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A Real-Time Spine Orthopedic System Based on Bluetooth Low Energy and Internet of Things

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ABSTRACT A real-time spine orthopedic system based on Bluetooth Low Energy (BLE) and Internet of Things (IoT) is proposed in this paper. The proposed system could realize the networking communication based on BLE, and upload the device data onto the cloud server via a 4G/5G communication network. IoT integrated with cloud servers and terminal applications allows the real-time monitoring process of spinal orthopedics. The digital linear actuator in the device can stretch through program control, in order to realize the accurate control of spinal orthopedic process. Then, the user could query and store the running information about the device through the personal computer-side web or mobile phone with remote control. In addition, the multi-device database is built on the cloud server, which is conducive to the further analysis and processing of spinal orthopedic data. This article presents the hardware design of spinal orthopedic device, builds the user software at the application layer, and forms the multi-device database through the cloud server. The final experimental results show that the proposed system can realize the function of spinal orthopedic and upload the device data in real-time.

INDEX TERMS Spinal orthopedic, Bluetooth Low Energy (BLE), Internet of Things (IoT), cloud database.

I. INTRODUCTION

Early-onset scoliosis (EOS) refers to the spine deformity that occurs before the age of 10, with a scoliosis angle greater than 10°. In order to improve the spine deformity while maximizing the growth potential of the spine, the common surgical operation for EOS is the growing rod technique [1]. The traditional growing rod (TGR) technology is to correct the patient's spine through surgery and use the growing rod for fixed support, which requires multiple operations during the patient's entire treatment cycle [2]. Therefore, the patient is also at increased risk of complications due to repeated operations. In addition, in the process of spine correction, the real-time correction effect of the spine is difficult to quantify and transmit. It is impossible to accurately adjust the surgical plan in time according to the current situation.

In view of the need for multiple surgical operations in the treatment cycle, a magnetic control growing rod (MCGR) technology that add a magnetic control module to the growing rod was proposed in [3]. The size of the magnetic field can be changed by the external controller, and then the internal magnetron module can generate magnetic force to push the growing rod to prop up the deformed spine. Later clinical experiments show that MCGR can correct spinal deformity by controlling the growth of implanted growing rod through external magnetic field. The authors of [4] used a deep learning algorithm to classify scoliosis and applied it to routine scoliosis screening. The experimental results showed that compared with the manual diagnosis and analysis by relevant experts, the algorithm has good accuracy in the diagnosis of scoliosis.

With the continuous development of Bluetooth Low Energy (BLE) [5] and wireless charging technology [6], as well as the widespread application of the Internet of Things (IoT) and cloud technology [7], [8], there may be better solutions for spinal orthopedics. BLE technology can realize wireless communication between devices. Compared with classic Bluetooth, BLE further reduces the overall power consumption and increases the running time of the device on the basis of reducing the data transmission delay [9]. The authors of [10] used BLE for data acquisition from opportunistic sensors and investigated the performance of

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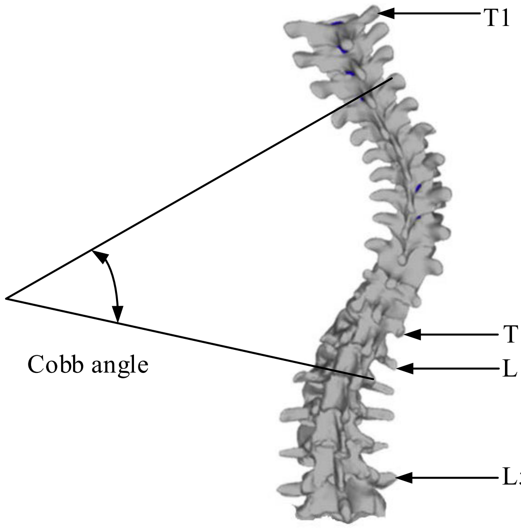

FIGURE 1. Schematic diagram of cobb angle [18].

