Design of Rechargeable Battery System for Mandibular Distraction Osteogenesis Device

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***Abstract*—Distraction Osteogenesis (DO) is a novel limb lengthening technique for reconstruction applications in the human body. In Maxillofacial Reconstruction Applications (MRA), DO has got an important role and has been used as an effective solution compared to conventional reconstruction methods. Recently, the application of Automatic Continuous Distraction Osteogenesis (ACDO) devices has been emerging. Different methods have been used and ACDO devices could enable a successful automatic DO procedure. However, this novel technology is still limited to be used in human MRA. One of the important aspects in future developments on such ACDO devices is to make the device portable by implementing a rechargeable battery solution in the system. The purpose of this study is to design a high-power rechargeable battery system to be used in future development of such ACDO devices. The designed system has the capability to provide necessary power for running a ACDO device while meeting required standards and specifications. Results of the performed studies have validated the feasibility of the designed rechargeable battery system for future developments of the ACDO devices.**

***Index Terms*—Rechargeable battery system, automatic distraction osteogenesis, medical devices.**

I. Introduction

Distraction Osteogenesis (DO) is a novel limb lengthening technique in human body reconstruction. DO can be used for generating bone tissue, filling skeletal defects, or correcting bone defects. In Maxillofacial Reconstruction Applications (MRA), DO has got an important role as a new solution for bone regeneration and reconstruction without the need for bone graft. In this technique, the bone generation happens along with adaption of limb's tissues with a more predictable result [1]-[8]. A standard DO procedure starts with bone osteotomy and installation of mechanical bone distractor. Subsequently, a variable latency phase of several days for soft callus formation takes place, and then, the distraction phase begins. After the distraction phase, there is a consolidation phase, after which the device is removed [9]-[11]. In conventional methods, during the distraction phase, the DO device is activated manually with low accuracy, low reliability and a long treatment period [11]-[15]. Recently, Automatic Continuous Distraction Osteogenesis (ACDO) devices have been emerging as an enhanced solution with a better performance while providing more advantages in comparison to the previously mentioned conventional DO methods [16]-[25]. In the DO method, automatic devices have enabled applying a continuous distraction on the bone regeneration procedure which have provided superior results in the outcome of the treatment [2], [16], [17]. Therefore, by implementing advanced engineering techniques, high precision automatic controllers and linear movement methods in an ACDO device; a faster DO procedure with a better bone generation quality while reducing side effects and complications during the treatment is possible. ACDO devices could be categorized into two groups; motor-based systems by implementing an electro-mechanical system and linear components [1], [2], [12], [13], [21], [26]-[28], and hydraulic-based system by implementing a reservoir, pump, pressure relief valve, and other linear components [18], [29]-[32]. In both categories, developed devices can generate motion in a linear axis.

ACDO devices are recently emerging in MRA; research and developments have been more focused on developing distraction methods and technical aspects of ACDO devices. Recently developed ACDO devices can completely cover all technical standards and requirements of the DO procedure in an automatic continuous distraction manner. All treatment conditions could be covered in an ACDO procedure. Therefore, further developments on successful ACDO methods could potentially be used in human MRA. More research and development needs to be conducted on other aspects in an ACDO device. Designing small size and portable devices is one of main challenges which requires more attention in future developments; most of developed devices are prototype and ex vivo models, and do not have standard criteria to be used in human MRA. In addition, ACDO devices need a power source for running the system. In most previous studies, a non-portable power supply is used for providing the required power; this limits the application of such devices. A portable ACDO device, which meets required standards for a successful DO

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procedure, would be an ideal choice for human MRA. Only a few studies have been performed on designing and developing a portable battery system for developed devices. Fig. 1 represents a battery system which has been developed for an ACDO device developed by Chung *et al.* [21]. This system utilized a UBC322030 polymer Lithium-ion (Li-ion) battery. The chosen battery proved to meet all the electrical characteristics of the ACDO system, however, since this battery system formed part of an implantable ACDO device, it was essential that the battery was a suitable size for the system and did not present major safety concerns. In the work presented by Magill *et al.* [31], various power sources were utilized. The rationale of this power system implementation was that each power supply was utilized only when power was required from a certain device within the control system, thus maximizing battery life. A coin cell battery, 3.3 V power supply and 12 V power supply were the main components within the power system. Only the coin cell which powered the real-time clock chip was consistently active.

