks: 1 - Upper elbow motor assembly that Includes an EC Maxon motor, a winding shaft, and a motor bracket; 2 - Lower elbow motor assembly; 3 - Brachium (Upper arm) segment; 4 - Elbow articulation joint; 5 - Antebrachium (Forearm) segment; 6 -Cable anchor points; 7 - Wrist base featuring elbow cable connections; 8 - Wrist spherical joint; 9 - Platform interface; 10 - Actuation cables; 11 - Wrist motor assembly: Comprising QB motors, a drive shaft, and a motor housing; 12 - Wrist-specific cable attachments; b) The anatomical human arm used for reference

Elbow Mechanism

The elbow joint is actuated by two antagonistic motor assemblies (upper and lower). This configuration enables bidirectional torque generation and allows joint stiffness modulation through controlled co-contraction of opposing cables. The antagonistic cable-driven architecture was selected to enhance compliance and reduce distal inertia, which is essential for rehabilitation-oriented wearable systems.

Cable anchor segments are equipped with spherical joints that allow consistent cable displacement while maintaining alignment even under slack conditions. These spherical joints reduce friction and allow the cables to rotate freely during complex joint movements, thereby improving mechanical efficiency and transmission smoothness.

Wrist Mechanism

The wrist mechanism is actuated by four tendons connected to a distal platform interface. Three cables facilitate roll and pitch rotations, while a fourth diagonally oriented cable generates torque for yaw adjustment. The three primary cables are uniformly spaced, and their attachment points form the vertices of an equilateral right triangle on the moving platform.

This tendon-based design reduces distal mass and enhances system wearability, which is advantageous for upper limb rehabilitation applications.

Kinematic Modeling

The kinematic architecture of the device was established using homogeneous transformation matrices to define the spatial relationship between the stationary upper arm base and the functional segments of the exoskeleton.

A fixed coordinate system was defined: Frame 0: stationary shoulder reference; Frame 1: static elbow reference; Frame 2: rotating elbow frame;

Elbow Kinematics

The elbow joint was modeled as a pure rotational transformation about the x-axis by an angle θ_1, representing flexion-extension motion. The transformation from Frame 1 to Frame 2 is therefore defined as a single-axis rotation.

To reach the wrist base (Frame 3), a translation d_0 along the y-direction of Frame 2 was applied. Subsequent translations defined the cable attachment geometry:

- Translation d_1 along the z-direction;
- Translation $-d_2$ along the y-direction.

These sequential transformations resulted in Frame 5, which defines the attachment point of the first cable on the elbow platform. The spatial relationship between Frame 1 and Frame 5 was derived by multiplying the individual transformation matrices.

The cable displacement between Frames 5 and 6 was determined by solving the inverse kinematics problem. This displacement corresponds to the cable length change subtracted from the reference length of the cable.

Antagonistic Cable Configuration

To complete the antagonistic setup, a symmetrical lower assembly was introduced. Frames 9 through 13 represent the mirrored configuration of the upper motor and cable system. Sequential translations defined the lower cable attachment geometry, and the displacement between Frames 10 and 11 determined the required cable length variation for the second motor.

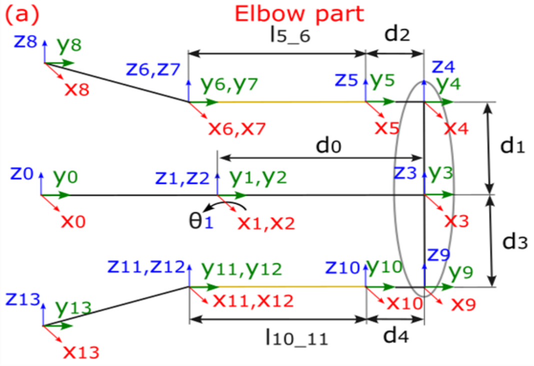

Figure 2 (a) - Schematic representation of the robotic arm (elbow part), illustrating the spatial configuration of coordinate frames, joints, structural links, and the cable-driven transmission system

This symmetrical configuration enables controlled bidirectional torque generation at the elbow joint.

