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Research on the mechanical structure and control system of prostheses based on intelligent solutions

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Abstract. According to a report released by the World Health Organization in 2011, the number of disabled people worldwide accounts for about 15% of humanity, many of whom are lower limb amputees who lost the ability to walk and climb stairs. However, for various reasons, the proportion of amputees fitted with prostheses or orthotic devices is deficient, and society has a significant demand for prostheses. Since the end of the 20th century, prosthetic intelligence has gradually become the primary goal of prosthesis research. Intelligent prostheses can better restore the function of the inherent limb. There are various solutions for both the mechanical structure and control systems of prostheses, such as stepper motor drives, magneto-rheological liquid intelligent control drives, hydraulic and pneumatic dual-cylinder type drives, and pneumatic device drives. This paper will analyze these solutions and discuss how better integration of different solutions can bring new ideas to the research of intelligent prostheses.

Keywords: intelligent knee prosthesis, mechanical structure design, control system, intelligence.

1. Introduction

Artificial limbs, or prostheses, are an essential area of research in the field of medical devices. Artificial limbs are designed to provide restorative support to amputees in terms of appearance, function, or both. They are ideal assistive devices, especially for amputees who have lost their motor abilities.

In addition to genetic factors, the most common causes of limb loss in amputees are traffic accidents, work-related injuries, war, and disease-related limb necrosis. According to a survey issued by the World Health Organization in 2011, around 15% of the global population has a disability, many of whom have difficulties walking or climbing stairs [1]. As a result of CDC statistics, researchers have estimated that about 1 in 1900 newborns suffer from congenital limb loss, some of these infants being born without both upper and lower limbs [2]. Approximately 185,000 limbs are amputated annually in the United States, per the Amputee Coalition [3]. In China, around 352,000 people with physical disabilities undergo rehabilitation training, but fewer than 100,000 are fitted with prosthetics and orthotics. Currently, there is an enormous demand for prostheses in society.

Lower limb amputees frequently have undamaged arms, allowing them to use their upper limbs to operate wheelchairs and crutches or to maintain their balance while wearing prostheses. The advantages of prostheses over wheelchairs and crutches for amputees are that they do not rely too

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heavily on the upper extremity for operation and can be adapted to a wider variety of road conditions; therefore, a thorough study of artificial limbs is the research that most directly addresses the motor needs of amputees.

How to better restore the performance of the inherent limb is the key topic that needs to be addressed in prosthetics research. Various dimensions, such as appearance restoration, motor support, limb perception, etc., are included in performance metrics. Typically, research on lower prostheses focuses on motor support. Human movement is controlled by the central nervous system, and the prosthesis should as closely as possible match the mechanical qualities of the limb joints and the user's control requirements. A significant contribution has been made to the advancement of prosthetic research by the advent of computer simulation technologies and intelligent control systems. Intelligent prostheses are those that can automatically modify their structural characteristics to accommodate the user's mobility requirements. Intelligent prostheses can meet the user's control requirements more effectively than conventional mechanical structures. This paper will review the history of prosthetic limb research, discuss the difficulties that have been solved, analyze the challenges that still need to be solved, and offer some suggestions for the future study of intelligent prosthetic limbs. It is designed to aid researchers in their investigation of intelligent prostheses.

2. The basis of intelligent research on prostheses

Due to the various locations of amputation among amputees, their prosthetic requirements vary. In order to reduce the cost of prosthesis differential design and manufacture, Ottobock, a leader in the prosthetic business, shifted from global solutions to modularized solutions for finished prosthetic products in the 1960s [4]. Using the knee prosthesis as an example, which has the most complex structure, the prosthesis can be divided into a socket, adapters, a knee joint, an ankle joint, and a silicone foot (a humanoid foot wrapped in a prosthetic footplate to meet the footwear-wearing and aesthetic functions). The patient's differentiated design only requires the prosthetic orthotist to construct a suitable socket for the patient's amputation; the remaining components can be differentiated to match the patient's demands using standard adapters and tubes of varying lengths.

This provides a solid foundation for prosthetic research, allowing researchers to concentrate on the two essential movable components of the knee and ankle joints that sustain mobility. Typically, patients with below-knee amputations require only one movable component of the ankle joint, which swings less during walking, and the damping supplied by mechanical construction can meet walking requirements in the majority of cases. Therefore, knee joint design has been the target of intelligent prosthetic research.

