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Comparative analysis of energy saving effect of passive exoskeleton designs

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Abstract. Nowadays, exoskeletons have a wide range of application in many fields. Among various types of exoskeletons, passive exoskeletons have become a major development field in exoskeleton device due to their lightweight and simple structure characteristics. This study provides an analysis of an ankle passive exoskeleton and a full lower limb passive exoskeleton design on their respective energy-saving effect during walking. The two selected designs both represent common approaches within the fields of ankle and full lower limb exoskeleton. Through a comparative evaluation of the structures and energy-saving methods of the two designs, the study validates the effectiveness of both designs. Drawing from the characteristics of the designs and comparative analysis, the study discusses the performance and limitations of both designs and outlines potential improvement and applications of both designs. Base on the analysis and the findings, the study aims to contribute to further advancement of passive exoskeleton design and offers some suggestions for its development.

Keywords: Passive exoskeleton, Energy saving, Lower limb exoskeleton, Assistive device, Human walking.

1. Introduction

An exoskeleton robot, often referred as exoskeleton, is a kind of robot mechanism designed to be worn externally on the human body. In modern living and working environments, the strength and capabilities of human are often found to be insufficient. As a result, more and more concepts and design of exoskeleton has been adopted to augment the functional abilities of individuals in both daily life and work.

Lower limb exoskeleton is a significant classification within the field of exoskeleton today. This category contains various subtypes, including full lower limb exoskeleton and ankle exoskeletons. When classified by their intended applications, lower limb exoskeleton can generally be categorized into medical rehabilitation assistive and work-assistive types. Rehabilitation purpose exoskeletons are primarily used to assist treatment of paralyzed and other lower limb disorders. Typically, rehabilitation purpose exoskeletons are powered by the motor in the joint of exoskeleton to provide force to support the patient [1]. The work-assistive lower limb exoskeleton can find their usage in military and industries, allowing soldiers and workers to perform heavy-duty work [2]. The lower limb exoskeleton can also serve as a testing platform of the human kinematics [3].

To classify exoskeletons by their driving power, there are two categories: active exoskeleton and passive exoskeleton. Active exoskeleton is powered by external motor and actuators, it can provide force actively, often allowing for superhuman capabilities such as heavy loads lifting and long distance running with less effort [4]. Passive exoskeleton, on contrary, does not have external power, it only uses mechanisms to support human body. The passive exoskeleton is also capable for reducing the effort required for certain task, but it will not provide extra force or enhance the strength and mobility as active exoskeleton do.

Among all the directions that lower limb exoskeleton can be applied, a potential developing direction is on reducing the energy used by user during walking. Both medical rehabilitation assistive exoskeleton and work-assistive exoskeleton shares a primary goal of reducing the energy expended by the users. This is especially critical for medical rehabilitation assistive exoskeleton, as their main application is to assist lower limb-disabled patients. The ability to lessen the energy required for those patients can significantly enhance the effectiveness of the treatments and assistance.

Both active exoskeletons and passive exoskeleton can be utilized to address the problem of saving the energy in walking. A typical active exoskeleton solution is using actuators such as pneumatic and hydraulic cylinders [5]. The motors and actuators always provide additional power to support user, and it may also include pre-programmed gait patterns in some specific usages. For passive exoskeleton that cannot actively provide energy, common design approaches involve redistributing the load during walking, or introduce energy storage structures. The energy storage structures such as springs and elastic elements can store the energy expended during walking and release it when needed, thereby enhancing the energy utilization efficiency [6].

Compared to the active exoskeleton, passive exoskeleton has several advantages. Passive exoskeleton is characterized by its simplicity in contrast with the active exoskeleton with several external driving motor. Since it only consists mechanism, passive exoskeleton always has a lighter weight and an ease of use compare to the active exoskeleton. The passive exoskeleton is also typically considered as a cost-effectively and low-energy consumption design, which makes it more accessible for a wider range of users, bringing many benefits in rehabilitation and elderly care usage. Therefore, passive exoskeleton represents a significant developing direction for the future exoskeleton technology.

In this article, passive full lower limb exoskeleton and ankle exoskeleton is going to be discussed and compared using two specific examples. Full lower limb and ankle exoskeleton are both currently research hotspots within the field of passive exoskeleton. By compares the characteristic and the energy saving method of two typical passive exoskeleton design in walking assistance, the article aims to infer the advantages and applicability of these two designs, and provide guidance of future application of the passive exoskeleton.

