Research on Advanced Applications of Sensor Technology in Intelligent Prosthetic Limbs

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Abstract. Amputations are not rare cases the number of people who need to wear prosthetic limbs is more than thirty million, which is larger than many people used to consider. Intelligent prosthetic limbs bring huge convenience to these disabled people in daily life and make them more confident. However, the techniques are not mature enough currently. Intelligent prosthetic limbs have complex structures because they must detect not only human bodies' data, and prosthetic limbs' data, but also the surroundings. That is because all of these matters significantly influence prosthetic limbs. Besides, even a little inaccuracy may lead to inevitable damage. Therefore, sensors shoulder crucial responsibilities in prosthetic limbs. This paper introduces the principles and functions of different sensors used in prosthetic limbs. The current advantages and disadvantages of these sensors in prosthetic limbs are pointed out. And then, based on the shortages, the challenges and some solutions for these difficulties are discussed. This article helps readers learn about some basic principles of sensor applications and understand the advantages and disadvantages of these sensors.

Keywords: Prosthetic limbs, Sensors, Accuracy, Efficiency, Perceived frequency.

1 Introduction

According to the World Health Organization, nearly thirty million people need prosthetic limbs to help them move better. Those amputations are quite common. Traumatic amputations result from accidents or injuries, whereas surgical amputations are caused by a variety of conditions, including blood vessel illness, cancer, infection, excessive tissue damage, malfunction, discomfort, etc. Congenital amputation is the term for missing a part of the body before birth [1]. Unfortunately, just a small portion of that population can acquire proper prosthetic limbs. That is because intelligent limbs are not common for users, and they may not fit every patient's unique motor pattern and habit. Therefore, some people who lose parts of their legs seem like their lives lose hope and do not want to go outside to meet others, because they regard themselves as people who are disabled and cannot act normally. However, patients do not need to be self-abasement, instead, intelligent prosthetic limbs should provide patients' sense of confidence and comfort. The biggest difference between human

© The Author(s) 2024
Y. Yue (ed.), *Proceedings of the 2024 International Conference on Mechanics, Electronics Engineering and Automation (ICMEEA 2024)*, Advances in Engineering Research 240,
https://doi.org/10.2991/978-94-6463-518-8_69

body parts and prosthetic limbs is that the latter do not have feelings. Therefore, to improve those prosthetic limbs to make them fit more people's needs, more sensors are needed in prosthetic limbs. The reasons are that sensors can detect surroundings and make changes to different conditions, also, sensors can detect human bodies' muscles' movements and cooperate with muscles. Scientists have done much research and experiments in the last few years and developed new sensors, which are more accurate. comprehensive, and nimble. For instance, scientists developed novel arithmetic that can calculate legs' bending degree and movements more accurately; scientists created practical pressure sensors that can comprehensively measure the entire pressure between human body parts and their prosthetic limbs [2]. However, there are still many shortages of prosthetic limbs. Sometimes, prosthetic limbs cannot respond to human needs immediately, and they still cannot act normally as human bodies. Besides, some people will catch joint diseases by wearing those prosthetic limbs for too long time, which causes a lot of inconvenience. This passage can help readers know more about current prosthetic limb sensor techniques and help patients realize the developments in this field, which may increase their confidence when they wear prosthetic limbs. This paper introduces the theory of some sensor techniques and arithmetic used in prosthetic limbs and analyzes these sensors' advantages and limits. The analysis generally concentrates on accuracy, efficiency, and stability.

2 General Introduction of Typical Applications of Sensors in Prosthetic Limbs

To make the prosthetic limbs comfortable and intelligent, they should be able to detect human needs rapidly, and then those limbs should respond and take action accurately. For instance, if a person wants to walk, his/her artificial limb should receive electromyographic signals and then, combine users' moving intentions and accelerations to estimate their action trends. Therefore, prosthetic limbs can use bending sensors to change users' legs to an appropriate degree. In the whole process, tactile sensors are used to detect pressure between initial body parts and the prosthetic limbs, and tactile sensors give users enough support as well. In that basic process just mentioned in the passage, sensors shoulder significant responsibilities for prosthetic limbs to carry out normal functions, such as bending sensors, accelerometers, EMG, tactile sensors, and so on. This part mainly introduces three main sensor categories that are vital in creating and using prosthetic limbs. The first category is the inertial sensor, and this kind of sensor can detect users' actions and cooperate with them. Secondly, artificial limbs should contain a tactile sensor, which helps users to gain external force information. Lastly, the Electromyography sensor and this kind of sensor is used for detecting users' motion intentions by noticing users' neuron signals. To be specific, this passage gives examples of those different kinds of sensors and explains how they work in prosthetic limbs.