3. Quantitative indicators of prosthetic design

There are strong subjective elements and objective causes that affect the comfort level of amputees using prostheses, such as the testing environment, the amputee's use experience, and the degree of adaptation of other modules, primarily the socket, to the amputee. The majority of prosthetic limb research is still at the prototype stage, and many studies have only recommended improvements to various flaws of present prostheses and conducted design, testing, and analysis to establish the viability of these proposed modifications. There is rarely a consistent evaluation standard for prosthetic device performance.

It is the primary function of a prosthesis to facilitate the mobility of a person with an amputated limb, and numerous clinical studies have investigated the energy expenditure of the amputee during the process of using the prosthesis, which is mainly determined by the swing of the limb. After the development of the first intelligent prosthesis (IP), JM. B. Taylor and E. Clark et al. determined that intelligent prostheses spend less energy at high walking speeds by comparing the maximal oxygen intake of amputees wearing different prostheses [5]. Therefore, the key performance metrics of the prosthesis should concentrate on decreasing the user's energy consumption. On the basis of reduced energy usage, prosthetic research should result in reduced learning costs, a more stable gait, a lighter design, and quicker device responsiveness.

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4. Intelligent knee joint prosthesis

4.1. Basic requirements of prosthetic mechanical structure

As shown in Fig. 1 [6], the structure of the human knee joint varies markedly from that of a simple revolute joint, and the knee joint has a more complex curve of linked instantaneous centers of velocity during rotation. Therefore, in terms of prosthetic support for motion, the mechanical structure has a significant effect on prosthetic performance, and a more bionic prosthesis has a better fit to the motion of the limb and may therefore more precisely simulate the gait of the inherent limb. A good mechanical structure can lessen the difficulty of designing a control system for gait simulation in prostheses for researchers. Nonetheless, the weight requirement of the prosthesis restricts the complexity of the mechanical structure of the prosthesis, which must also be considered to support the control system.

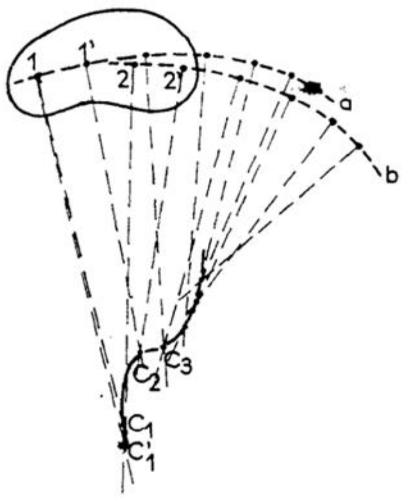

Figure 1. Knee joint instantaneous centers of velocity.

The mechanical structure of the knee prosthesis can be functionally summarized in two phases: support, which consists of supporting the body for stability during standing and alternating with the other leg during movement to support the body in order to move forward or backward, and flexion and extension, during which the knee joint provides a forward or backward swing that is briefly suspended. In this way, two aspects of the mechanical construction of the prosthesis elicit design input:

Anthropometric:

(i) Diameter not exceeding the inherent limb.

(ii) The dimensions of the horizontal axis of the femur-to-knee prosthesis, when attached to the socket assembly, should correspond as closely as possible to the inherent limb.

(iii) When attached to the tibial and ankle-foot components, the dimensions of the knee prosthesis from the horizontal axis to the sole of the foot should match those of the inherent limb as closely as possible.

(iv) When we swing, the pattern of change in the instantaneous center of velocity is consistent with that of the inherent limb.

Mechanical properties.

(vii) It is capable of withstanding the axial pressure during support, and the mechanical structure remains stable during the process of bearing the pressure.

(viii) It is capable of withstanding the tension transmitted by the femur and tibia or the load in the normal direction to the axis.

(ix) The material and structure can withstand continuous cyclic loading without structural damage or material fatigue.

The design of the mechanical structure of the prosthesis should include the nine aspects listed above, which can ensure the prosthesis's primary function.

The mechanical structure design of a prosthesis should take both the supporting phase and the swinging phase into account. The 20th century prosthetic products were limited by the function of the mechanical components to support the swing phase with elastic elements and the support phase with manual or automatic mechanical self-locking, respectively. However, the prostheses in this stage were frequently single-axis revolute joint structures, which were cumbersome to use and could not meet the design input of aspect (iv) above, so this design was gradually phased out in the subsequent commercial products.

To improve the gait simulation impact of a single-axis revolute joint, numerous businesses have devised multi-axis designs in which pneumatic or hydraulic springs with long service lives provide the leg extension torque. Fig. 2 depicts Ottobock's 3R60 series. This multi-link can be used to support motion by storing bending energy and releasing extension energy via a pneumatic or hydraulic mechanism. It is also the most common type of prosthesis worn by amputees today.

