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Article

Study on dexterous structure and control of bio-inspired musculoskeletal robots in artificial intelligence environment

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Abstract: The design and development process of bio-inspired musculoskeletal robots in the artificial intelligence environment integrates mechanical design, control algorithms, real-time computing, variable sensing, and other fields of technology, which can provide effective mechanical support for the user's actions in the process of use, and has a broader application prospect in a number of fields. In the process of exoskeleton robots moving from experimental research and development to practical applications, the comfort of the use process is an important evaluation criterion. Therefore, from the perspective of user comfort, this paper takes the waist exoskeleton robot as the research object, and conducts a design study on the structure and control of the exoskeleton robot.

Keywords: artificial intelligence; bio-inspired; musculoskeletal robots; structural design; control

1. Introduction

Exoskeleton robots drive the user's limbs through its mechanical structure to provide movement assistance for the user's movement, or assist the user to complete specific actions. These remarkable devices are designed to enhance human capabilities, making them invaluable in a variety of applications. Imagine a world where individuals can regain mobility, strength, and independence thanks to these innovative technologies. Currently, exoskeleton robots are widely used in many fields such as medical aids, special equipment, logistics handling, etc. Their versatility allows them to adapt to different environments and tasks, making them essential tools in modern society. Compared with traditional manual work, the application of exoskeleton robots can effectively reduce the user's action load and make the work process safer and more efficient [1]. This is particularly important in settings where physical labor is required, as it helps to alleviate the strain on workers' bodies. For instance, in warehouses and factories, workers often face the risk of injury from repetitive movements or heavy lifting. By integrating exoskeleton technology, employers can significantly decrease the physical demands placed on their workforce, leading to fewer injuries and a healthier work environment. Moreover, this technology contributes to increased productivity, allowing workers to perform their tasks with greater ease and efficiency. In the context of aging population and industrialization, the demand for exoskeleton robots will increase day by day. As the global population ages, more individuals will require assistance with mobility and daily activities. Exoskeletons present a viable solution to support these individuals, enabling them to maintain their independence and improve their quality of life. Additionally, as industries continue to evolve and expand, the need for efficient and safe labor solutions becomes increasingly critical. Exoskeleton robots can bridge this gap, providing the necessary support to meet the demands of modern work environments.

Suit Bot, developed by LG CLOi Research & Development, is a portable, easy-to-wear assistive device equipped with freely rotatable joints and self-adjusting fixtures. These features simplify the process of putting on the device, allowing users to easily adapt to its use. The Suit Bot provides the user with a natural assistive device for walking, standing, and working in a variety of conditions. Its design realizes the goal of “supporting and reinforcing the user’s legs, improving mobility, and reducing the need for limb strength.” This is particularly beneficial for elderly individuals or those recovering from injuries, as it helps them regain their mobility and confidence in performing daily tasks. The ATOUN MODEL Y Series, developed by Panasonic’s ATOUN subsidiary, takes a different approach by utilizing a resin frame instead of the conventional metal frame. This innovation significantly reduces the weight of the device, making it more comfortable for users to wear for extended periods [2]. The devices operate in assist mode, walking mode, and braking mode, and automatically switch between each mode according to the user’s needs. This adaptability ensures that users receive the right level of support at any given moment, enhancing their overall experience and effectiveness while using the device. Cyberdyne’s HAL (Hybrid Assistive Limb) is another significant advancement in exoskeleton technology. This full-body assisted exoskeleton robot can be used to assist people with disabilities or semi-disabilities in walking and rehabilitation. One of its standout features is its ability to significantly reduce the pressure on the lumbar region while providing complete assistance [3]. This is crucial for users who may struggle with balance or strength, as it allows them to regain mobility and independence. The HAL not only aids in movement but also plays a vital role in rehabilitation, helping users improve their physical capabilities over time. Additionally, the lumbar exoskeleton robot PB1, developed by the Maibu Robotics team, exemplifies the advancements in exoskeleton design. This device is portable and breathable, achieved by reducing the weight of the mechanical components and minimizing the contact area between the product and the user’s body. Such thoughtful design simplifies the wearing process, making it more user-friendly. By effectively protecting the user’s lumbar region, the PB1 reduces the incidence of lumbar disorders that can arise from prolonged stooping and lifting. This focus on user comfort and health is essential, as it directly impacts the usability and effectiveness of the device. Through the research of existing exoskeleton robots, it is found that the update and optimization of current exoskeleton robots are mostly focused on the replacement of materials, optimization of modeling, and updating of accessories. While these improvements are important for enhancing performance, there is less emphasis on the improvement of the comfort of the user. This gap is significant, as comfort is a critical factor that can influence the overall effectiveness of exoskeletons. If a device is uncomfortable, users are less likely to wear it consistently, which undermines its intended benefits.