Wrist Kinematics

The wrist assembly consists of a base and a moving platform connected by a central link of length h. Frames 3 and 19 were defined at the centers of the base and moving platform, respectively.

A spherical joint was incorporated between these components. To model this structure:

- A translation of $h/2$ along the y-axis defined an intermediate frame;
- A three-axis rotational transformation represented roll, pitch, and yaw about the x-, z-, and y-axes;

- A final translation of h/2 along the y-axis completed the transformation sequence.

The composite transformation matrix defined the spatial relationship between the wrist base and moving platform.

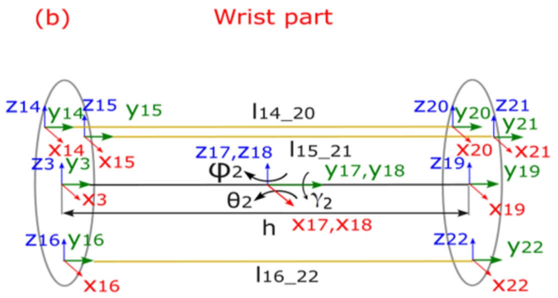

Figure 2 (b) - Schematic representation of the robotic arm (wrist part), illustrating the spatial configuration of coordinate frames, joints, structural links, and the cable-driven transmission system

Cable attachment points on the wrist platform were determined using additional transformation matrices. By solving the inverse kinematics equations for the parallel cable-driven mechanism, the required cable lengths for roll, pitch, and yaw movements were calculated.

Experimental Validation

A laboratory prototype was constructed to validate the proposed kinematic model. Controlled joint rotations were introduced at the elbow and wrist, and corresponding cable displacements were measured. The experimentally obtained cable length variations were compared with theoretical predictions derived from the inverse kinematic model across the defined operational workspace.

Agreement between experimental measurements and model predictions was used to evaluate the accuracy and consistency of the proposed kinematic formulation.

Ethical Considerations

This study involved mechanical modeling and prototype testing only. No human participants, patient data, or biological materials were used. Therefore, ethical approval was not required in accordance with institutional and national research regulations.

3. Results

Overall Kinematic Validation

The experimental evaluation assessed the relationship between joint rotations and corresponding cable displacements in both the elbow and wrist mechanisms. The results quantified the operational workspace and confirmed the predictable behavior of the cable-driven architecture.

The cable-driven actuation system enabled remote actuator placement while maintaining consistent motion transmission across the defined rotational ranges. Measured cable displacements demonstrated stable and repeatable trends throughout the tested workspace.

Elbow Mechanism

The kinematic assessment of the elbow module focused on the relationship between the elbow rotation angle θ1 and the displacement of the antagonistic cables.

During the upward lifting motion (Figure 4), as the elbow angle increased from minus sixty to sixty degrees, the displacement of the upper cable dL (5–6) increased progressively, while the displacement of the lower cable dL (10–11) decreased correspondingly. During the downward motion, the opposite pattern was observed: the upper cable displacement decreased as the lower cable displacement increased.

This reciprocal displacement behavior confirmed the functional symmetry of the antagonistic actuation mechanism and demonstrated consistent bidirectional cable response across the tested range of elbow motion.