BLE both analytically and experimentally. The experimental results showed that the BLE sensor node is able to achieve a lifetime of more than one year at a rate of 10 Mbit/day. In order to study BLE beacons for IoT applications, the data processing procedure to generate the BLE-compatible advertising packages was proposed in [11]. The application of wireless charging technology in smaller electronic devices has effectively solved the battery life problem caused by the miniaturization of the device [12]. IoT platform allows various devices to access the Internet, receive information from the device, and store and manage the information through a cloud database [13], [14]. At the same time, it can also control the device through remote control commands [15]. Considering the advantages of the above technologies, this paper proposes a spinal orthopedic system based on BLE and the IoT platform.

II. SPINAL ORTHOPEDIC THEORY

A. COBB ANGLE AND ORTHOPEDIC EFFECT OF SCOLIOSIS

Making a vertical line along the extension line of the spine at both ends of scoliosis and the included angle between the two vertical lines is the Cobb angle of the coronal plane of the spine [16]. The schematic diagram of Cobb angle is shown in Fig. 1. In the treatment of spinal correction, the size of Cobb angle determines the treatment method of scoliosis and the amount of correction [17]. Whether conservative treatment or surgical treatment, the purpose is to restore the deformed spine to its original position as much as possible.

The T1 in Fig. 1 represents the first thoracic vertebra and L5 represents the fifth lumbar vertebra. The vertical distance between the centers of the two is the T1-L5 spine length. The quantitative relationship between this parameter and Cobb angle is shown below:

$$\Delta L = L_0 - \alpha \Delta\theta + \beta \Delta\theta^2 \tag{1}$$

where, L_0 represents the initial value of the T1–L5 spinal length, $\Delta\theta$ is the amount of change in Cobb angle, ΔL represents the increase in T1–L5 spinal length, α and β represent the coefficients of the fitted curve [19].

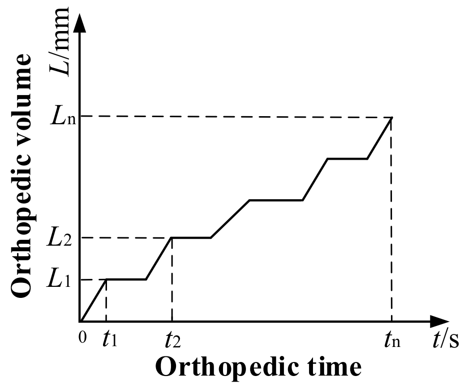

FIGURE 2. Spinal orthopedic method based on linear actuator.

B. SPINAL ORTHOSIS BASED ON BLE AND LINEAR ACTUATOR

In the surgical treatment of EOS, the TGR technology can preserve the growth potential of the spine to the greatest extent while treating scoliosis. However, due to the physiological characteristics of the spine, the theoretical maximum amount of orthopedic unable be produced by a single operation in the TGR orthopedic [20]. At the present, there is no optimal conclusion on the regular extension of the interval of the traditional growing rod. However, repeated surgical operation in the treatment cycle is easy to lead to complications and other problems. Therefore, this paper proposes a spinal orthopedic method based on BLE and linear actuator. The orthopedic function of the linear actuator in the body is controlled by BLE communication, and the orthopedic amount of scoliosis is converted into the stroke of the linear actuator.

As shown in Fig. 2, the whole treatment cycle can be divided into n stages according to time and orthopedic amount. The linear actuator can generate orthopedic amount according to actual needs. In addition, since the system is controlled by external BLE command, the problem of repeated surgery in the treatment cycle is avoided while ensuring the accuracy of scoliosis correction. The relationship between the total stroke of the linear actuator and the number of operation is as follows:

$$L_n = \sum_{i=1}^{n} \Delta L_i \tag{2}$$

where, L_n is the total stroke of the linear actuator after n times of operation, ΔL_i is the distance of a single operation.