2.1 Motion Information Acquisition

Firstly, Liu et al. proposed a wearable motion capture device using combined microflow sensors to accurately measure tri-axis motion velocity and acceleration, overcoming drift and instability issues with an integral-free approach [3]. In this study, scientists use a tri-axis dimension to detect human motions in daily life. This method is an innovation because traditionally, people use the integral of motion acceleration, which may cause errors. As a result, even with noise blockers, there are still non-negligible errors. With the accumulation of motions, those errors also increase, and then the results and measurements may not be accurate enough and bring troubles. However, using microflow sensors can avoid errors by using inertial sensors to detect acceleration and motions without using integral. Besides, Takeda and colleagues introduced a novel approach for assessing human gait posture by utilizing a portable acceleration sensor unit. By placing these sensors on the abdomen and lower limbs, they were able to capture angular velocity and acceleration during walking. The researchers found that this technique yielded valuable insights for diagnosing gait abnormalities. Additionally, they developed a method for estimating gait posture that could determine the three-dimensional position of joint centers. By calculating flexion-extension joint angles at the hip and knee joints in healthy individuals, they were able to compare their results with those obtained from a camera motion capture system [4]. Moving on, G oteborg, Sweden's thesis explores the creation of an attitude estimation system for orthopedic and prosthetic devices that utilizes human limb orientation as an input signal. The system consists of a sensor module that measures angular rates, acceleration, and magnetic field components. An Extended Kalman Filter is employed to merge these measurements with a system model based on quaternion attitude representation. The algorithm is tested in a hardware-in-the-loop setting and implemented on a 32-bit microcontroller to minimize power consumption. The accuracy of the system is assessed for axes perpendicular to the gravity vector, with limitations identified in estimating the angle around the vertical axis due to the influence of the earth's magnetic field [5].

2.2 Motion Intention Recognition and Processing

Secondly, tactile sensors, including pressure sensors, bending sensors, and twist sensors, play a crucial role in prosthetic limbs' movement. To detect the pressure between prosthetic limbs and users' initial body parts, scientists have developed a tactile sensor composed of soft silicone that can be put between a prosthetic limb and standard connection cuffs to aid in the prosthetic limbs' ability to perceive pressure throughout. As a result, it permits a dispersed measurement of the interaction pressure, remains user-friendly, and may be used with connection cuffs of various sizes and forms. There are eight sensitive elements on a printed circuit board (PCB) that form the basis of the tactile sensor's operation. The TX, which can emit LED light, and the RX, which can receive light, are located on the PCB. Fig. 1 indicates that pressure squeezes the soft silicone portion, changing its shape. As a result, the sensor will have an impact on how much light RX can receive, and it will then function as a proportional pressure transducer overall [2]. The size of the silicone bulk and the quantity of light receivers influence the pressure detection's spatial resolution. Moving on, the bending sensor is vital for detecting the knees and feet's angles. Bending sensors are significant for artificial limbs because humans' legs and feet need to bend to different degrees during sitting, walking, or even running. However, because of its imperceptible changes, bending sensors must be so accurate that they should be able to capture every little bend in knees and ankles. Bending sensors can detect the bending angles in human bodies and then increase their resistances when angles increase and reduce their resistances when bending angles decrease. Using this technique, the measurements in artificial limbs' bending angles can be more accurate and flexible.

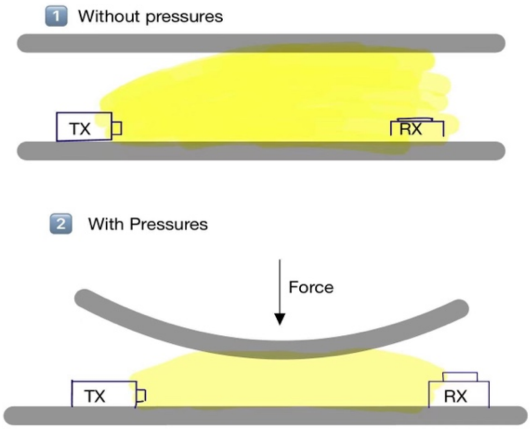

Fig. 1. The perception principle of a tactile sensor. (Picture credit: Original)