Based on this, this paper takes the waist exoskeleton robot as the research object from the perspective of user comfort. By focusing on user comfort, we can ensure that these devices not only assist users in their physical tasks but also promote their well-being and encourage regular use. A design study on the structure and control of exoskeleton robots is essential to address these comfort issues. By prioritizing comfort in the design process, we can create exoskeletons that users are eager to wear, maximizing their potential benefits and improving the quality of life for those who rely on them.

2. Application scenario analysis

At present, heavy equipment, catering logistics, medical rehabilitation and other fields still use manual lifting or carrying to complete the work content, staff handling or lifting and other actions are very easy to cause joint and muscle strain, especially the incidence of lower back pain has been rising year by year, this work caused by the lower back disease has also caused widespread concern in the medical and health industry [4]. Aiming at the phenomenon of high incidence of lower back pain and high incidence of lumbar diseases in the logistics industry, using the analysis, it can be found that the operation process and operation posture will have a greater impact on the low back load. Therefore, this exoskeleton robot takes the airport and other places that need to be handled manually as the working scenario, and by designing the lumbar exoskeleton robot for the logistics handling field, it can improve the working safety and comfort by reducing the load on the user's lumbar region. The force situation before and after the lumbar support is shown in **Figure 1** below.

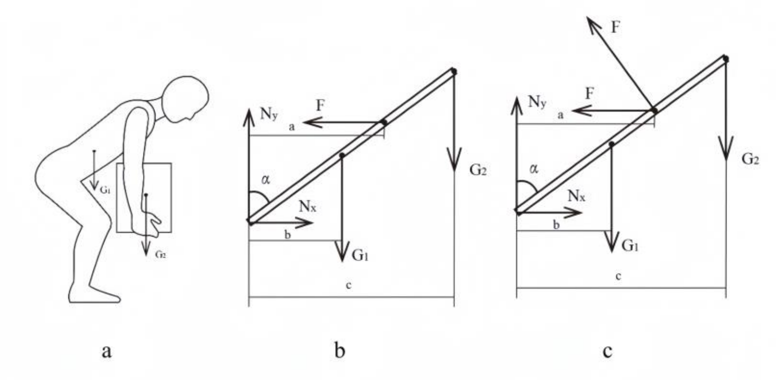

Figure 1. Force before and after lumbar assistance.

As can be seen from the figure, the human body in the handling process in addition to bear the body weight G_1 need to bear the weight of the weight of the additional gravity G_2. without the use of assistive equipment to lift heavy objects, where G_1 for the body weight, G_2 for the additional load weight and N on behalf of the lumbar spine joint reaction force, N_X, N_Y for the decomposition of the joint reaction force in the horizontal and vertical direction of the force, F on behalf of the arm, back muscles and abdominal muscles of the combined force. The moment M applied to the lumbar spine is given by the formula:

$$M = G_1 \times b + G_2 \times c \tag{1}$$

The equation for the moment M1 applied to the lumbar spine after applying the assist is:

$$M_1 = G_1 \times b + G_2 \times c - F \times \cos(\frac{\pi}{2} - \alpha) \times \alpha \tag{2}$$

Analyzing the change in moment before and after the use of the booster device, it can be seen that by adding vertical tension to the back it is possible to significantly reduce the load on the lower back during operation.

3. Comfort design

3.1. Force process analysis

The force analysis of the waist exoskeleton robot mainly includes the analysis of the mechanical structure of the prototype, the counterweight method and the location of the force, the simulation of the user's digital human model with different physiological parameters through the Jack Human Factors Simulation Software, the assignment of different force conditions to the digital human and the analysis of force conditions, the analysis of the shortcomings of the design in the prototype and the proposal of the improvement plan.