III. DESIGN OF MATERIALS

A. SYSTEM ARCHITECTURE

The system is mainly composed of wireless charging module, lithium battery, power management module, control part, linear actuator, growing rod, mobile terminal program and cloud database. The control part is composed of main control

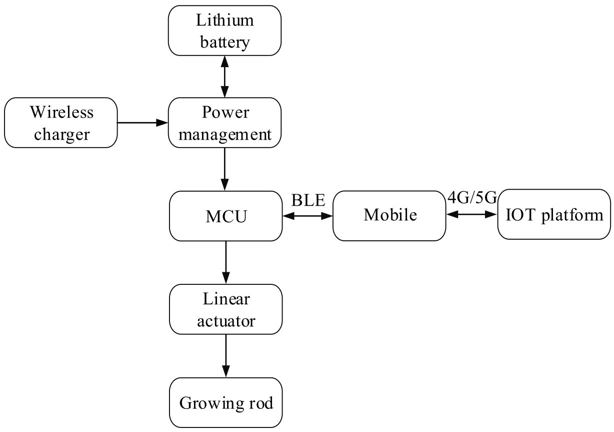

FIGURE 3. Structure diagram of spinal orthopedic system.

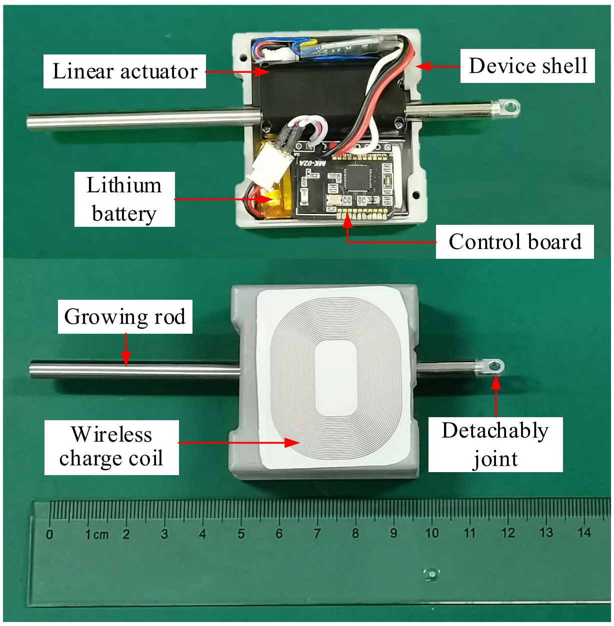

FIGURE 4. The physical figure of spinal orthopedic device.

chip and driving circuit of linear actuator. The MCU of this system transmits information with external communication equipment through BLE. It could accept control commands and feeds back the current status of the device to the external communication equipment. In addition, the chip can output a PWM signal of corresponding frequency to the drive circuit to drive the operation of the linear actuator. During the system idle time, the chip will enter the low-power mode to reduce the system power consumption. As the part of the device, the mobile phone communicates with the cloud database through the WeChat applet. The received information will be uploaded to the cloud database of the IoT platform for data storage and management. The structure diagram of spinal orthopedic system based on BLE and IoT platform is shown in Fig. 3.

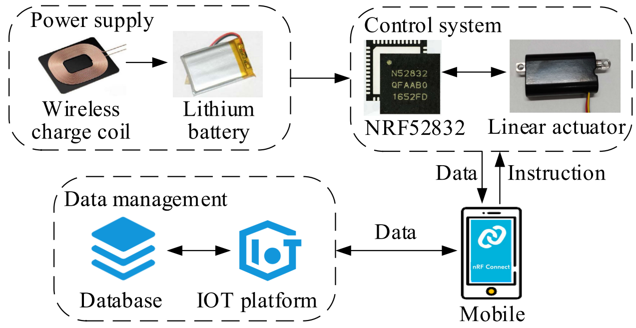

FIGURE 5. Architecture diagram of control system.