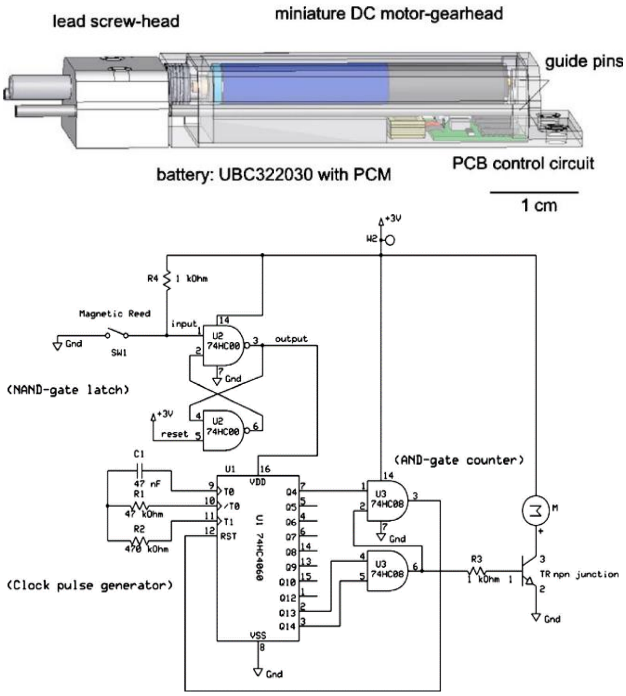

Fig. 1. A designed and developed battery system for ACDO device [1]

However, the application of developed ACDO devices is still limited to experimental and animal studies. There are still various limitations for using such ACDO devices in human MRA [1], [12], [21]. The purpose of this study is to design a rechargeable battery system specifically for a recently developed ACDO device [2], [33]; The distractor is a recent solution in ACDO devices which has shown superior performance compared to previously developed devices. By implementing the Multi-Axis Automatic Controller (MAAC) linear control method [34]; this device has a very high distraction accuracy, 7.63 nanometers per distraction step, while enabling a continuous distraction force by using a novel automatic linear controlling method. This device has met all necessary requirements of a standard DO treatment protocol. Therefore, further developments on this distractor could be making this device portable. Designing a high-power and rechargeable battery system is one of the main steps for making this device a suitable mobile distractor for human MRA. The objective is that by implementing such a battery system, the ACDO device can be made mobile, which can potentially result in the implementation of this technique in human MRA. In the proposed battery system, a power conservation system, DC switches, a display, storage device, and a controller are used. The proposed system can provide necessary power for running the mentioned device. It has a long endurance and it is rechargeable. The battery system has the capability to get attached to the distractor and provide necessary power for continuously running the distraction procedure. After the theory and design of the proposed battery system, the simulation results of the battery test is presented to validate the feasibility of the design, to assess the performance of the designed battery system, and to identify key challenges that need to be addressed in further development of the system.

II. Design of Rechargable Battery System

To power the distraction process, the design of the rechargeable battery system consists of four battery cells, a controller, four temperature sensors, a power switch, a DC-DC power step-down, and a current shunt. This system has the capability to provide a 5 V DC power supply which is to power the automatic distractor [2] with stable and accurate output power, and is required to provide accurate and noiseless operation. Fig. 2 illustrates the working principle and block diagram of the designed system.

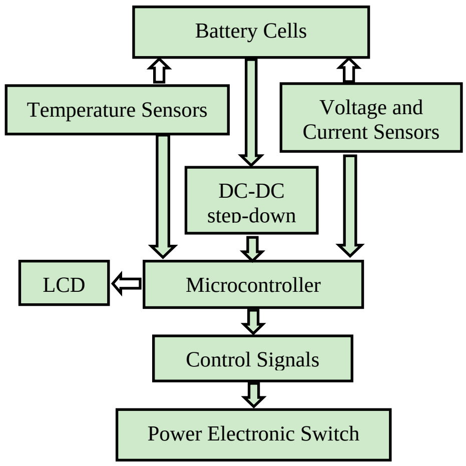

Fig. 2. Block diagram of the designed battery system

In the design of the battery system, four SAMSUNG INR18650-25R cells, with specifications mentioned in Table 1, are used. The cell configuration of the battery is two cells connected in series and two cells connected in parallel. This combination provides a nominal 7.2 V DC output with 5000 mAh power. The output of the cells is connected to a LM2596S 3A adjustable step-down DC-DC power supply. The output is set at 5 V DC. The output of step-down power supply is used as the power source of the circuit.