Ten subjects were selected to participate in the implicit association test voluntarily, of which the age distribution was 20~30 years old, six were male and four were female. The reaction time and judgment results of different subjects were recorded and imported into the data statistics software for analysis, and the results were used as the basis for exoskeleton robot design tendency analysis. In order to make the structural dimension design of the waist exoskeleton robot more in line with the requirements of user experience and comfort, Jack Human Factors Simulation Software is firstly applied to construct the user's digital human model. In the three-dimensional digital human database of Jack software, according to GB1000–1988 "Chinese Adult Human Body Dimensions", the digital human models of 5%, 10%, 50%, 90% and 95% are built in order.

By analyzing the use process of the waist exoskeleton robot, it can be found that the structural components of the prototype such as the back plate, waist connection plate and leg connection plate are in contact with the user's body for a long period of time and remain relatively stationary, therefore, the size design of the above structural components will have a greater impact on the comfort of the use process, and to ensure that the structural dimensions of the lumbar-assisted exoskeleton robot match the user's physiological dimensions will greatly enhance the comfort of the use process [5]. The physiological parameters of each part of the digital human were generated using Jack software, as shown in **Figure 2**.

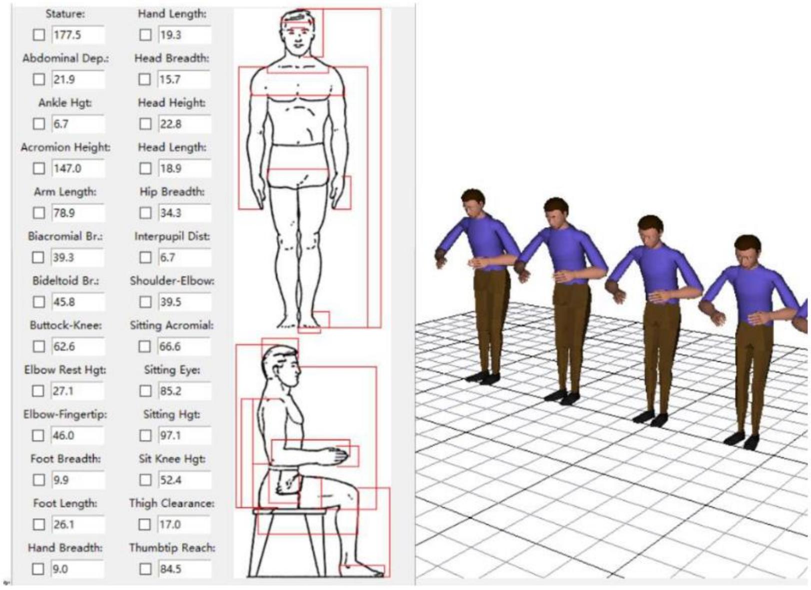

Figure 2. Physiological parameters of each part of the digital human.

Analyzing the dimensions of each part of the digital human with different occupancy ratios, it is found that there are problems of unreasonable dimensions during the structural design process of the prototype design, which are mainly reflected in the problems of excessive length of the leg connecting plate, insufficient length of the waist connecting plate, and inappropriate design of the width of the back plate, etc. Modifications are proposed for the dimensions of the above connecting components, as shown in **Table 1**.

Table 1. Modification of structural dimensions of connection components.

	Prototype size/(mm)	Modified size/(mm)
Length of leg attachment plate	230	190
Waist connection plate length	390	430
Waist connection plate width	85	55
Backplane width	150	100

The principle of the lumbar exoskeleton robot booster is to simulate the principle of hip joint movement through the drive assembly, the leg connection plate and the back plate are fixed with the user's body through the binding device, and the rotation of the drive assembly drives the back plate movement, which generates a lifting and pulling force on the user's back to reduce the user's movement load [6]. Therefore, in the actual use process, the height of the back plate structure of the waist exoskeleton robot is determined by the position of the force application point of the assistive device. In this paper, we use Jack Human Factors simulation software to construct a physiological parameter digital human, and improve the height of the back plate by combining the simulation results, and the final height of the back plate is 340 mm. The height of the backplane before and after the improvement is shown in **Table 2** below.

Table 2. Improved front and rear back panel heights.

