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Discussion Based on the Key Parameters About The Structural Design and Improvement Methods of Knee Exoskeleton Robots

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Abstract:

In lower limb rehabilitation treatment, the recovery and reconstruction of the knee joint have always been important and difficult points. Knee exoskeleton robots play a crucial role in this area. Patients can use exoskeleton robots to assist in limb movement and carry out recovery training. It can significantly improve the rehabilitation effect, the quality of life, and patients' lower limb motor function. Early knee exoskeleton robots have many defects and flaws, such as being too heavy, poor comfort, and taking up a large volume. This paper focuses on these key parameters and introduces the latest development status of knee exoskeleton robots. According to the optimization classification for different parameters, this paper introduces the structural design and control strategies of such robots. The optimization degree and practicality of different designs are explored. In addition, this paper also proposes the optimization space of the existing key parameters of knee exoskeleton robots. This paper also predicts some possible future development directions, such as high-performance reducers, soft designs driven by cables.

Keywords: Exoskeleton robot; Knee joint; Key parameters

1. Introduction

Nowadays, exoskeleton robots are widely used in medical recovery and other fields. According to statistics from Fortune Business Insights, the global rehabilitation robot market size reached 529.8 million US dollars in 2018, and the expectation is that it will reach 2.6173 billion US dollars by 2026 [1]. The compound annual growth rate was about 22.1% during this period. The continuously expanding market promotes the optimization and development of exoskeleton robots. Among them, the optimization of knee exoskeleton robots is particularly crucial in lower limb rehabilitation treatment. However, the disadvantages in key technical parameters such as weight and volume still limit their large-scale popularization and application. Considering these factors, it is very important to review the optimization design of existing knee exoskeleton robots.

Yao introduced common lower limb rehabilitation robots and classified and summarized them according to their functional characteristics [2]. His paper discusses the differences and characteristics of different optimization methods, and analyzes the future development trends of the design directions of specific parameters. This paper introduces some new creations of knee exoskeletons. Shi showed the application of Bowden cables in knee robots [1]. Sarkisian and his group established a new structure with a self-aligning mechanism and verified its effectiveness through experiments. It can be attached to normal knee exoskeletons.

This paper will conduct a review in the following order: summarize the optimized design of the main performance parameters of knee exoskeleton robots; the control strategies of relevant structural designs; and look ahead to the optimization methods of key parameters in the future.

2 Optimization Design of Different Parameters

2.1 Diversified Lightweight Design Schemes of the Knee Exoskeleton Robot

2.1.1 Assessing high-capacity knee exoskeletons in walking: stiffness modeling and advanced control

The current knee exoskeletons face several issues, such as low control bandwidth, insufficient stiffness range, and discontinuous torque control. Baimyshev has designed a new lightweight knee exoskeleton and developed a quasi-constant drive conductor. The design focuses on using custom high-torque-density motors and low-pitch gears. The exoskeleton weighs only 2.1 kg per side (a total of 3.5 kg for both sides), significantly reducing the weight. A key aspect is the rigid modeling of the QDD conductor, which is compared with an exoskeleton based on series elastic actuation (SEA). The data shows that the QDD exoskeleton offers a higher stiffness control bandwidth (16 Hz, 100 Nm/rad), a wider stiffness range (0-350 Nm/rad), and higher torque tracking accuracy (root mean square error of 0.34 Nm, equivalent to 6.22% of the expected peak torque). Therefore, the QDD model outperforms traditional models in performance. Another focus is the development of a continuous torque controller based on stiffness, which can efficiently calculate biological torque in real-time.