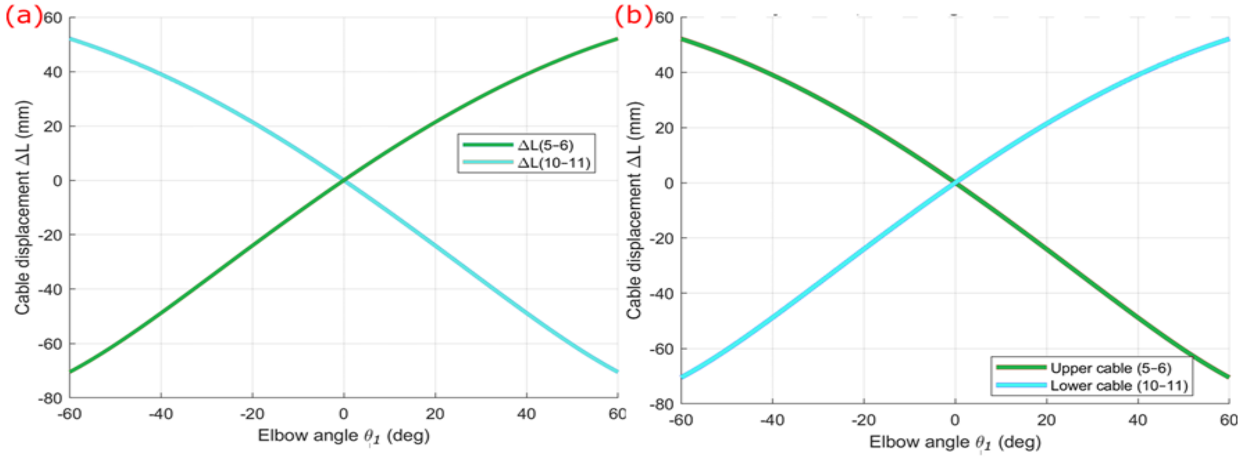

Figure 4 - Graphs of elbow rotation with respect to the antagonistic cable displacements: (a) upward lifting; (b) downward putting

Wrist Mechanism

The wrist mechanism was evaluated across roll, pitch, and yaw rotational movements with respect to the four cable displacements (Figure 5).

During roll motion, cables 16–22 and 15–21 exhibited opposing linear displacement trends.

During pitch motion, cables 14–20 and 15–21 demonstrated symmetrical displacement curves relative to platform rotation.

Yaw rotation produced a smaller displacement range compared to roll and pitch, typically between minus eight millimeters and six millimeters.

Across all three rotational axes, cable displacement patterns remained continuous and consistent within the defined operational workspace.

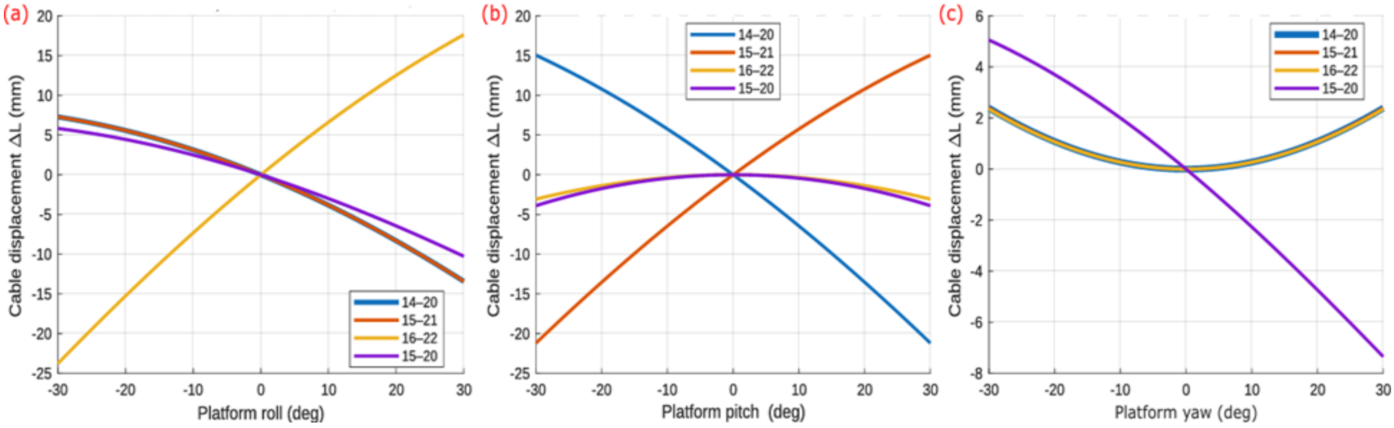

Figure 5 - Graphs of wrist joint rotation with respect to four cable displacements. Rotations represent the following directions: (a) roll; (b) pitch; (c) yaw

4. Discussion

The present study developed and experimentally validated a cable-driven elbow–wrist exoskeleton designed to provide accurate motion transmission while maintaining mechanical compliance suitable for rehabilitation applications. The results demonstrated predictable and symmetrical cable displacement behavior across the defined operational workspace for both elbow and wrist mechanisms, supporting the correctness of the proposed kinematic model. For the elbow module, the antagonistic cable configuration produced reciprocal displacement patterns during flexion and extension. This behavior confirms the mechanical feasibility of generating bidirectional torque through opposing cable actuation. The symmetrical response observed during upward and downward movements indicates stable torque transmission and consistent geometric alignment.