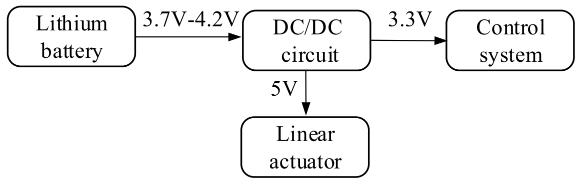

FIGURE 6. Schematic diagram of power conversion circuit.

Through the system design, the spine orthopedic device based on BLE is shown in Fig. 4. The length of the device shell is 46mm, the width is 45mm and the thickness is 20mm. The control board is connected with the linear actuator through the driving circuit and can receive the control command through BLE communication to drive the growing rod for elongation. Both ends of the linear actuator are connected with a growing rod. The growing rod at one end is provided with a detachable interface, which can replace the growing rod of different lengths. The wireless charging coil is attached to the shell. When implanted into the body, it can receive the electric energy transmitted by the external wireless transmitting device to power the system.

B. HARDWARE

1) SYSTEM CONTROL CORE

This system selects NRF52832 produced by Nordic Semiconductor Company as the MCU. The Architecture diagram of control system with NRF52832 as the core is shown in Fig. 5. As an ultra-low power, Bluetooth-enabled microcontroller, NRF52832 supports BLE, and provides 12 PWM output channels.

The chip can be used in personal wireless wearable devices for communication of heart rate and blood oxygen saturation detection data [21]. As a general multi-protocol system on chip (SOC), it can communicate autonomously and keep the CPU dormant during the communication process to reduce system energy consumption.

2) POWER CONVERSION CIRCUIT

The operating voltage range of the lithium battery of this system is 3.7V-4.2V, the operating voltage of the MCU of the system is 3.3V, and the operating voltage of the linear drive is 5V.

Therefore, the voltage of the lithium battery needs to be converted through the power conversion circuit to supply power to the MCU and linear actuator. As shown in Fig. 6, the power conversion circuit is divided into two parts: voltage stabilization and boost. In order to power the main control chip, the voltage stabilization part uses the linear voltage regulator chip TPS73633 to convert the voltage of the lithium battery into 3.3V. To ensure the linear driver power supply, the boost part uses the synchronous rectification boost chip PS7516 to boost the lithium battery voltage to 5V.

3) WIRELESS CHARGING MODULE

The spinal orthopedic device communicates with the outside world through BLE in the body, and drives the linear drive to perform spinal orthopedic work. The lithium battery used in this device has a capacity of 400mAh, which is difficult to power the device for long-term operation in the body. In order to solve this problem, a wireless charging solution is proposed in this paper. The designed power is equipped with a wireless charging module. And the lithium battery in the spinal orthopedic device receives the electrical energy of the sending device outside the body through the receiving module and the wireless charging module. In this way, the devices implanted in the body can be wirelessly charged to ensure the normal operation of their functions.

The highly integrated wireless receiver chip BQ51013b produced by Texas Instruments (TI) is selected as the fully synchronous rectifier of the wireless charging receiver. The AC/DC conversion efficiency of this chip can reach 93%. By configuring its peripheral circuit, the wireless charging module can provide the lithium battery with a rated output voltage of 5V and an output current of 1A.

4) DIGITAL LINEAR ACTUATOR

For a better realization of the orthopedic effect of the spine and improve the accuracy of the orthopedic, a digital linear actuator is selected to provide power for the device. The relevant parameters of the digital linear actuator used are shown in Table 1.

The maximum thrust that the linear actuator can generate is 30N, the total stroke is 20mm, and the stroke of a single operation can be controlled at 1mm. The MCU can control the operation of the linear actuator by outputting the PWM signal. In the drive circuit of the linear actuator, the DRV8837 chip is used to be the drive chip. This chip could read the PWM signal output by the MCU through the signal acquisition channel. As a drive chip, it can also control the linear actuator operation according to the instruction.