TABLE I. BATTERY CELL SPECIFICATIONS

SAMSUNG INR18650-25R Battery Cell	
Nominal capacity	2500mAh
Nominal voltage	3.6 V
Discharge end voltage	2.5 V
Max. continuous discharge current	20 A
Charging voltage	4.20 +/- 0.05 V
Standard charging current	1.25 A
Length	6 5.85 mm
Weight	45.0 g

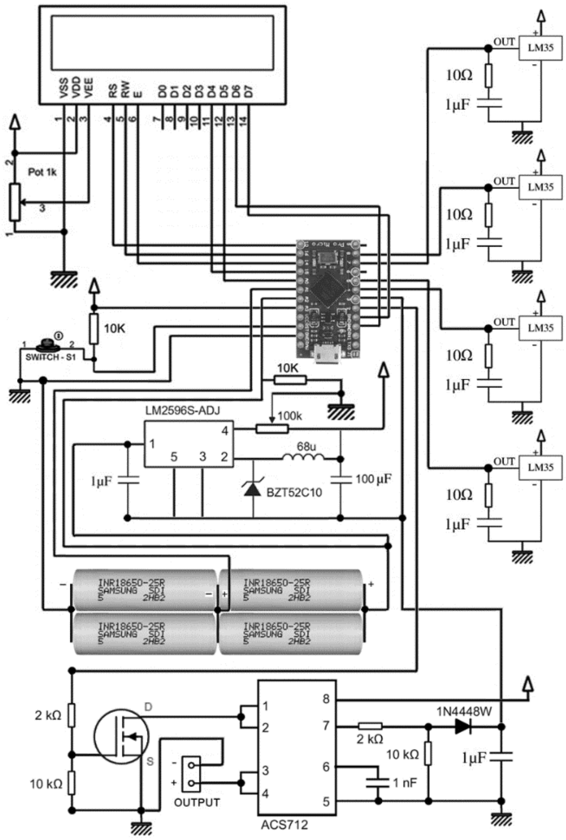

Fig. 3. The designed circuit of the system

An Arduino Leonardo Pro is implemented in the design as the controller of the battery system. This microcontroller has a very small size while utilizing an ATMEGA32U4 running in 16 MHz/5 V. This controller board has 9 channels of 10-bit ADC, 12 digital I/O ports, 5 PWM ports, and Rx and Tx hardware serial connections. Four digital temperature sensor IC, LM35DZ, are implemented in the design and connected to the microcontroller for real-time temperature measurement of each cell within the battery system. These sensors are fixed on the surface of each cell. The implementation of temperature sensing is to ensure that the cells do not experience rapid increases in temperature. If rapid temperature increases are detected, the output power of the battery is to be disabled such that no more current can be drawn from the battery as it is an indication of an error within the cells. Within the design of a Li-Ion battery system, it is essential to ensure that over-discharge does not occur. Along with temperature increases, another indication of the occurrence of a short circuit or errors within the cell is current spikes or discharge currents above the expected discharge current of the system. Thus, a DC current sensor ACS712 is implemented parallel to the battery cells and connected to the microcontroller for measuring the current. The voltage of each series connection is thus monitored by means of analog voltage sensing by implementing two ADC ports of the microcontroller. A MOSFET IRF540 driver is implemented as an electronic switch for switching the output power of the system. Based on the mentioned principles, the system is designed. A 2×16 character liquid crystal display panel is connected to the controller to display the measured voltage, current, and temperature of battery. Fig. 3 illustrates the designed circuit for the rechargeable battery system. Accordingly, battery testing examinations has been performed to justify the selected battery cells for future development of the system.

III. RESULTS

After the design of the battery system, it is required to perform a discharge test on the battery to ensure that the system requirements are met. The battery was set up as shown in Fig. 4. Within the battery set-up, two sets of parallel stings were connected in series with one another where each parallel string consisted of two cells. A Bitrode MCV 16-10 universal battery tester was used to complete the test procedure. The standard discharge test which was implemented on the battery consisted of a discharge procedure in which the battery was discharged at 1.6 A until a predefined cut-off voltage was reached. Since the battery consists of two cells connected in series and two cells connected in parallel, and the fact that the standard cut-off voltage of the Samsung 18650 Li-Ion cell is 2.5 V, as per the specifications mentioned in Table 1, the cut-off voltage for the discharge of the battery was set to 5 V.