Figure 2. Multi-link knee joint 3R60.

4.2. *Prosthetic mechanics in intelligent solutions*

With the widespread usage of computer-aided design (CAD) and computer-aided engineering (CAE) software in the 21st century, the mechanical structure of prostheses has become increasingly accurate and sophisticated. As the functions of intelligent prostheses are gradually determined and executed by the control unit, research on intelligent prostheses tends to converge with research on intelligent bionic legs for walking robots. In addition, after a decade, some teams referred to research on intelligent prostheses as research on intelligent bionic legs [7]. Active medical devices replace passive medical devices in the development of prostheses, necessitating a more stringent structural design. In addition to the previously indicated requirements, the selection of actuators and the design of the related structural system are also essential studies.

Depending on their respective characteristics, the various options for the design of the knee joint structure and the various options for the actuator can be integrated in a variety of ways.

a. **Stepper motor drive:** This design is still commonly utilized in commercializing intelligent prosthetic solutions, with Ossur's Power Knee® presenting as a representative example (see Figure 3). The advantages of collaboration between stepper motor and linkage are low cost, easier control, and servo-driven capacity. However, there are issues with higher noise, possibly incoherent gait, imprecise positioning, and the design does not match the human leg's physical swing curve, necessitating training costs.

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Figure 3. Ossur Power Knee.

b. **Magnetorheological fluid intelligent control drive:** This drive mainly uses magnetorheological fluid to alter the fluid's viscosity in reaction to a changing magnetic field. This control has a rapid response and a significant viscosity change. Moreover, compared to hydraulic drives, sealing requirements and manufacturing process requirements are extremely modest. These characteristics allow it to adapt effectively to a variety of control methods, and it is also very compatible with mechanical systems. Due to the excellent controllable properties of magnetorheological fluids, the most recent Rheo® prosthesis can already be linked to cell phones for IoT, allowing users to check the status of the prosthesis at any time and automatically recognize movements such as walking, climbing stairs, sitting, etc.

c. **Hydraulic and pneumatic dual-cylinder drive:** a hydraulic device to offer standing support and a pneumatic device offering swing support during movement, two cylinders incorporated into one motion damper. Dual-cylinder systems have both the advantages and disadvantages of pneumatic and hydraulic components, as well as high process and sealing requirements. Currently, Blatchford's Orion® 3 is the only mature product, having replaced the previous Orion® series and Adaptive Knee®.

d. **Pneumatic device drive:** the earliest intelligent prosthesis IP has adopted this solution. By controlling the parameters of the pneumatic device, we can achieve the intelligence of the prosthesis.

In current prosthesis research, it is challenging to strike a technological and financial balance between mechanical structure, actuators, and control systems. Multi-link mechanisms and high-performance actuators add weight to the prosthesis, while sensors and controllers required for control systems require installation locations to be reserved. Future studies may yield a better solution.

4.3. Early intelligence of the prosthesis

There is a difference in the load on the knee joint at different gait speeds, and the larger the kinetic energy required from the knee joint, the faster the gait speed. A knee prosthesis with a totally mechanical structure that relies on the rebound properties of a pneumatic or hydraulic device or spring to supply leg extension torque has a factory-set elastic coefficient that cannot accommodate the user's need for varying gait speed. When Akio Nakagawa proposed in 1986 the use of a microprocessor to adjust the opening of the needle valve of the internal pneumatic element of the prosthesis to change the elasticity coefficient of the pneumatic device and thus be able to provide kinetic support at different gait speeds [8], he was addressing this specific problem. The technique was made public in 1989 and licensed to the British prosthetic manufacturer Blatchford the following year. Engineer Saced Zahedi developed the first commercial product, Intelligent Prosthesis (IP), as depicted in Fig. 4 [9]. Before the amputee uses the prosthesis, an expert records the knee joint movement information during the amputee's gait speed from slow to fast, selects five different gait speeds, calculates the opening of the needle valve in the prosthesis that should be provided with the threshold value of the knee joint movement information when the adjustment should be made, and then sets up the microprocessor based on this information.

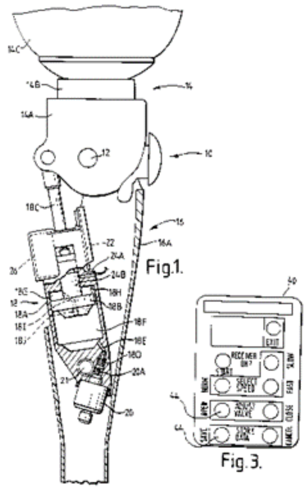

Figure 4. the IP developed by Saced Zahedi.