C. SOFTWARE

1) DESIGN OF EMBEDDED PROGRAM

The spinal orthopedic device uses the digital linear actuator as the power source. In order to ensure that the driver can accurately achieve the expected goal, the travel of the driver is decomposed. Different driving instruction sets are designed to ensure that the device can accurately drive the power source according to different treatment schemes in the process of actual operation. Record the initial position of the driver as the origin. The stroke of the driver under the different instruction sets is shown in Table 2.

The embedded program flow chart of spine orthopedic system is shown in Fig. 7. After the system is powered on, start initialization, then start Bluetooth broadcasting and wait for the host to connect. When Bluetooth connection request is detected by the MCU, the security components of the

TABLE 1. Digital linear actuator parameters.

Parameters of linear actuator	Value
Rated voltage	5V
Rated current	100mA
no-load speed	12mm/s
Total stroke	20mm
Maximum thrust	30N

TABLE 2. Driver stroke under different instruction sets.

Instruction set	Single stroke(mm)	Times	Accuracy
I	1	20	
II	2	10	
III	4	5	±0.01mm
IV	5	4	
V	10	2	

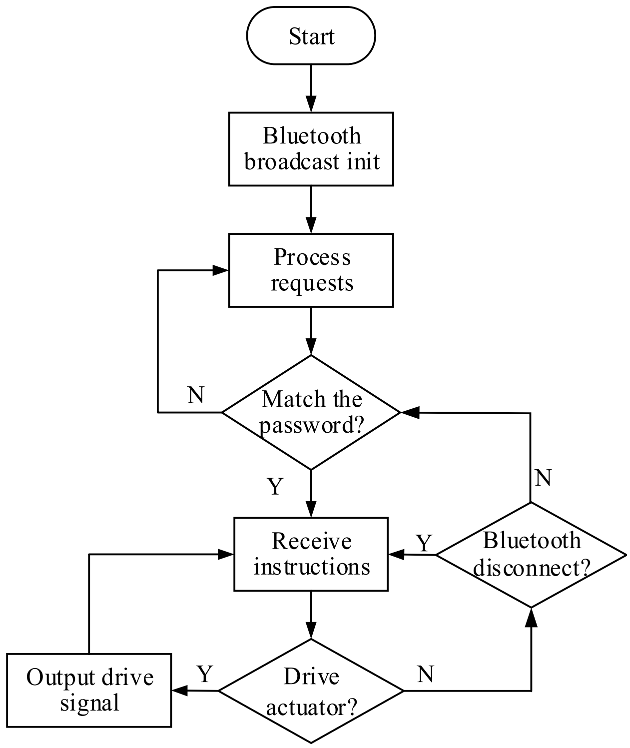

FIGURE 7. Flow chart of the main program.

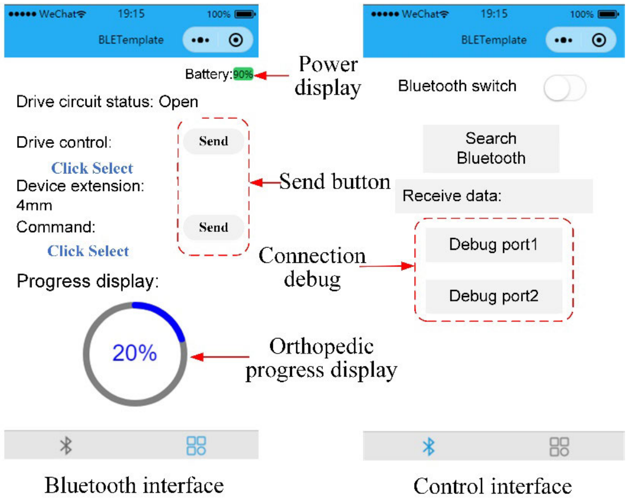

FIGURE 8. WeChat applet interface.