	Back size range	Original Backplate Height	Improved back panel height
Height/mm	346–408	281	340

3.2. Interaction process analysis

The exoskeleton robot interaction process design evaluation focuses on analyzing the user's visual field and upper extremity reach to ensure that the operating components are within the user's comfortable visual and upper extremity range of motion. In order to achieve these goals, it is important to ensure that the interaction interface is always within the user's visual field during use [7]. In the horizontal direction, there is a central clear visual area of 60° with the best observation effect and a maximum visual field of 120°, beyond which it will be difficult to recognize; in the vertical direction, the visual area of 25°~30° above and below the visual plane is the visual area with the best observation effect, and the maximum range of the visual area is within the range of 52°~65° above and below the visual plane.

With reference to the comfortable range of motion of human joints, it can be seen that the left and right neck rotations should be less than 45° in order to ensure that the rotating posture does not cause additional burden. In order to analyze the range of vision during the operation process, the visual field analysis module in Jack software is applied to create a standing digital human, construct the visual field range when the neck rotation is less than 45° and the visual zone is in the area with better observation effect, and obtain the visual field area of the digital human in the comfortable range of activity, and the results of the visual field analysis can be seen that the interaction interface located in the right side of the drive device is located outside the comfortable visual field [8]. It is inconvenient for the observation and operation process. Therefore, it is necessary to adjust the position of the control interface during the optimization process to ensure that the user can make adjustments within the comfortable range of activity.

Table 3. Range of motion of upper extremity joints.

Number	Cartilage	Movement	100% ROM/ (°)
1	Elbow joint	Flexure	140.5
2	Shoulder joint	Prehensile	183.6
		Unfolding	63.2
		Chargeable	56.4
		Outreach	184.1
3	Wrist joint	Palpation	67.6
		Dorsiflexion	60
		Inflexion	49.6

Since the user has to wear the equipment independently and adjust the position of the fixation components to keep them in a relatively fixed state with the body, and at the same time has to switch on/off or adjust the exoskeleton robot according to his/her own needs, it is necessary to make sure that the components interacting with the user are in an easily accessible area [9]. From the range of motion of the human joints, we can know the activity area of the upper limbs, as shown in **Table 3**, during the design process, we need to ensure that the fixation components and interaction buttons are in the accessible area of the upper limbs.

4. Waist exoskeleton robot design program

4.1. Styling design

In order to enhance the visual perception comfort of the waist exoskeleton robot, the styling design enhances the modeling affinity by adding smooth lines, and extracts the modeling curves and design inspirations from the biological modeling. The overall shape of the lumbar exoskeleton robot adopts a soft curve design, inspired by the whale in the deep sea, full of mystery and power [10]. At the same time, the curve design is more suitable for human physiological curve, which enhances the comfort and avoids the damage caused by collision to the user in the process of using.

4.2. Color design

From the user's point of view, the appearance of exoskeleton equipment should be avoided as much as possible during the use of exoskeleton assistive devices, and the design of the equipment should be integrated into the use environment as much as possible in order to minimize the extra burden on the user's vision in the work environment [11].

The visual acuity expression characterizes the ability of the eye to recognize small changes, and its value reflects the ability of visual adjustment, and at the same time can reflect the interface design or product design of the pleasantness. In the following experiments, the airport environment is used as the background for the experiments, and the color scheme that is less visually stimulating to the users is proposed by testing the subjects' ability to discriminate the Lamb's Circle visual acuity testing interface in the same environment. In order to reduce the visual stimulation caused by the product color to the user in this environment [12]. This design takes the waist exoskeleton robot as the object, and the use scenario is the airport and other handling scenarios, in order to avoid additional visual stimulation to the user in the airport use environment, the color scheme of the booster product should be as similar as possible to the environment color.

Based on the above analysis, in order to obtain more accurate simulation results, this simulation chooses to include the airport environment indoor, outdoor, day and night and other scene pictures, the use of PS and other color processing software to extract the most characteristic colors in the above pictures as the background color, according to the frequency of occurrence of the extraction of the following 10 groups of RGB color number, as shown in **Figure 3** below [13].