IP and the contemporary meaning of "intelligent" still have a large gap, and while this product also exposed the technical shortcomings of the 1990s, the battery and processor life is very short and cannot support the frequency of daily use of the prosthesis; the battery and processor must be replaced on average yearly. However, IP led the research on intelligent prosthetics, allowing more scientists to develop novel intelligent prosthetic solutions.

4.4. Stages of development of intelligent prostheses

4.4.1. Open-loop control stage. IP and other products derived from Nakagawa's theory share a similar design. During operation, the device's step speed sensor provides real-time step speed to the microprocessor and adjusts the needle valve opening when the step speed reaches a critical value to provide motion support for the user's step speed change. Changing the elasticity coefficient of the damping components to match the user's gait speed is a core part of most modern intelligent prostheses, which are based on this innovative design. At this stage, however, the control system of the intelligent prosthesis simply controls the swing phase, while the standing phase is still handled by a mechanical self-locking device. This design provides limited gait support, has a high learning cost, and does not significantly reduce patient energy consumption because of the extra weight of the IP due to the control system [10]. As the microprocessor could only respond to the input of the gait sensor to adjust the needle valve opening and could not guarantee the needle valve's accuracy, the degree of cooperation between the control system and the mechanical system of the prosthesis decreased as a result of aging, wear and tear of devices, and degradation of the battery's performance. In the following phase, the prosthesis utilizes a closed-loop control system.

4.4.2. Closed-loop control stage. At this stage, additional sensors have been added to the prosthesis, and the input from these sensors gives the microprocessors information on the actual motion of the device, forming a closed-loop control system. For instance, Ottobock's C-Leg® adds pressure sensors beneath the foot, which considerably enhance the control precision of the prosthesis through the collaboration of pressure sensors and speed sensors, and the user no longer needs to spend time presetting the prosthesis due to the closed-loop control. Ottobock also declared that C-Leg is the first intelligent prosthesis because its closed-loop control is closer to the contemporary concept of intelligence. In studies comparing the C-Leg to other prostheses, Jacquelin Perry and Judith M. Burnfield confirmed the C-Leg's lower energy costs. [11]

At this stage, the design of control systems for prostheses became an essential area of research. Some researchers have developed intelligent control solutions, such as intelligent algorithms, which can significantly enhance the processing efficiency and control precision of microprocessors. In 2003, Southeast University (China) introduced genetic algorithms and fuzzy control PIDs to increase the convergence speed and global search capability and optimized the control parameters with pseudo-parallel genetic algorithms, thereby optimizing the control system [12].

4.4.3. Closed-loop control stage. During this stage, the performance of microprocessors increased, enabling prostheses to access more data and run more complex control programs. Many teams, therefore, have shifted their focus from identifying the parameters required for the prosthesis in the current condition in terms of step speed to identifying the parameters required in terms of its current condition in real time. Intelligent prosthesis control solution research is now being optimized in this direction. In this time, the sensitivity of the system to the sensor has gradually increased, many prostheses have abandoned the previous pressure sensors in favor of more precise angle sensors, and data processing units have also experienced technological developments, allowing built-in algorithms to supply more efficient output from the control system. Ottobock's C-Leg, for example, allowed support for complex activities such as stair climbing by receiving the system state at high frequencies during this time [13]. After this stage, many products can support seamless switching between walking and standing. See Fig. 5.

Figure 5. The latest generation of C-Leg, C-Leg 4.

4.4.4. Totally bionic stage. During the movement of the human leg, as described above, the trajectory of the instantaneous center of the velocity of the knee joint changes nonlinearly during the whole process of the swing phase. Intelligent prostheses need to more accurately fit the movement of the healthy leg, thus reducing the patient's energy consumption and learning costs. On the mechanical side, previous prosthetic products are mostly single-axis mechanisms, and more advanced prostheses should use multi-link mechanisms that better fit the swing curve of the inherent knee. At the same time, the algorithm should be able to support a wider variety of movement forms to switch between, for example, various sports.

5. Basic framework of intelligent prosthesis research

Intelligent prosthetic research aims to fully restore all limb functions, including motor and sensory functions. At this stage, however, the emphasis is on the bionics of motor function. The key to motor function is determining how and under what conditions to provide energy for movement. Researchers are accustomed to classifying prostheses by the form they provide power, which usually includes passive prostheses, active prostheses, and semi-active prostheses, the latter two being the main targets of intelligent prosthetic research.