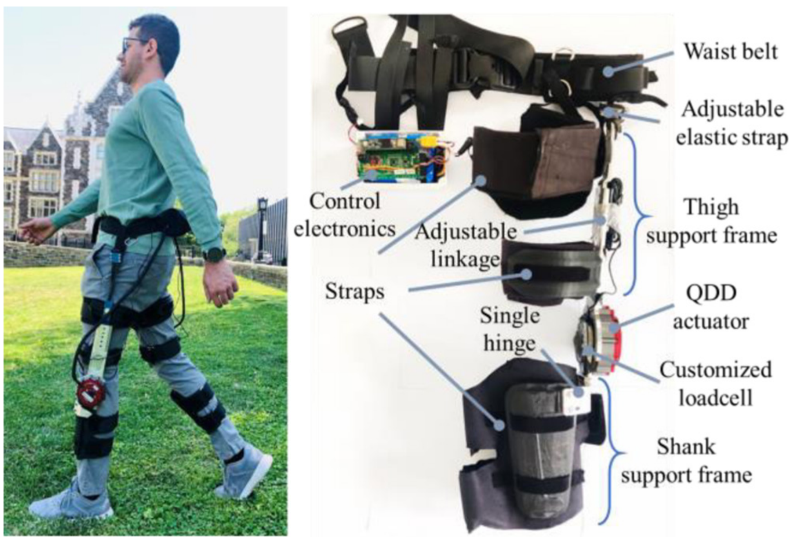

Fig. 1. The exoskeleton with QDD actuator [3]

In experiments, eight healthy subjects wearing the knee exoskeleton showed a reduction in their measured knee and ankle muscle activity by 8.60% to 15.22% compared to no assistance. Additionally, the average muscle activity of two knee flexors and one ankle plantarflexor was also reduced. The reduction was 1.92% to 10.24%. These data in Fig. 1 fully demonstrate that the exoskeleton can reduce muscle activity.

Baimyshev successfully designed a portable exoskeleton with the characteristics of lightweight, high stiffness, control bandwidth, and high torque tracking accuracy, which opened up a new direction for the development of exoskeleton technology. However, this stiffness model is only applicable to a few terrain conditions and needs further expansion. In the future, the auxiliary torque mode can be further optimized, and the adaptability of the controller to

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different terrains can be expanded.

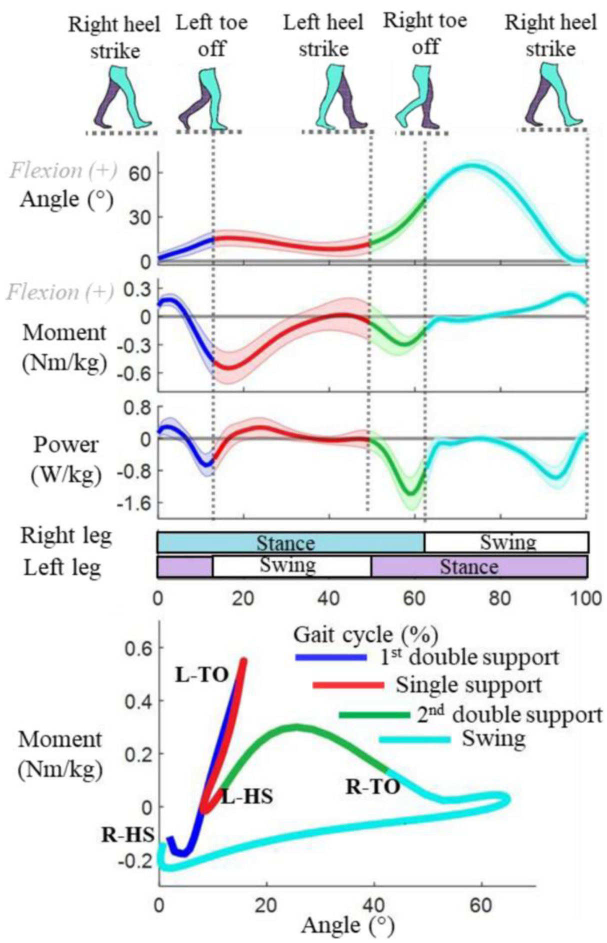

Fig. 2. The effect data diagram of the samples [3]