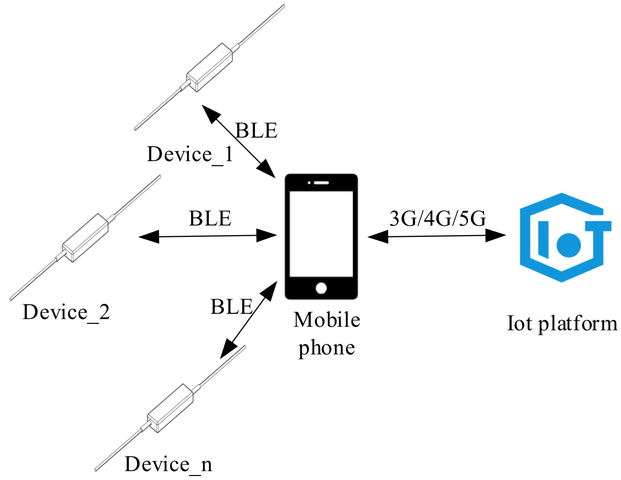

FIGURE 9. Multi-device cloud data management system based on IoT.

MCU will send a password verification request for the host. After the verification, system will connect the Bluetooth and wait for the command of the host. If the verification fails, it will disconnect and wait for the connection request of the host again. When receiving the command sent by the host, feedback the received information to the host, and then judge the command. If it is the control command of the motor, the system will turn on the power supply of the motor and output the control signal. After this, the system will upload the data and return to the command receiving place. If the determination result is no, determine whether Bluetooth is disconnected. If the command is Bluetooth disconnection, the system will enter the standby mode and wait for the connection pairing request of the host again. Otherwise, the system will return to the command receiving place and continue to accept the command of the host.

2) DESIGN OF USER APPLICATION

The design and development of the mobile terminal program in the system is based on the WeChat developer tool Stable Build. The designed WeChat applet is used as the medium of information communication between the spinal orthopedic device and the IoT platform in the system. This not only realizes the transmission of motor drive commands and the display of orthopedic progress, but also allows the uploading of data to a cloud database via mobile communication. The user interface of WeChat applet is shown in Fig. 8.

Through the WeChat applet, users are able to more intuitively view the correction progress and wirelessly control the on/off of the driving circuit and the operation of the driving device. Moreover, the applet can also store the operation log through the mobile network, thus ensuring the real-time display and recording of the orthopedic process and improving the safety and reliability of the system. On this foundation, in order to facilitate users to view the operation of the equipment in real time, the user interface of the applet is designed and laid out.

3) DATA MANAGEMENT SYSTEM BASED ON CLOUD SERVER

The cloud server receives the operation information of the underlying device from the mobile applet through 3G / 4G / 5G mobile network. The collected equipment operation data is uniformly managed by the database. After the database is processed, the data can be transmitted to the mobile terminal through HTTP protocol, which is convenient for users to view. Furthermore, through the orthopedic progress in the uploaded data, the multi-device based spinal orthopedic model is established to further mine the spinal orthopedics scheme.

The multi-device cloud data management system based on the IoT is shown in Fig. 9. Create the data management system in the cloud server, establish a database of PHP scripts, and open the HTTP access interface.

The mobile terminal program can access the database through HTTP protocol to upload and download data. The user can also select the viewing device in the user interface of HTML web page and enter the database of the selected device to view real-time data and historical data.

IV. ASSESSMENT AND ANALYSIS

A. SYSTEM EXPERIMENTAL PLATFORM

As shown in Fig. 10, the experimental platform of spinal orthopedic system mainly includes thrust test bench, spinal orthopedic device, wireless charger and communication devices. The tension of the device and the elongation of the growing rod have an important influence on the orthopedic effect. Therefore, the thrust test bench is used to simulate the spine and measure the tension of the orthopedic device on the spine. The wireless charger is used to charge the experimental device during the test. The communication devices include a mobile phone with client program and a personal computer that can connect to the Internet and access device information