Furthermore, a study developed by Wang and his groupmates demonstrates that an inertial measurement unit (IMU) was used to monitor the motion status of a lower limb amputee's healthy leg. IMU data from the early swing phase of a healthy leg was analyzed and fed into a convolutional neural network (CNN) to predict motor intention without expert involvement. This method can help adaptively calibrate the control strategy of a driving power intelligent prosthesis for both unilateral amputees and healthy individuals. The motion state of lower limbs has inherent regularity. Regularity is usually studied in a single gait cycle, which consists of a swing phase and a stance phase. Then, there are steady phrases and transitional phrases during a swing phrase. Inspired by the hierarchical organization of the mammalian visual system, CNN has achieved notable technological breakthroughs in object detection, semantic segmentation, and image classification. Because of its great regularization and efficiency in local architecture, it has been an engineering success. When it comes to processing signals and time series, CNN is highly effective. This is especially true for wearable sensor-based human activity recognition. To improve intent recognition, this research attempts to build a CNN structure that automatically extracts high-level and mid-level features from sensor data without any prior information [6]. Lastly, recognizing the intention is a vital step to help prosthetic limbs become more intelligent. When people move by their legs, their brains' neurons will spread signals to their muscles, and then, users' muscles will contract or relax. Thus, people can move their bodies as an entire system, in which every component can cooperate well with each other. Prosthetic limbs can be more intelligent if they can also connect other body parts, which means that prosthetic limbs should be able to percept muscles' movements and respond to them. SEMG, a non-biological electrical signal, directly reflects human movement intention when neurons transmit it to lower limb muscles, allowing for accurate estimation without loss of information [7]. In this method, there are eleven electrodes put into users' lower muscles to detect muscles' movements. Therefore, based on the experiments mentioned in the article, the accuracy reaches 99.7% [7]. sEMG, in fact, is a kind of sensor that can detect the weak electrical potential produced by muscle cells in response to electrical or nerve activation [8]. Additionally, signals that are produced by walking and running may be different so that EMG can make a judgment first. Therefore, with EMG, the artificial system can notice if users want to run, walk, or sit down using their legs, and then, EMG can inform other parts of prosthetic limbs to prepare for the following movements. Furthermore, after detecting and judging many different motion styles, EMG can divide motions into different models by bending angles, forces, and so on. For instance, Hammerstein and Hill muscle models are two kinds of models that are divided by muscle force. After deciding on models, active training will start to train prosthetic limbs [8].

3 Challenges of current sensor technology in the application of intelligent prosthetic limbs and Prospects

3.1 Accuracy

Accuracy is a significant factor in deciding whether sensors are proper in making prosthetic limbs. Prosthetic lower limbs, especially knees and feet, need to be extremely flexible and accurate. That is because there are slight differences in bending degrees, neuron signals, moving trends, and some other measurements in different movements. Therefore, to make those prosthetic limbs fit in with users better, those sensors must be very accurate. However, Table 1 indicates that accuracy is still the most serious problem in sensor applications in prosthetic limbs. Those inaccurate sensors are included in many different aspects, such as in sEMG and bending sensors.

For instance, sEMG is the mainstream sensor type in commercial upper limb prostheses. However, sEMG has disadvantages such as limited signal stability and being easily affected by sweat and skin surface conditions; and the number of signal sources is insufficient, and it is very difficult to control multi-degree-of-freedom prostheses with only two sets of electrodes. To solve this problem, scientists extract and distinguish information from signals to catch users' true motion intentions better. For example, in comparison to conventional Champagne, SBF, and other methods, the Bayesian source filter for signal extraction (BSFE) can increase the signal-to-noise ratio and improve the resolution of nerve beam signals by a factor of three to twenty. Additionally, the cooperation of IMU and sEMG can increase the accuracy of electroencephalograms by more than 50%. With an accuracy of 83.5%, MMG assesses the contraction and relaxation of muscle movement only based on the lateral vibration of the muscle, avoiding interference from perspiration and skin [9].

Furthermore, for the double-angle problem in bending sensors, scientists found that The axis can be analyzed based on the position of the cylinder piston during knee joint movement. To solve the issue of double values, the piston position where the potentiometer output derivative is zero can be determined, and a Hall sensor can be used to detect when the cylinder passes. This method helps establish a single-value mapping relationship between the potentiometer output and the knee joint bending angle. By setting the Hall sensor at a knee angle of 83°, the double value problem is resolved by identifying the piston motion position.