2.1.2 Design of a lightweight knee exoskeleton that can assist human movement and collect motion energy

Most existing exoskeletons rely on external power sources, leading to issues with limited battery life. This paper introduces a Bowden cable-driven knee exoskeleton using a single electromagnetic unit, which creatively combines auxiliary and energy harvesting functions through mode switching. Additionally, this exoskeleton can function as a knee shock absorber, with damping adjustable in real-time based on actual needs. The exoskeleton consists of a waist support, lower limb mounting components, and a Bowden cable drive system. The Bowden cable drive system compensates for changes in hip joint angles during walking, ensuring reliable motion transmission. During the modeling phase, Shi used the Lagrange method to establish dynamic equations, analyzed energy losses due to interactions, determined the transmission efficiency of the Bowden cable system, derived formulas for power generation, and analyzed power output under different loads. Six healthy subjects participated in the experiment, and the results showed that during the process of descending stairs, the average activity of thigh muscles decreased by 7.91%, with a maximum power generation of 3.2 W.

The exoskeleton designed in this paper has advantages in lightweight optimization, energy acquisition and auxiliary movement, which provides an important idea for the development of lightweight and sustainable exoskeleton The exoskeleton designed in this paper demonstrates significant advantages in lightweight optimization, energy acquisition, and movement assistance, offering a promising pathway for developing sustainable and low-burden exoskeletons. However, current limitations include the need for rigorous real-world validation of its energy harvesting efficiency during diverse walking conditions, potential trade-offs between extreme lightweighting and long-term structural durability, and the lack of extensive user trials to quantify the consistency of its movement assistance benefits across varied populations..

2.2 Some Bionic Designs to Achieve Better Freedom of Movement and Flexibility

2.2.1 The inadequacies of the traditional lower limb exoskeleton knee joint in terms of bionics and versatility

Yang Yiyong has proposed a new design for a planar two-degree-of-freedom parallel mechanism [4]. This design aims to enhance the biomimetic effect of knee joint movements, improve adaptability to different individuals, and ensure the system's safety and lightweight design by optimizing the structure and parameters of the mechanism. Below is a summary of the key points of this design.

Compared with the planar three-degree-of-freedom parallel mechanism (Fig. 2) and the planar two-degree-of-freedom parallel mechanism (Fig. 3), the latter is selected as the optimal solution due to its simple structure (4 motion components, 2 actuators), light weight, and low control difficulty. Its kinematic model is solved through position inversion and forward solving.