Such antagonistic architecture mimics the functional principle of human muscle pairs, where agonist–antagonist activation enables both motion generation and joint stabilization. This biomimetic approach is supported by [4], who emphasized that mimicking human muscle dynamics through variable stiffness is essential for natural human-robot interaction. Furthermore, the use of cables instead of rigid links aligns with the findings of [12], who demonstrated that cable-driven differentials significantly enhance the transparency of upper-limb rehabilitation devices by decoupling motor mass from the moving segments. This reduction in distal mass is a critical factor; as noted by [12], minimizing joint misalignment and reflected inertia is vital to preventing secondary injuries during robotic therapy.

The wrist mechanism demonstrated coordinated multi-axis motion through a four-cable tendon-driven configuration. The observed linear displacement trends during roll and pitch rotations confirm effective force distribution among the primary cables. The comparatively smaller displacement range during yaw rotation reflects the geometric constraints of the platform-based parallel structure. Importantly, no discontinuities or irregular cable behavior were observed within the tested workspace, indicating mechanical transparency and predictable kinematic coupling. This stability is consistent with the optimized cable-driven shoulder-elbow designs proposed by [13], which utilize tendon tension to maintain a singularity-free operational workspace.

One of the principal advantages of the proposed design lies in the cable-driven actuation strategy. By relocating actuators proximally, distal mass and reflected inertia are reduced compared with rigid transmission systems. Lower inertia at the joint level may improve wearability and comfort, which are critical factors in orthopaedic rehabilitation devices intended for prolonged use. This design choice is further validated by [5], who argued that adaptive impedance control—made possible by compliant transmission—is superior for assisting patients with variable biological signals. Additionally, the incorporation of spherical joints at cable anchor points enhances alignment and reduces friction during complex joint maneuvers.

The integration of these mechanical features provides a foundation for more advanced control schemes. As demonstrated by [6], hybrid position/force control is particularly effective in exoskeletons when the mechanical structure is lightweight enough to allow for rapid corrective movements. Furthermore, the ability to estimate and modulate stiffness via antagonistic cables, as explored by [13], ensures that the device can adapt to the patient's specific stage of recovery, shifting from rigid guidance to high-compliance assistance. While the current study focused on mechanical modeling and prototype validation without human subjects, the validated kinematic framework provides a robust basis for implementing these hybrid control algorithms in future clinical trials.

The developed cable-driven architecture addresses a critical gap in wearable robotics by balancing kinematic accuracy with mechanical safety. As noted by [15], cable-driven systems offer a distinct advantage over rigid-link counterparts by providing a high power-to-weight ratio, which is essential for patients with significant muscle weakness. The antagonistic configuration used in the elbow module not only mimics biological muscle pairs but also allows for the implementation of safety-oriented control strategies. [16] demonstrated that such compliant transmission systems inherently protect the user from excessive torque, a feature that is paramount in post-traumatic orthopedic rehabilitation.

The reliability of the forward and inverse kinematic models established in this study provides the necessary framework for task-specific training, which was identified as a key factor in accelerating neuroplasticity and functional recovery in upper-limb patients [17].

5. Conclusions

This study developed and evaluated a four-degree-of-freedom cable-driven elbow–wrist exoskeleton and assessed its kinematic performance through mathematical modeling and prototype-based validation. The antagonistic cable-driven architecture reduced distal mass and joint-level inertia while enabling bidirectional torque generation at the elbow joint. The derived homogeneous transformation framework defined a consistent operational workspace and established the relationship between joint rotations and cable displacements. Experimental findings confirmed agreement between theoretical inverse kinematic predictions and measured cable length variations for both elbow and wrist mechanisms. The antagonistic configuration supported reciprocal cable behavior and enabled controlled joint motion across the tested range. The proposed mechanical design provides a validated structural foundation for further development of controlled and compliant upper limb rehabilitation systems.