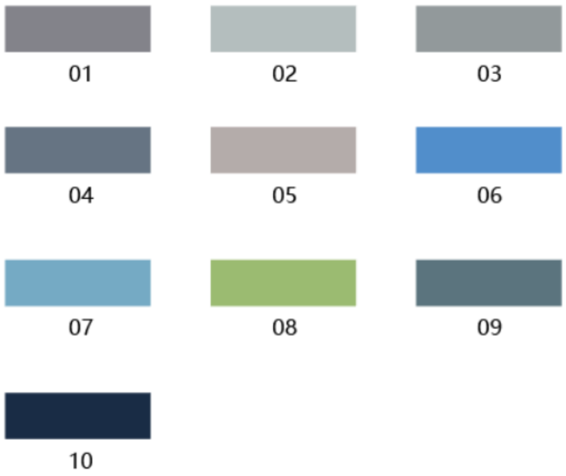

Figure 3. Background color extraction.

According to the color extraction results of the airport scene, it can be seen that the overall color of the airport is darker gray-blue or gray-green, so if you want to reduce the user's visual stimulation of the waist robot color can be considered blue-green, and if you want to increase the product recognition of the waist exoskeleton robot, you can choose a brighter red or orange [14].

4.3. Interaction design

Considering the user's visual experience and safety factors, the collective color of the waist exoskeleton robot is chosen to be a brighter blue, according to the reference formula to determine the color design of the interaction interface and the design of the location of the interaction interface, the power indicator located on the lower side of the back plate of the prototype is placed in the left side of the drive mechanism, the control switches and adjustment components are located in the front side of the right side of the drive mechanism, and the design of the interaction interface is optimized to be as shown in **Figure 4** below.

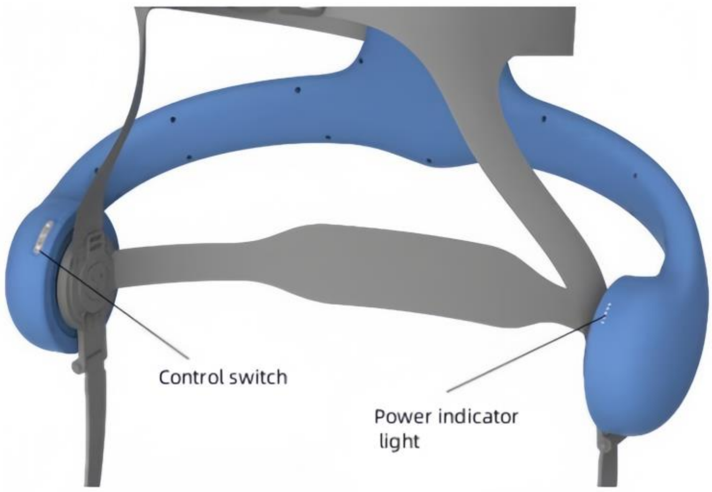

Figure 4. Optimized design of interaction interface.

4.4. Tie-down structure design

Exoskeleton robotic products usually have multiple strap structures designed to secure the device to the user's position to provide assistance, and the design has a decisive impact on the effectiveness and location of the assistance applied [15]. Generally speaking, in the process of weight-bearing product design, in order to reduce the burden on the neck and shoulders, the width of the shoulder straps is usually designed to be about 4.8–6 cm; at the same time, the local force is reduced by setting the inclination angle of the belt in the range of 15.2°~27.4°, and the wearing process is simplified by integrating and reducing the number of fixation components, so that the final lumbar exoskeleton robot is as shown in **Figure 5** below.

Figure 5. Effect of lumbar exoskeleton robot.

5. Discussion

The design and development process of bio-inspired musculoskeletal robots in the artificial intelligence environment is a fascinating intersection of various technological fields. This integration of mechanical design, control algorithms, real-time computing, variable sensing, and other advanced technologies is pivotal in creating systems that can effectively support human movements. These bio-inspired robots are not merely mechanical devices; they are sophisticated systems that mimic the natural biomechanics of the human body [16,17]. This capability allows them to provide effective mechanical support for the user's actions during operation, making them invaluable in numerous applications ranging from rehabilitation to industrial labor [18]. As we consider the transition of exoskeleton robots from experimental research and development to practical applications, it becomes clear that one of the most critical factors influencing their success is user comfort [19]. While the technical specifications and performance metrics of these devices are essential, the user's experience cannot be overlooked. Comfort is not just a matter of preference; it is a fundamental aspect that affects usability, effectiveness, and user acceptance. If a device is uncomfortable, users are less likely to wear it consistently, which ultimately undermines its intended benefits. Therefore, understanding and prioritizing user comfort is crucial in the design and development of exoskeleton robots.