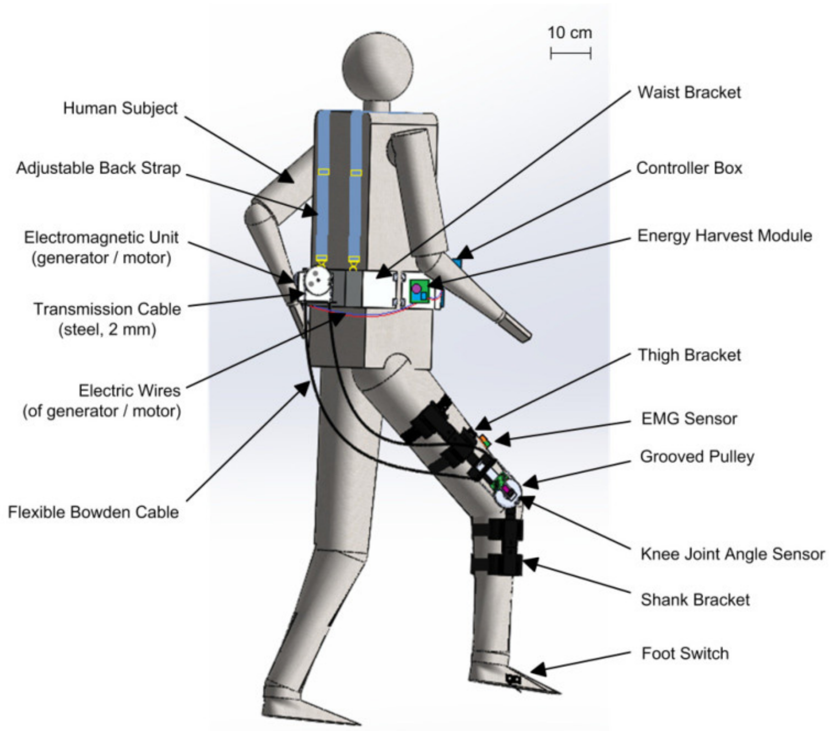

Fig. 3. The 3D model of the exoskeleton with Bowden Cable [5]

Work space and motion performance by analyzing the motion curve of the knee joint during normal walking (Fig. 4), it is verified that the workspace of the parallel mechanism can cover the bending and stretching trajectory of the knee joint. The performance of the mechanism is evaluated using the condition index (uu) and global flexibility index (EE) to ensure it stays away from singular posture points, thereby avoiding the risk of loss of control. Optimization objectives include work space coverage: Ensure that the movement trajectory of key points on the lower leg is within the working range of the mechanism; Adjustability: adjust the stroke of the active part (h1, h2h1, h2) to adapt to different personnel; Kinematic performance: The optimization of the span (aa) and the length of the connecting rod (l1, l2, l1, l2) is aimed at maximizing the condition index.

The final parameters are: a=100 mm, l1=67.26 mm, l2=86.03 mm, a=100 mm, l1=67.26 mm, l2=86.03 mm, with driving strokes of 45 mm and 70 mm, respectively. Simulation results show that compared to traditional single-hinge structures, this design significantly reduces the driving force, thereby reducing the system's weight. Bionics: The active parts drive the variable instantaneous motion of the knee joint, which is consistent with the principle of human muscle groups pulling bones, and can more realistically reproduce the flexion and extension trajectory of the knee joint. Universality: By adjusting the position of the active parts, the mechanism can adapt to different individual knee joint sizes (Fig. 5) without custom design. After measuring the trajectory of the user's knee , the system can automatically adjust the driving parameters to achieve personalized adaptation.

The planar two-degree-of-freedom parallel mechanism exoskeleton knee joint proposed in this paper surpasses traditional designs in biomimicry, lightweight design, and multifunctionality, making it particularly suitable for the rehabilitation training of patients with lower limb paralysis. Future research could further explore the design of hip joints or enhance human-machine interaction performance by integrating sensors and real-time control algorithms.

2.2.2 Bionic knee joint design scheme based on multi-factor fuzzy comprehensive evaluation

This article examines the current reliance on imported high-performance prosthetic knee joints in China and proposes a bionic knee joint design scheme based on a multi-factor fuzzy comprehensive evaluation [6]. The aim is to develop a core component of lower limb prosthetics with independent intellectual property rights, low cost, and reliable performance. Through functional decomposition, structural optimization, and motion simulation, the study achieves a bionic design for knee joint movement and stability. Below is a summary of the key points:

Architectural design. The Core design of the bending and

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stretching motion is realized by rotating the hydraulic cylinder, and the buffer ring and torsion spring are integrated to improve the damping effect; the microprocessor recognizes the road conditions behind and controls the stepper motor to adjust the hydraulic valve. Kinematics: The torque variation during the backward bending process was analyzed by 3D simulation (Fig. 5) to verify whether the peak torque is within the design range (F1 = 120 N, F2 = 240 N; F1 = 120 N, F2 = 240 N) to ensure the stability of the motion.