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

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Author contributions. Conceptualization – K.O.; methodology – M.A.; examination – S.Y. and A.T.; formal analysis – S.U., Zh.S. and I.Y.; writing (original draft preparation) – M.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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Жоғарғы аяқ-қолды оңалтуға арналған тростық жетекті шынтақ–білезік экзоскелетінің кинематикалық көрсеткіштерін бағалау

Есіркепов Ш. [1*], Төлешев Ә. [2], Үсен Ш. [3], Игенбай Е. [4], Серік Д. [5], Әлібек М. [6]

[1] Ғылыми қызметкер, Назарбаев Университеті, Астана, Қазақстан. E-mail: sharafatdin.yessirkepov@nu.edu.kz
[2] Ғылыми қызметкер, Назарбаев Университеті, Астана, Қазақстан. E-mail: adilet.toleshev@nu.edu.kz
[3] PhD докторант, Satbayev University, Алматы, Қазақстан. E-mail: u.shylmyrza@satbayev.university
[4] PhD докторант, Satbayev University, Алматы, Қазақстан. E-mail: igembay@satbayev.university
[5] Кіші ғылыми қызметкер, Satbayev University, Алматы, Қазақстан. E-mail: serik@satbayev.university
[6] Аға оқытушы, Astana IT University, Астана, Қазақстан. E-mail: murat.alibek@astanait.edu.kz

Түйіндеме

Бұл зерттеудің мақсаты: ортопедиялық және жарақаттан кейінгі жағдайлардағы жоғарғы аяқ-қолды оңалтуға арналған тростық жетекті шынтақ–білезік экзоскелетінің кинематикалық көрсеткіштерін бағалау.

Әдістері. Шынтақтың бүгілуі–жазылуын және білезіктің көпбағытты қозғалыстарын қолдауға арналған төрт еркіндік дәрежесі бар тростық жетекті экзоскелет жобаланды. Қатты механикалық жүйелерде жиі кездесетін дистальды массаны азайту және буын сәйкессіздігін төмендету мақсатында тростық жетекті механизм қолданылды. Шынтақ буыны бір айналмалы механизм ретінде құрылып, екі антагонистік қозғалтқышпен жабдықталды, бұл екі бағытты айналу моментін қалыптастыруға және ко-қысқару қағидаты арқылы буын қаттылығын реттеуге мүмкіндік береді. Білезік модулі үш айналмалы қозғалысты қамтамасыз етеді және төрт сіңір арқылы іске қосылады. 3 трос айналу және еңкею қозғалыстарын басқарады, ал диагональды орналасқан трос бұрылу қозғалысын қамтамасыз етеді. Кинематикалық модельдеу біртекті түрлендіру матрицалары арқылы жүргізілді және буын бұрыштары мен тростардың орын ауыстырулары арасындағы тәуелділік анықталды. Сандық модельдеу MATLAB ортасында орындалды және кейіннен шағын көлемді прототипте тәжірибелік тексерумен расталды. Өлшенген трос орын ауыстырулары теориялық кері кинематикалық есептеулермен жұмыс аймағы бойынша салыстырылды.

Нәтижесі. Тәжірибелік нәтижелер теориялық болжамдар мен өлшенген трос көрсеткіштері арасында жоғары сәйкестікті көрсетті. Шынтақ механизмі -60 градустан 60 градусқа дейін тұрақты бүгілу және жазылу қозғалысын қамтамасыз етті. Білезік модулі 3 ось бойымен бірқалыпты айналу қозғалысын көрсетті және сынақ аймағында механикалық айқындықты сақтады. Модельдік және тәжірибелік трос орын ауыстырулары арасында елеулі ауытқулар анықталған жоқ, бұл ұсынылған кинематикалық модельдің дәлдігін растады.