From the perspective of user comfort, the waist exoskeleton robot serves as an excellent research object. The waist is a critical area for support, particularly for individuals who may experience lower back pain or require assistance with mobility. A well-designed waist exoskeleton can alleviate strain on the lumbar region, allowing users to engage in activities with greater ease and less discomfort. This focus on the waist region also highlights the importance of ergonomics in the design process. By ensuring that the device conforms to the natural curvature of the body and distributes weight evenly, designers can enhance the overall comfort and functionality of the exoskeleton [20]. The structure of the exoskeleton robot plays a significant role in determining user comfort. For instance, the materials used in construction can greatly impact both weight and breathability. Lightweight materials are essential for reducing fatigue during prolonged use, while breathable fabrics can help prevent overheating and discomfort. Additionally, the design should allow for a range of motion that aligns with natural human movement patterns. This consideration ensures that users can perform tasks without feeling restricted or encumbered by the device.

Control algorithms are another critical component that influences user comfort. The ability of the exoskeleton to respond in real-time to the user's movements is vital for creating a seamless interaction between the device and the individual. Advanced sensing technologies can provide feedback on the user's posture and movements, allowing the exoskeleton to adjust its support dynamically. This adaptability not only enhances comfort but also improves the overall effectiveness of the device. Users should feel as though the exoskeleton is an extension of their own body, rather than a separate entity that hinders their natural movements. Moreover, user comfort extends beyond the physical aspects of the device. Psychological factors also play a significant role in how users perceive and accept exoskeleton technology. For many individuals, especially those who may be recovering from injuries or living with disabilities, the act of wearing an exoskeleton can evoke feelings of vulnerability or dependence. Therefore, it is essential to design these devices with a focus on empowering the user. This can be achieved by incorporating features that enhance the user's sense of agency and control, such as intuitive interfaces that allow for easy adjustments and customization.

Field testing and user feedback are invaluable in the design process of exoskeleton robots. Engaging users in the development phase can provide insights into their needs, preferences, and challenges. This participatory approach helps ensure that the final product is not only technologically advanced but also user-friendly. By gathering data on user experiences, designers can identify areas for improvement and make necessary adjustments to enhance comfort and usability. The broader application prospects of bio-inspired musculoskeletal robots are promising. In addition to rehabilitation and mobility assistance, these devices have the potential to revolutionize industries such as construction, manufacturing, and logistics. By reducing the physical strain on workers, exoskeletons can help prevent injuries and enhance productivity. However, for these applications to be successful, user comfort must remain a priority. If workers find the devices uncomfortable or cumbersome, they may resist using them, negating the potential benefits.

In conclusion, the design and development of bio-inspired musculoskeletal robots must prioritize user comfort as a key evaluation criterion. The waist exoskeleton robot serves as a valuable case study in this regard, highlighting the importance of ergonomic design, adaptive control algorithms, and user engagement in the development process. By focusing on these aspects, we can create exoskeletons that not only provide mechanical support but also enhance the quality of life for users. As we continue to advance in this field, it is essential to remember that the ultimate goal is to empower individuals, enabling them to achieve their full potential with the assistance of technology.

6. Conclusion

In this paper, the exoskeleton robot design process is studied from the perspective of user experience, simulation software is used to propose modifications to the design of the exoskeleton robot prototype that does not satisfy the user's comfort, and the optimized product is evaluated for comfort, and is designed in addition to a lumbar exoskeleton assisted robot. As a whole, this paper designs a musculoskeletal robot, which achieves the established research objectives, but the use scenarios of the robot developed in this paper are mainly for airports, and in the future, it is necessary to collect user feedback information in a timely manner through the addition of sensing components and other methods to the design process of the exoskeleton robot, and to increase the function of the product's intelligent monitoring and information analysis, so that we can obtain the user's action requirements under different use scenarios and make timely improvements to the comfort of the exoskeleton robot should be improved in time.

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Conflict of interest: The author declares no conflict of interest.

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