2. Analysis

2.1. Introduction to the ankle exoskeleton example

The ankle exoskeleton is a type of exoskeleton that mainly focused on enhancing the functionality of the ankle joint. The ankle exoskeleton in Ref. [7] is a representative of conventional design while also include a certain degree of innovation. It utilized clutches and rigid triggers to perform energy reduction objectives based on user's gait. The design consists four main components, a clutch, an extension spring, a shank brace and a shoe. The clutch, which is the most crucial component in the design is placed on the outer side of the shoe. The extension spring, connected with the clutch and shank brace using a rope, serves as an elastic element for storing and releasing energy during the walking process. The shank brace is used to fixed the exoskeleton, and provide an attachment point for the rope on the extension spring.

By studying the gait cycle of human walking, the group developed a dual-trigger structure [7], controlled by a trigger rod and a trigger button. When the rear foot touches the ground, a trigger button at the heel of the exoskeleton is pushed upward, initiating the clutching of the exoskeleton. When the exoskeleton is clutched, the lower end of the extension spring is fixed, so the spring can be stretched to its maximum length at this point, storing energy during process. The trigger rod and the connected mechanisms transmit the force from the ground into the clutch. The trigger rod also engages the clutch and enhancing user comfort by effectively utilizing the ground reaction force. When foot is lifted during walking, the clutch released and the pulley at the lower end of the rope is able to rotate freely in both directions. The rope can then be easily pulled in and out of the pulley without hindering the natural rotation of the ankle. The energy stored is released when lifting the foot for forward propulsion, thereby reducing the energy expended by the user during walking.

2.2. Introduction to the full lower limb exoskeleton example

The full lower limb exoskeleton is a type of exoskeleton that covers the most part of human lower limb. The full lower limb exoskeleton design in Ref. [6] is a typical representation of a full lower limb exoskeleton design. The design consists three joints and three sections, namely hip joint, knee joint, ankle joint as well as waist section, thigh section and calf section. A plate located on the back of the hip joint is also designed, enable user to carry loads. The waist section and the load plate, connected with the hip joint, is fixed with user's waist. The thigh section that connects hip joint and knee joint is fixed with the user's thigh. The calf section that connects knee joint and ankle joint is fixed with the user's shank.

The design is also based on the study of human gait. The majority of energy loss during walking occurs during swing stage and when the heel strikes the ground. The hip does not contribute much in reducing the energy cost [8]. A torsion spring placed in the knee joint resist the angle change between the thigh and calf, storing energy that would be lost. Towards the end of the swing phase of the leg, the torsion spring release the stored energy. A coil spring is located in the ankle joint to further reduction of the energy cost. The inner ring of the coil spring is fixed in the clamping groove on the feet plate's boss while the outer ring is hooked on the inner wall of the ankle-calf plate. This configuration allows the outer ring of the coil spring to move with the user's calf while maintaining the coil spring's center of rotation fixed with in the ankle joint during walking. The coil spring in the ankle joint acts as a shock absorber when the heel strikes the ground. It then gradually releases during the subsequent phases of the gait cycle. This release of stored energy assists in pushing the foot off the ground and reduces the overall energy cost of walking.

2.3. Analysis of two exoskeleton design

2.3.1. Comparison of dimensions and physics properties. The comparative analysis of dimensions and physical data for the exoskeleton plays a crucial role in determining their potential utility and application area. For instance, if the volume or mass of a rehabilitation exoskeleton is too large, it may limit its application to the rehabilitation facilities rather than within a patient's home [9].

The ankle skeleton design in Ref. [7] utilizes various materials, including 6061 Al-alloy, stainless steel, rubber and light-weight shank brace. The total weight of the exoskeleton is 765.5 g including the shoe. An Al-alloy plate is designed to hold the main mechanism of the exoskeleton, with a weight of 349 g accounting for 45.6% of the total weight. The weights of the shank brace and the extension spring are 42 g and 46.2 g, respectively. The main mechanism of the exoskeleton including the shoe weighs 328.3 g. The size of this design is not specified. But the thickness of alloy plate is given as 10 mm and the flange of the pulley is 1 mm. It can be inferred from the picture of the design [7], the highest point of the main mechanism, is at the same height with user's ankle. The shank brace is fixed under the knee of the user.