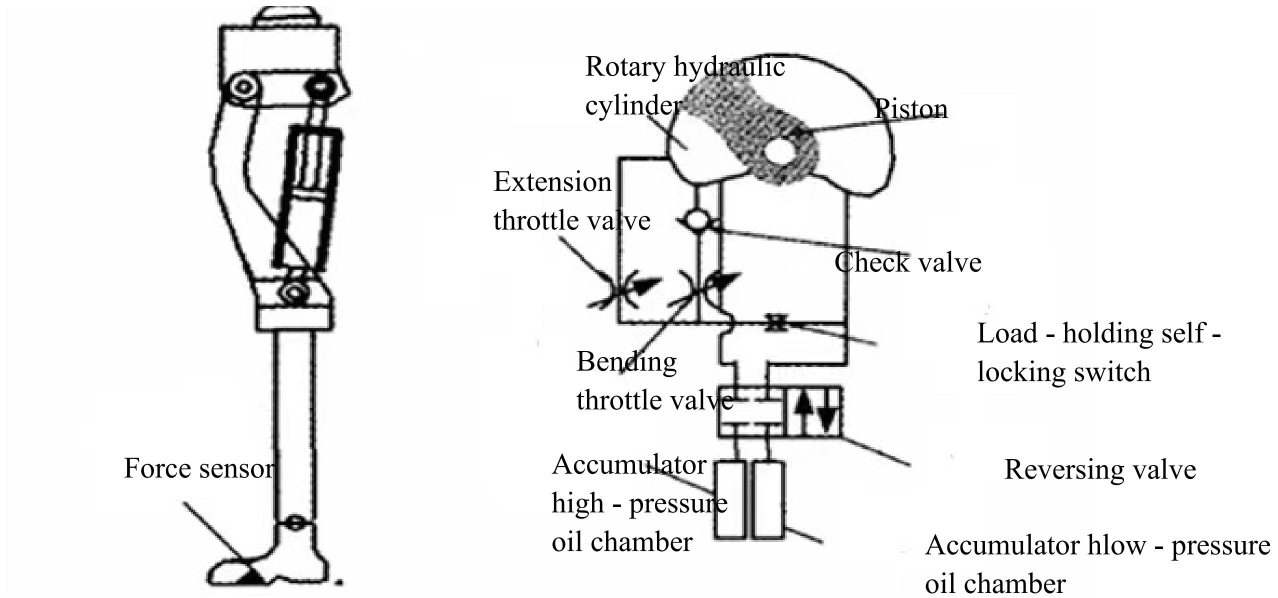

Fig. 4. Schematic diagram of the new knee joint control flexion and extension action system [6].

Performance advantages: no dead point, strong environmental adaptability (can adapt to a variety of road conditions), easy maintenance, size and cost better than similar foreign products The presented exoskeleton demonstrates significant performance advantages, including the elimination of kinematic dead points, robust environmental adaptability across diverse terrains, ease of maintenance, and superior size/cost efficiency compared to similar foreign products. However, current limitations include the lack of quantitative field data on long-term durability under sustained harsh conditions, potential compromises in peak torque output due to the compact design optimizing for size/cost, and the absence of formal user trials validating maintenance procedures for non-technical personnel. Future work will prioritize adaptive terrain control algorithms and advanced composites to enhance performance while maintaining compactness, alongside rigorous real-world validation.

2.3 New Design of Exoskeleton for the Knee Joint to Improve Comfort

2.3.1 Five-bar lower limb rehabilitation exoskeleton for enhanced human-machine compatibility

Currently, lower limb rehabilitation exoskeletons are primarily categorized into two types: rigid and flexible. Rigid exoskeletons simplify the knee joints to a single-axis rotation, which does not match the multi-axis rotation of the human knee. Flexible exoskeletons, on the other hand, fail to provide stable support for patients with lower limb movement disorders. To address these issues, which fail to adapt to patients with lower limb movement disorders. Jiang has innovatively designed a new knee exoskeleton, which consists of two mechanical legs. Each leg includes a gridle, thigh rod, knee five-bar mechanism, and three drive devices. The hip joint has one degree of freedom, the knee joint has two degrees of freedom, and the ankle joint is passive. The knee joint uses a five-bar mechanism and the rotating rod is driven by a rotary mechanism. A linear actuator drives the prismatic rod. The leg rods are adjustable in length to accommodate different user needs.