Қорытынды. Әзірленген тростық жетекті шынтақ–білезік экзоскелеті қатты жетекті жүйелермен салыстырғанда төмен механикалық инерция мен сенімді кинематикалық көрсеткіштерді көрсетті. Ұсынылған конструкция және модельдеу тәсілі жоғарғы аяқ-қолды ортопедиялық оңалту технологияларында жетілдірілген басқару стратегияларын дамыту үшін берік механикалық негіз қалыптастырады.

Түйін сөздер: экзоскелет құрылғылары, жоғарғы аяқ-қол, оңалту, биомеханика, кинематика, роботтық технологиялар.

Оценка кинематических характеристик тросового экзоскелета для локтевого и лучезапястного суставов

Есиркепов Ш. [1*], Толешев А. [2], Усен Ш. [3], Игенбай Е. [4], Серік Д. [5], Алибек М. [6]

[1] Научный сотрудник, Назарбаев Университет, Астана, Казахстан. E-mail: sharafatdin.yessirkepov@nu.edu.kz
[2] Научный сотрудник, Назарбаев Университет, Астана, Казахстан. E-mail: adilet.toleshev@nu.edu.kz
[3] PhD докторант, Satbayev University, Алматы, Казахстан. E-mail: u.shylmyrza@satbayev.university
[4] PhD докторант, Satbayev University, Алматы, Казахстан. E-mail: y.igembay@satbayev.university
[5] Младший научный сотрудник, Satbayev University, Алматы, Казахстан. E-mail: d.serik@satbayev.university
[6] Старший преподаватель, Astana IT University, Астана, Казахстан. E-mail: murat.alibek@astanait.edu.kz

Резюме

Целью данного исследования являлась оценка кинематических характеристик тросового экзоскелета для локтевого и лучезапястного суставов, предназначенного для реабилитации верхней конечности при ортопедических и посттравматических состояниях.

Методы. Был разработан тросовый экзоскелет с четырьмя степенями свободы для поддержки сгибания и разгибания локтевого сустава и многоплоскостных движений лучезапястного сустава. Для снижения дистальной массы и уменьшения несоосности суставов, характерной для жестких механических систем, использована тросовая архитектура привода. Локтевой модуль выполнен как одностепенной вращательный механизм с двумя антагонистическими двигателями, что обеспечивает двунаправленное формирование крутящего момента и регулирование жесткости сустава за счет коактивации.

Модуль лучезапястного сустава обеспечивает три вращательных движения и приводится в действие четырьмя сухожилиями. Три троса управляют вращением и наклоном, а диагонально расположенный трос обеспечивает движение по оси поворота. Кинематическое моделирование выполнено с использованием однородных матриц преобразования для установления зависимости между углами суставов и перемещениями тросов. Численное моделирование проведено в среде MATLAB с последующей экспериментальной проверкой на уменьшенном прототипе. Измеренные перемещения тросов сравнивались с расчетами обратной кинематики в пределах рабочего пространства.

Результаты. Экспериментальные данные продемонстрировали высокое соответствие между теоретическими расчетами и фактическими перемещениями тросов. Локтевой механизм обеспечил стабильное сгибание и разгибание в диапазоне от минус шестидесяти до шестидесяти градусов. Модуль лучезапястного сустава обеспечил плавные вращательные движения по всем трем осям и сохранил механическую прозрачность в пределах исследованного рабочего пространства. Существенных расхождений между модельными и экспериментальными данными выявлено не было, что подтверждает корректность предложенной кинематической модели.

Выводы. Разработанный тросовый экзоскелет для локтевого и лучезапястного суставов продемонстрировал надежные кинематические характеристики и снижение механической инерции по сравнению с жесткими приводными системами. Предложенный конструктивный и моделирующий подход формирует прочную механическую основу для дальнейшей разработки усовершенствованных стратегий управления в ортопедической реабилитации верхней конечности.

Ключевые слова: экзоскелеты, верхняя конечность, реабилитация, биомеханика, кинематика, робототехника.