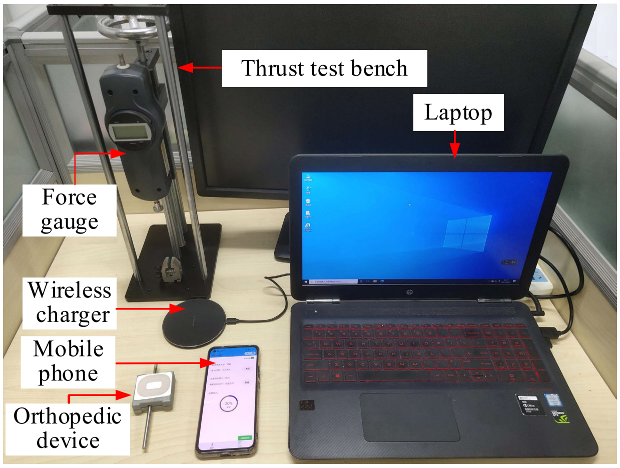

FIGURE 10. Experimental platform of spinal orthopedic system.

TABLE 3. Test results of orthopedic performance.

Test items	Test parameters	Test results
Performance	Maximum thrust	30.06N
	Average speed	11.8mm/s
Stroke	Maximum stroke	20mm
	Single minimum stroke	1mm

TABLE 4. Test results of system power consumption.

System state	Current(mA)	Consumption(mW)
Bluetooth broadcast	7.35	29.55
Bluetooth connectivity	7.14	28.70
Data transmission	7.82	31.44
Orthopedic state	125.45	508.7

from the cloud database. Then, the communication devices are used to verify the BLE communication function of the spinal orthopedic device and the transmission of device data.

B. HARDWARE TEST

After the experimental platform is built, the hardware function of the spinal orthopedic system is tested comprehensively. In the user program of the mobile phone, BLE communication is used to control the extension of the orthopedic device. The power of the linear actuator is accurately tested by using a thrust test bench with a division value of 0.01N. In the hardware test, 500 times of remote control are automatically carried out through the mobile phone program, and the orthopedic device can produce a maximum thrust of 30.06N during elongation. The orthopedic performance test results are shown in Table 3.

The application scenario is complex and the device works in vivo, so it is necessary to detect the running power consumption of the system. The current parameters of spinal orthosis device are recorded under different working status of system operation, and the power consumption in each state is calculated. A total of 200 tests are carried out under the condition of power supply voltage of 4.02V. The power consumption test results of spinal orthopedic system are shown in Table 4. The power consumption of the system during Bluetooth broadcasting is 29.55mW. After Bluetooth connection, the minimum power consumption without data transmission is 28.70mW, because the system enters the low power consumption mode. In this case, the power consumption of the system is reduced by 2.7% compared with Bluetooth broadcasting. The system will generate 125.45mA working current when driving the linear actuator to extend.

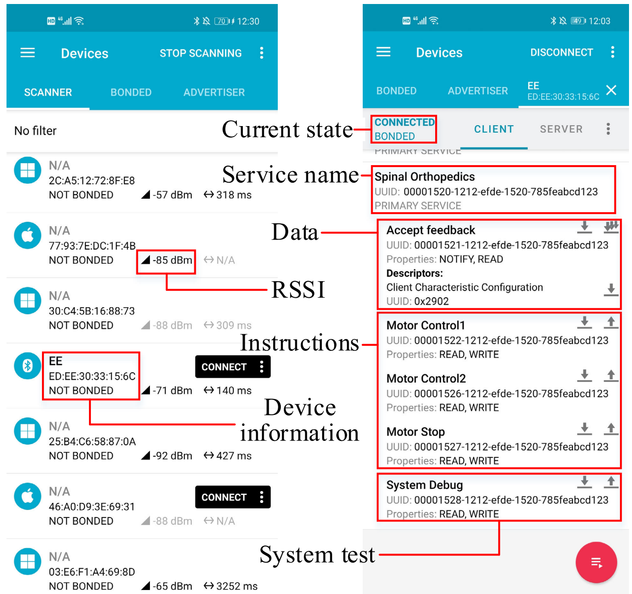

FIGURE 11. Test interface of bluetooth communication.