3.2 Perceived Frequency

Perceived frequency is crucial in receiving information and vital signals. If sensors have difficulties in collecting signals, they cannot make decisions accurately and properly. Therefore, people know that perceived frequency is a fundamental measurement for sensors to carry out normal functions. Based on Table 1, people can see that only sEMG meets difficulty in receiving signals. Therefore, because sEMG is vital for detecting human body muscles' movements to forecast human motion intentions, knowing slight muscle movements is important. To solve the problem, scientists found out that TMR is a technique that uses muscle tissue as an indirect amplifier to obtain nerve signals through the intact cortical-peripheral nerve pathway [9]. Therefore, using this TMR technique, sEMG can detect even very slight movements in human bodies and receive slight neuron signals, which helps a lot in making the forecast of motion intention more accurate.

3.3 Efficiency

Sensors in prosthetic limbs, which need quick responses and immediate decisions, are required to detect data efficiently. After collecting data on human movements and moving intentions, those data should be shared for the entire prosthetic limbs' systems effectively. That is if data cannot be generated into the system, the prosthetic limbs still cannot respond to their measurements. Table 1 demonstrates that foot pressure signals cannot be easily generated into the systems. Thus, scientists pointed out that the control method needs to divide the gait cycle into the support period and the swing period. The support period refers to the foot from the ground to the foot from the ground, and the swing period refers to the foot from the ground to the foot from the ground. Different control methods are adopted during the support period and the swing period. During the support period, keep the needle valve fully closed, enhance the stability of the prosthetic limb, and improve the energy storage characteristics of the lower limb prosthetic limb. During the swing period, adjust the opening of the needle valve according to the angle of the knee joint. To divide the support period and the swing period, you need to find the moment when the tip of the foot is off the ground and the foot is on the ground [10]. The signals cannot be generated because, in different motion conditions, the movements and pressure conditions cannot be regarded as the same condition, so separating periods and using different methods can effectively solve this difficulty.

Table 1. Sensors' comparison in accuracy, perceived frequency and efficiency

Sensor type	Accuracy	Perceived frequency	Efficiency
sEMG	Being easily affected by sweat and skin surface conditions.	Difficult to control multi-degree-of-freedom prostheses with only two sets of electrodes	Surface EMG (sEMG) cannot be used to quantify the force developed by a muscle at a given time, as direct measurements are difficult due to the large number of muscles involved.
Tactile sensors (Pressure sensors)	The sole pressure division support phase and swing phase can be directly detected.	Only detect some points' pressure cannot represent the entire pressure condition.	The foot pressure switch is difficult to integrate into the intelligent prosthetic body.
Acceleration sensors (Hall sensor)	Structural strength limitation	Signal only high and low-level change, easy to detect and use	The information provided is limited and cannot be relied upon to differentiate between the support and swing phases
Bending sensors (The potentiometer)	The output cannot be relied upon to accurately determine the supporting and swinging phases.	With a large amount of information, you can get the knee angle information at any time.	Poor robustness and short lifespan

4 Conclusion

This passage has introduced many sensors' applications in the prosthetic limbs, such as bending sensors, twist sensors, inertial sensors, and EMG, and pointed out their advantages and shortages in carrying out normal functions in patients' daily lives. The first part explains motion capture sensors, tactile sensors, and EMG's basic working theories and their significance. Moving on, the second part mainly compares the accuracy, efficiency, and perceived frequency of sensors that are mentioned in the first part. Also, after comparing their characteristics, this part demonstrates the challenges of using those sensors in prosthetic limbs.

Lastly, part two also gives some solutions that may solve the difficulties. Nowadays, techniques in making prosthetic limbs are becoming more and more mature. There are many solutions and methods to improve the accuracy, efficiency, and signal receiving. In the future, scientists might try to combine these sensors and try to make them cooperate better with each other and form a better prosthetic limbs system. This article teaches readers some fundamental concepts regarding the uses of sensors and makes them aware of the benefits and drawbacks of various sensors. However, there are still many challenges that cannot be solved currently. Fortunately, scientists are paying more attention to prosthetic limbs and doing more and more research. With the development of technology and scientists' efforts, prosthetic limbs must be more convenient and comfortable for users to wear. At that time, disabled people could wear these prosthetic limbs and move freely without worries and anxiety.

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