The semi-active prosthesis is based on the passive prosthesis' mechanical structure and includes a control system. The pneumatic or hydraulic components of the prosthesis continuously store and release energy with the user's movement, and the control system is designed to optimize this process.

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In a continuous road condition, the human gait is virtually the same when traveling at a speedy rate, and the prosthesis provides alternating torques of support and leg extension during this process; as the gait speed changes, the needed torque also changes. For instance, running requires more torque than constant-speed walking. As the user's motion varies, a semi-active lower prosthesis demands that the mechanical structure of the prosthesis be altered to meet the current gait condition. A technique called intention recognition is one that monitors and forecasts the state of movement as it changes over time. The fundamental control requirement of a semi-active prosthesis is the recognition and alteration of the user's intentions based on the input signal. In most systems, sensors give the input signal, the microprocessor performs intention recognition, and the pneumatic or hydraulic device's damping settings are altered by the microprocessor. For instance, the proposal of Akio Nakagawa is to employ a computer to alter the valve opening of a pneumatic component so that the prosthesis can provide five distinct damping levels.

In current research, sensors in intelligent prostheses are essential components for intention recognition, and many solutions tend to aggregate input from multiple sensors for more precise recognition. Semi-active prostheses require information such as step speed, acceleration, the pressure on the sole of the foot, joint torque and angle, or motion parameters of the healthy leg in order to recognize motion intent, make predictions, or react to state changes.

As the name implies, active prostheses are prostheses that actively provide torque to extend the legs, such as those powered by motors. Active prostheses are better than semi-active prostheses because they are better able to perform tasks that require the device to actively provide a higher leg extension torque, such as stair climbing. The necessity to actively provide torque makes active prostheses respond in a predictive rather than a relatively laggy manner, which requires a higher level of movement intention recognition, and thus active prostheses require physiological electrical signals as input. Physiological electrical signals include surface-electromyographic (sEMG) signals, central nervous system signals, and electroencephalography (EEG). The sEMG signal is the current option selected by many commercial products, although this still has some problems. The sEMG signal responds to the state of the muscle, and there are differences in muscle state between users. Muscle exhaustion will also interfere with the recognition of intent.

Active prosthesis and passive prosthesis have the same point of control system, i.e., intention recognition. Types of signal sources for intention recognition inputs:

Movement information: the sole of feet pressure, gait, joint angles.

Biological information: Electromyography (usually surface EMG), Electroencephalography (EEG).

Environmental information: Image input based on machine vision systems, etc.

As stated previously, designs for prostheses based on motion data comprise the majority of current commercial products. Still scarce are prosthetic products based on biological information. The idea of using surface EMG signals to control prostheses was first described in 1988 [14], but due to hardware performance limitations, it has not been actively applied in prosthetic research until recent years. Future research on prosthesis control systems will require more effective learning capabilities that can recognize the user's movement intentions more precisely by learning the user's movement patterns.

6. Intelligent prosthesis research outlook

Intelligent prosthesis research has many challenges, the first of which is the rising cost of prostheses as a result of the increasing cost of electronic components. Additionally, due to the problem of aging electronic components, the hardware system of intelligent prostheses generally lasts for less than ten years. Due to waterproofing requirements, etc., the cost of replacing electrical components of intelligent prostheses is also very costly. Furthermore, many prosthetic designs do not enable disassembly and can only be replaced at the end of their service life. In the group of disease-induced amputees, low-income groups had a higher risk of amputation, according to the data [15]. A critical issue that must be solved is how to ensure the intelligent function of the intelligent prosthesis while effectively reducing the cost of use.

As indicated in Chapter 4, the available space for intelligent prosthesis design is very limited, making it nearly impossible to apply the multi-link mechanism to the active prosthesis structure, which is a critical challenge for prosthesis intelligence. The performance of the multi-link mechanism in restoring inherent limb gait is excellent, but it is less compatible with motors and other drive devices. The study of drive devices and joint rotation restoration in active prostheses is a crucial issue that must be resolved in the current design of the system.

In addition, there is a lot of space for development in software, both in terms of algorithmic advancements and the performance of microprocessors that can be utilized in prostheses, hence increasing the possibility of software programs for prostheses. As a result of the growth of smart phones, companies now provide prosthetics that are Bluetooth-compatible and can be connected to smart phones. This may be a novel design concept: the prosthesis may be able to upload data to a smart phone through a Bluetooth module, the phone's program will evaluate the data, and the prosthesis will be able to adapt to the user's intelligent control solution. In addition, the connection with the phone allows the prosthesis to be upgraded over-the-air, allowing the user to improve their experience by upgrading the built-in algorithm of the prosthesis.

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