C. COMMUNICATION FUNCTION TEST

In the Bluetooth function test, the Bluetooth communication function of the main control chip of the orthopedic device is tested by using the NRF connect mobile terminal Bluetooth debugging program. The device can connect with the outside through Bluetooth, receive the control command through Bluetooth and send its own operation to the mobile phone. The spinal orthosis device communicates with the mobile phone through Bluetooth, and the communication test interface is shown in Fig. 11.

The connection interval is 7.5ms, the packet length is 20bytes, and the packet is sent 5000 times. The time interval between two data frames is 22.3ms, the average transmission rate is 5.45Kbps and the packet loss rate is 0. The latency of the 4G network of the cloud server with database is around 18ms and the transmission rate is about 100Mbps. Through the data transmission between spinal orthopedic device and IoT platform, the IoT communication function of the system is tested. The results show that the system can stably upload the operation data of the equipment. Users

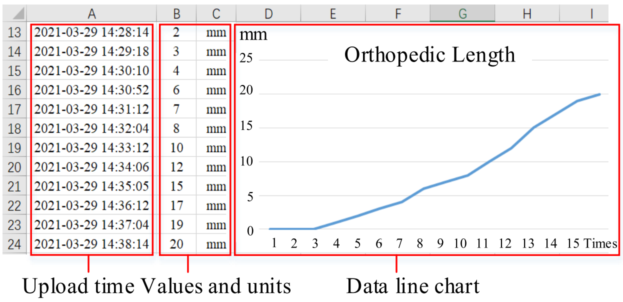

FIGURE 12. Export data from the server to excel in.csv format.

TABLE 5. Comparison of different treatment methods for EOS.

Items	Method	Repeated surgeries	Real-time
TGR system	Surgery	Yes	No
MCGR system	Magnetic	No	No
System in this paper	BLE	No	Yes

can monitor the operation of the device through the mobile application on the mobile phone and the visual user interface of the personal computer network. The operation data of the device can be exported from the cloud database to excel for further processing and data mining, as shown in Fig. 12.

Based on the user interface of mobile and IoT platform, the spinal orthopedic system proposed in this paper is more convenient in orthopedic operation compared with the MCGR system and TGR system. In addition, the orthopedic effects of the MCGR and TGR system need to be obtained through other medical imaging devices [22]. The system proposed in this paper enables real-time monitoring of spinal orthopedics through the Internet of Things. The comparison between this system and the other two systems for EOS treatment is shown in Table 5.

V. CONCLUSION

To solve the problem that the traditional scoliosis orthopedic treatment needs to be carried out many times and unable effectively monitor the orthopedic effect, a spinal orthopedic system based on IoT and BLE is proposed in this paper. The data transmission between the controlled device and the mobile application is realized through BLE technology. The mobile application is designed to realize network communication and real-time data upload. The device operation database on the cloud server side is built to realize the real-time access of device data, and cooperate with the visualization interface to process and feedback the data. The test results of the system prove that the system can communicate and control wirelessly through BLE, and realize the spinal orthopedic function by controlling the digital linear actuator. The experimental results show that the system provides a reliable solution for real-time spinal orthopedics and orthopedic data management.

VI. DISCUSSION

The above experiments are performed with equipment to simulate the spine. In the future, deep learning algorithms will be used to analyze the data in the database to form more suitable orthopedic solutions for patients. Then, animal experiments would to be conducted, and hope this system can be used for clinical treatment of EOS soon.

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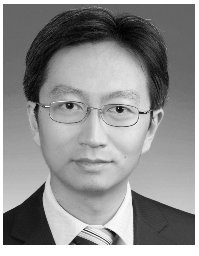

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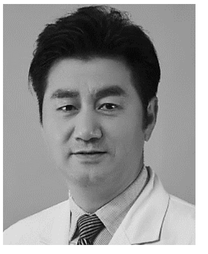

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