The full lower limb exoskeleton design in Ref. [6] is a virtual design based on the SolidWorks simulation. The material used in simulation is Al-alloy 2014-T6 and the weight of the brace is not considered in the simulation since it does not influence the strength and the energy reduction effect of the design. The size of the full lower limb exoskeleton is not specified. The positioning holes on the waist, thigh and calf section enable the adjustment of exoskeleton's length and width, allowing for customization to different user.

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It is generally believed that ankle exoskeletons are expected to be lighter and more compact compared to full lower limb exoskeleton. From the data presented above, it is clear that both the ankle exoskeleton and the full lower limb exoskeleton align with the understanding. Furthermore, due to the higher density of the 2014-T6 Al-alloy used in the full lower limb exoskeleton compared to the 6061 Al-alloy used in the ankle exoskeleton, the mass different between these two designs is expected to be more significant.

2.3.2. Comparison of energy reducing effect. The walking trial is carried out for the ankle exoskeleton design in Ref. [7], while the Ref. [6] does not have a real-world experimental data. The energy reduction effect of the full lower limb exoskeleton design can be inferred from Ref. [8], and the specific setting of the spring is also determined in Ref. [8]. The data of the ankle exoskeleton walking trial is listed in Table 1, the data is based on the high stiffness spring trial in Ref. [7], which represents the best performance of the exoskeleton. The stiffness of the spring in the model is 9.05 N/mm and the data is collected in a 1 minute's walking trial.

Table 1. Energy reduction of ankle exoskeleton [7]

	Normal walking	Energy-saving walking	Reduction rate
EMG signal in speed 4 (km/h)	804.8	269.6	66.50%
Tensile force (N) in speed 4 (km/h)		101	
EMG signal in speed 5 (km/h)	1256.7	349.9	72.20%
Tensile force (N) in speed 5 (km/h)		107.3	

EMG signal, short for electromyography signal, is a measurement that indicates the electrical activity of muscles [10]. The EMG signal of the trial is the peak value taken from test participants' soleus. The significant decrease of the EMG signal shows that the muscle does not actively participate in energy-saving walking compare to the normal walking. It can also be inferred that a faster walking speed improves the energy-saving efficiency of the design. This may be attributed to the increased stride length during relatively fast walking, which results in a greater extension of the spring, consequently, storing and releasing more energy [7]. The tensile force in Table 1 is the maximum spring force during the walking trial. Based on Hooke' Law, the greater extension of spring leads to a larger tensile force, and the greater extension of the spring may be the result of a faster walking speed with a greater stride. This aligns with the earlier hypothesis that contributes to the energy-saving effect.

Table 2. Energy cost rate of different stiffness ankle spring [8]

Stiffness (N m/rad)	knee-lock energy cost rate	heel-strike energy cost rate	joint friction energy cost rate
1	0	0.130	0.048
2	0	0.118	0.046
3	0	0.104	0.044
4	0	0.098	0.042
5	0	0.090	0.040
6	0	0.080	0.044

The energy-saving effect of full lower limb exoskeleton design in Ref. [6] is based on the theory in Ref. [8]. The stiffness of the spring is specified based on the calculated data in Ref. [8]. Based on the mathematical model developed in Ref. [8], the energy cost rate is unattainable when the stiffness of the spring at ankle joint exceeds 7 N m/rad due to the unrealistic knee angle under these circumstances. The energy cost rate in different stiffness of ankle joint spring is presented in Table 2.

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It can be inferred from the Table 2 that the ankle joint spring does not affect the energy cost rate of the knee joint. The ankle joint spring absorbs the energy when the heel strikes the ground, effectively reducing the energy losses during this phase, thereby reducing the energy cost in walking. The joint energy cost rate shown in Table 2 reflects a pattern of initial decline followed by an upward trend. Since the design in Ref. [6] does not specified spring's stiffness, a spring with a stiffness of 5 N m/rad could potentially offer the most effective energy-saving effect. The knee spring does not have any further verified experimental data. A similar design of a knee exoskeleton that reduce the energy expended during the stair descendent [11] can be a reference. In the design presented by Ref. [11], spiral spring located at the knee joint can reduce the energy expenditure, as indicated by the reduced EMG signal in the associated muscles. It is sure that the spring at the knee joint can reduce the energy in specific tasks. However, additional simulation and experiment are required to further confirm the energy-saving effect.