Fig. 4. Battery test procedure

Fig. 5 shows the current which was drawn during the battery test and is respresented against the capacity of the battery. Fig. 6 shows the voltage change during battery discharge versus the capacity of the battery. These graphs show that the battery has a capacity of 4.8 Ah and is thus suitable for the ACDO application. The battery successfully discharged at a current of 1.6 A for approximately three hours where the battery voltage dropped from a fully charged battery of 8.4 V to the cut-off voltage of 5 V. It is important to note that the test was implemented at a discharge current of 1.6 A, while the requirements of the ACDO system is only 160 mA. At a discharge current of 1.6 A, the battery took three hours to discharge and it can thus be deduced that the battery will last 30 hours upon the discharge current of 160 mA, as per the system requirements.

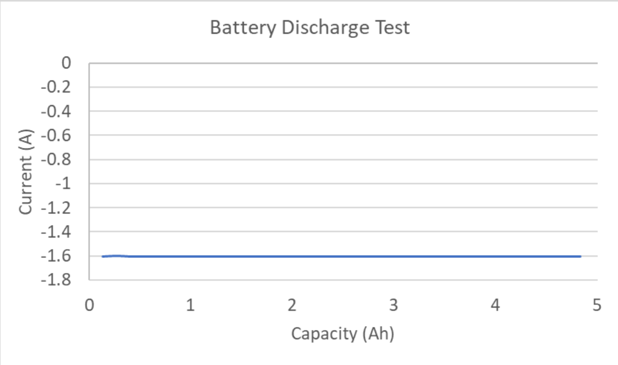

Fig. 5. Battery discharge test result: Representation of the current versus capacity during the battery discharge procedure

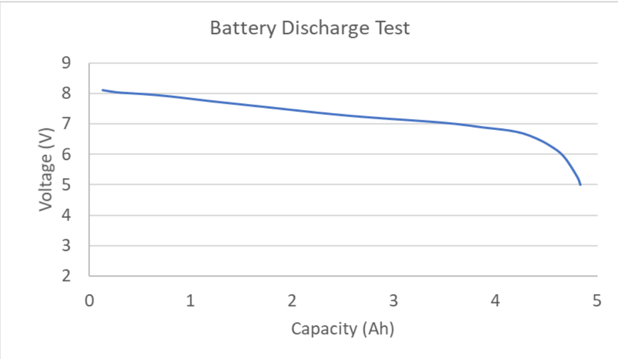

Fig. 6. Battery discharge test result: Representation of the battery voltage versuss capacity during the discharge procedure

The cells implemented within the testing procedure were of good health and it can thus be observed on the graph in Fig. 5 that no current spikes were observed within the discharge procedure. The observation of no current spikes within the discharge procedure indicates that there were no internal short-circuits or excessive temperature increases within the cells as the discharge test was conducted. Therefore, the selected cells are suitable for ACDO device and if monitored and controlled correctly, will not raise any safety concerns during the operation of the system.

IV. Discussion

DO is a recent solution regularly used in MRA. Recently, ACDO devices have been developed and implemented in DO procedures. One of the future developments of such a novel technology is to make the device portable to make the solution suitable for human MRA. A few studies have been performed for developing a functional and safe battery system to be implemented with developed ACDO devices. Upon the development of a portable battery system, there are various aspects to consider. These considerations include the battery chemistry which will be utilized, the energy density of the selected battery, the integration of the battery system with the developed device and, the monitoring and control of the battery. It is vital to ensure that the battery system does not only meet the electrical requirements of the device but falls within the weight and size constraints of the system, thus making the energy density of the selected battery an essential factor upon the design of a portable battery system. Additionally, since the device is powered by a battery system, it is essential to ensure that the system is safe, and that the temperature, voltage and current of the system are continuously monitored. The battery system developed by previous authors raised numerous concerns with regards to the safety of the implementation of the battery system. One such concern was the heat generation of the Li-ion battery due to discharge of the battery. The implementation of polymeric materials within the ACDO device was thus required to prevent excessive heat generation from the device [21]. Additionally, since the system was implantable and thus presented size constraints, the operation of the battery was not monitored while the system was active. This could cause for concern as the current and voltage of the system was not continuously monitored, and the user would not be aware if there was a fault in the battery during operation. Such faults could include a short circuit in the battery, usually presented in the form of rapid increase in temperature and current spikes, or over discharge of the battery. In the work presented by Magill *et al.* [31] it is stated that the developed power system is to maximize battery life. Although the design of the power system did indeed maximize battery life, the fact that the control system utilizes various power systems could increase room for error and failure of the system as well as increase the size and weight of the control system. Alternatively, powering a system from a single supply could contribute to the simplicity of the system and reduce unnecessary errors. In both developed battery systems for distraction osteogenesis devices [21], [31], the power systems proved to meet the design requirements of the ACDO devices, however, monitoring and control of each battery system was not implemented or clearly indicated within the literature.