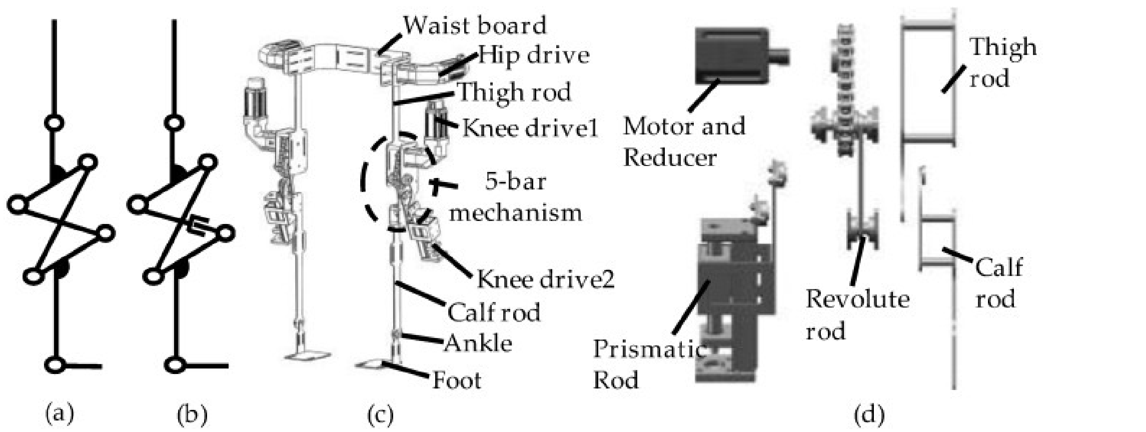

Fig. 5. Design and optimization of multiaxial knee lower limb rehabilitation exoskeleton [7]

The exoskeleton for the knee joint discussed in this paper employs a five-bar mechanism to accommodate the internal rotation angle (ICR) of different individuals' knee joints, thereby reducing discomfort caused by mismatches between the mechanical structure and human movement. By incorporating PID feedback control, it reduces the angle deviation caused by signal loss from the stepper motor, further enhancing the exoskeleton's performance and improving user comfort. Overall, this design makes the exoskeleton's gait more human-like, thus enhancing both wearing and using comfort. Although the five-bar mechanism enhances adaptability, it increases weight and compromises flexibility. Future designs should optimize the structural layout and implement lightweight design to improve flexibility and reduce volume.

2.3.2 The effect of powered knee exoskeletons with self-aligning mechanisms on comfort and performance

The key innovation of this paper is the significant effectiveness of the self-aligning mechanism, which significantly reduces users' limb reaction forces and moments, enhancing comfort and performance. This provides important insights for the design and application of powered exoskeletons. In terms of mechanical structure, the self-aligning mechanism of the powered knee exoskeleton used in this study has three passive degrees of freedom (pDOF). The mechanism operates in a prismatic-rotational-rotational (PRR) mode and is connected in series with an active rotational degree of freedom (flexion and extension). The pDOF is connected to the low-friction linear guide of the exoskeleton's lower leg section. The track is realized. Its slider is connected to a special rotary joint. The lower leg section features a C-shaped frame and adjustable straps, ensuring a secure fit for different users. The thigh section is connected to the user's legs via a flexible plastic shell with Velcro. Additionally, a 3D-printed locking system is designed to lock the self-aligning mechanism during the experiment.