Based on the discussion above, both designs of the exoskeleton are effective in reducing energy expenditure during walking. It is worth noting that the full lower limb exoskeleton possesses an additional capability to bearing loads, which an ankle exoskeleton cannot achieve. The design in Ref. [6] is simulated using a 50 kg weight. The maximum displacement of the feet plate is 0.6 mm, which is considered to be within the safe range. This indicates that the design has the ability to carry a certain amount of weight without experiencing failure.

2.3.3. Limitations of the designs. The ankle exoskeleton design performs well during regular walking on flat ground. However, some real-world testing is still required. During walking tests in real-world environments, rough terrain conditions and variation in gait may lead to failures in trigger button and trigger rod activation, potentially resulting in a malfunction of the entire exoskeleton. The mechanism of the exoskeleton is located very close to the ground and lacks protection, which may result in poor durability when operating in relatively harsh environments. The stiffness of spring might also impact the overall performance of the exoskeleton, as improper stiffness can affect the storage and release of potential energy in the spring. Some further research based on the proper spring stiffness can be performed [7].

For the design of the full lower limb exoskeleton, the top priority for validating its usability is to conduct physical testing. The data for the ankle joint spring has been partial validated in Ref. [8], but the stiffness of the knee joint spring still requires further verification. The knee spring design in the full lower limb exoskeleton may also lead to a reduced flexibility of the lower limb. The knee spring impede the angle change between thigh and calf [6], this can limit the effectiveness in providing comfortable and natural movement assistance.

It is also essential to emphasize that both designs do not have a protective mechanism to prevent balance loss or falls. As passive exoskeletons, both designs cannot independently regain balance or maintain stability in accidents, unlike active exoskeletons. In practical applications, especially for rehabilitation purposes, additional devices are necessary to ensure the user's safety.

2.4. Potential improvement of the design

Both of the designs have room for improvement to enhance or keep their energy-saving capabilities. The ankle exoskeleton design has a design flaw where the shank brace may slip off during walking. The slippage of the shank brace results in a 11.8 mm reduction in operation length during the 5 km/h trial and a 13.1 mm reduction in operation length during 4 km/h trial [7]. The reduction of the operation length leads to an incomplete extension of the spring during walking, thereby weakening the energy-saving effect. A frame resembling the design in Ref. [12] can replace the shank brace to serve as the attachment point and prevent the slippage. The weight of the design can also be further decreased. It is possible to use alternative materials to manufacture the alloy plate that supports the main mechanism. The utilization of reinforced carbon fiber [13] can be considered as an option to reduce the overall weight.

Similarly, weight reduction is crucial for the full lower limb exoskeleton. Additionally, considering the potential load-bearing ability of a full lower limb exoskeleton, mechanical analysis is needed to determine suitable replacement materials. Furthermore, combining the two design is also a possible improvement. However, this improvement must take into account the potential issue of excessive weight on the ankle joint, which might affect user's normal gait.

2.5. Potential usage of the design

The ankle exoskeleton is marked with its small volume and light weight. It can be used to assist workers in jobs that require long-time walking, such as those in the manufacturing industries and construction sites. The energy reduce effect contributes to increased worker comfort and productivity. The design can also serve as a rehabilitation or a walking assistance tool for patients with muscle weakness or injuries. By adjusting the layout of the trigger button and trigger rod, the design may also potentially achieve correction for specific gait patterns [14].

For full lower limb exoskeleton, it could also serve as rehabilitation and assistive equipment. The additional load-bearing ability of full lower limb exoskeleton, compared to an ankle exoskeleton, makes it suitable for scenarios that involve the handling or transporting of weights. Due to its simple mechanical structure compares to the ankle exoskeleton design, the full lower limb exoskeleton could potentially become a prototype for other enhancement type exoskeletons.

3. Conclusions

In this paper, a detail analysis and comparison between an ankle exoskeleton design and a full lower limb exoskeleton is performed, with a specific focus on the energy-saving effects during walking. The research results have revealed the performance of these exoskeletons, presenting their respective strength and limitations. The ankle exoskeleton design was shown to be effective in reducing the energy expenditure during regular walking on flat ground. However, it was noted that the design could benefit from further real-world experiments to evaluate its performance on rough and diverse environments. Additionally, addressing the issue of shank brace slippage and exploring new materials for support plate and overall structure could enhance its overall usability. On the other hand, the full lower limb exoskeleton shows a potential in load-bearing and wider applicability, especially in weight transporting. The design's simple structure makes it possible for prototype development, which could serve as a foundation of other lower limb exoskeleton designs.

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