The proposed battery system for the ACDO device has shown to be superior to power solutions suggested in previous literature as it addresses the safety concerns presented within previous literature while meeting the system requirements of the ACDO device [2]. Monitoring and control of the battery system could ensure that the batteries operate within their designated voltage ranges, failure i.e. the occurrence of a short circuit within the battery, could be detected and the battery could be disabled prior to any damage being caused. In addition, over discharge of a Li-Ion battery reduces the lifespan of the battery and preventing this phenomenon thus contributes to increasing the lifespan of the battery. In the proposed system, the voltage and current of the battery will be consistently monitored, allowing the discharge control of the battery. Therefore, upon discharge, the battery will not discharge below the cut-off voltage as suggested by the manufacturer. The voltage sensors are important to monitor the voltage of the cells and the controller will thus switch the relay if the battery voltage reaches 5 V upon discharge. The current sensor is in place to detect the occurrence of a short-circuit or current spike within the battery system and reduces the risk of a battery explosion or damage as the battery system is to be shut off if a rapid and consistent current spike is detected. In addition, the current of the battery is monitored upon discharge to ensure that the relay is switched such that the discharge of the battery is disabled in the case of rapid high-current discharges. Finally, the temperature of the battery is consistently monitored, allowing for action to be taken in the case of a rapid or unforeseen temperature increase within the battery system. Therefore, in the proposed system reducing the risk of safety concerns within the battery system due to over discharge of the battery is possible. It is thus suggested that that the battery system for the ACDO device designed in this paper not only meets the power requirements of the ACDO device but also addresses the safety concerns which have been raised in previous studies.

V. Conclusion

In human MRA, the DO technique has received more attention as an enhanced reconstruction method compared to conventional techniques. Recently, a few ACDO devices have been developed. Experimental studies have been performed on animal models to validate the feasibility of this technique and the application of developed devices. ACDO devices have shown promising results in animal studies as an enhanced reconstruction technique. Recently research has been performed to expand the application of ACDO devices for enabling using this technique in human MRA, however, the application of such devices is still limited. One of the aspects that can potentially increase the potential of using such automatic devices in human MRA is to make them portable. A newly designed rechargeable battery system which utilizes battery cells, a microcontroller, temperature sensors, power switches, a DC-DC power step-down, and a current shunt is developed to power an ACDO device which has met all necessary functions for a successful procedure. This system has the capability to power an ACDO device requiring a power supply of 5V. The battery tests have validated that the system would be able to successfully and efficiently power an ACDO device drawing approximately 160mA for 30 hours. This indicates that the ACDO device, along with its portable battery system would be able to operate for 30 hours before it will need to be charged. In addition, the system can measure and monitor battery cell parameters and control the operation of the system. The temperature, current, and voltage of the battery are consistently measured and control mechanisms are implemented to increase the safety and lifespan of the battery. In the future development of the proposed system, the mentioned features of the rechargeable battery system, along with the suitable specifications of the ACDO device, can increase the potential of a successful continuous DO treatment in human MRA.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Francis le Roux, Shahrokh Hatefi, and Katayoun Hatefi researched the literature, conceived the study, and performed the product design and testing, and wrote the original draft of the manuscript. Khaled Abou-El-Hossein and Theo Van Niekerk contributed to the research plan and manuscript preparation; all authors read and approved the final version.

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