The self-alignment mechanism plays a crucial role in enhancing comfort. When the self-alignment mechanism is activated (in the unlocked state), the unexpected forces and torques between the user and the exoskeleton are significantly reduced. In both standing and tracking tasks, the average peak values of certain forces and torques decrease by 95% to 97%. This reduces pressure on the user's joints and skin, thereby directly improving comfort. According to a questionnaire survey, the comfort score in the unlocked state for standing tasks is 15.3% higher than in the locked state, and in tracking tasks, this score is 11.4% higher [8].

Table 1. A chart of different new designs and analysis.

Key parameter		Innovative approaches	superiority Assessed
Lightweight design	[3]	Low gear ratio gears, Alignment drive exoskeleton; C-type continuous torque controller	High stiffness control bandwidth; High torque tracking accuracy; Reduced muscle activity
	[4]	Single electromagnetic unit; Borden cable transmission system	Real-time damping regulation; Good effects that contribute to exercise; Light

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Free degree	[5]	Planar two-degree-of-freedom parallel mechanism; Structural and parameter optimization	High biomimetic degree; light weight, strong versatility; The fourth driving force
	[6]	Multi-factor fuzzy comprehensive evaluation method; Bionic knee joint, rotating hydraulic cylinder	Strong environmental adaptability; easy maintenance, low cost
Amenity	[7]	Five-bar mechanism, anthropomorphic exoskeleton	Optimize performance; Improve comfort
	[8]	Self-aligning mechanism	Reduce stray force and torque; Improve comfort

3. Method Application

The introduction of Bowden cables offers significant advantages for exoskeleton design, reducing actuator count and overall weight. Furthermore, the use of flexible transmission materials mitigates joint and muscle compression, enhancing user comfort. Building upon cable-driven approaches, research from Changshu Institute of Technology demonstrates their application in end-position estimation [9]. Integrated sensors within the cable detect bending, generating voltage signals; a processing unit then calculates the actual bending angles using these signals and a preset model to determine the cable's end-position in space, enabling accurate spatial tracking. Similarly, the principles of bionics, as referenced by Yin Song, provide valuable insights applicable to the holistic design of knee exoskeletons, guiding aspects of this research and development effort for a high-efficiency rehabilitation knee exoskeleton [10]. Regarding structural configurations, while five-bar, two-degree-of-freedom exoskeletons enhance comfort and provide greater movement freedom, their mechanical complexity results in increased weight and bulk. Similarly, adding self-alignment mechanisms to traditional exoskeletons improves comfort but also contributes to added weight. The bionics referred to by Yin Song could be applied to the whole knee exoskeleton design too. This article applies bionics in multiple aspects to the research and development of a high-efficiency rehabilitation knee exoskeleton [10]. Table 1 summarizes the innovative approaches in lightweight design, degrees of freedom, and amenity, along with their demonstrated advantages.

In terms of structural design, the structure of the knee is discussed in depth. The tissues of the knee joints are simplified according to their functions during movement. Bones and muscles with similar functions are combined. For example, the fibula and tibia are regarded as one bone because they have similar functions, and several muscles are grouped. Based on this, a knee joint mapping model and a knee joint structure based on structure are constructed.

4. Conclusion

This article summarizes the optimization design of key parameters such as weight and degrees of freedom, and concludes the existing structural designs. It analyzes the advantages, disadvantages, and innovation points of various designs. Regarding lightweighting, Baimyshev proposes methods of high-performance gear drives and Bowden cables to reduce weight. The former has certain advantages in load-bearing, while the latter can greatly reduce the number of motors. Yang discusses how to increase the degrees of freedom of exoskeletons and proposes the idea of optimization based on bionic principles. Jiang provides the latest ideas on the issue of comfort: multi-link auxiliary structures and self-aligning mechanisms. This research fills the gap in the summary of optimization methods for some key parameters. It can provide ideas for improving specific parameters in the design of new knee exoskeletons, achieving targeted enhancements. In the future, there is hope to extend the optimization methods and designs in different parameter fields to other parameters or the whole of knee exoskeletons.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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