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Self sufficient wireless transmitter powered by foot-pumped urine operating wearable MFC

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Abstract

The first self-sufficient system, powered by a wearable energy generator based on microbial fuel cell (MFC) technology is introduced. MFCs made from compliant material were developed in the frame of a pair of socks, which was fed by urine via a manual gaiting pump. The simple and single loop cardiovascular fish circulatory system was used as the inspiration for the design of the manual pump. A wireless programmable communication module, engineered to operate within the range of the generated electricity, was employed, which opens a new avenue for research in the utilisation of waste products for powering portable as well as wearable electronics.

1. Introduction

Portable and wearable devices are progressing at an accelerated pace and are thus becoming more available on the mainstream market. Despite the advances in ultra-low power electronics, powering those systems still poses a significant challenge. In addressing this issue, attention has been given to alternative energy sources such as electromagnetic [1, 2], solar [3, 4], thermal [5, 6], and mechanical [7, 8]. Using unwanted waste products, as a source of chemical energy, can be considered as an alternative method for such systems, particularly taking into account that it can be available for humans in a variety of environments. Human urine has been used for powering microbial fuel cells (MFC), producing sufficient power to run real electronic devices [9]. Furthermore, a highly efficient, flexible and light-weight MFC, has already been reported, which can be used in such wearable/portable energy harvesting applications [10]. However, a mains powered pump is normally required to continually feeding the fuel, which is necessary to increase the performance and biofilm community survival. That kind of MFCs have already been implemented in a self-sustainable manner on-board the EcoBot robots, and in particular on EcoBot-III [11]. Therefore, a wearable MFC self-sustainable system with the potential of being completely fed with human waste would require a manual pumping system, especially if used in outdoor conditions where gravity cannot be fully exploited.

Nature has long been a source of inspiration for engineers looking to solve problems, and in the context of low energy fluid circulation, the circulatory system of animals has been explored. Amongst many, fish have the simplest closed circulatory system, known as single cycle circulation [12]. These animals have a single circuit for blood, where the heart pumps the blood to the gills for re-oxygenation, then to the rest of the body, and back to the heart. The heart is consisting of one atrium to receive blood and one ventricle, a thick-walled chamber with a large number of cardiac muscles, to pump it [13]. Ostial valves, consisting of flap-like connective tissues, prevent blood from flowing backward through the compartments [14]. In fact, the pressure and suction created by cardiac muscles drive blood through the vessels, and the check valves keep the fluid moving only in one direction. The muscles surrounding the chambers and vessels help contract and expand the heart and vessels, which is key for the functioning of the circulation system.
In this paper, we present the first self-sustainable system, which is directly powered by wearable MFCs. It indirectly utilises energy from human walking for gaiting to circulate urine, as the fuel, through the MFCs. The design for the structure and material of the foot pumping system was inspired by the fish circulatory system. The whole system consists of 24 individual flexible MFCs positioned on the fabric of a pair of socks, whereas the foot pumping part was made of soft tubing and check valves; the whole wearable system was complemented by a programmable transmitter board. Evaluation data from the bench-based preliminary investigation into the aforementioned MFCs have been presented in Taghavi et al[15].

2. Materials and methods

The MFCs were fabricated as described in Taghavi et al [10], with a carbon fibre sleeve—Nafion tubing membrane—carbon fibre sleeve configuration. Briefly, carbon sleeves, playing the role of anode and cathode in a single chamber MFC, were positioned inside and outside of the Nafion tubing membrane. Due to the braided structure of the carbon sleeves, they could attach tightly to the inner and outer side of the membrane simply by pulling and pushing the ends, respectively. The cathodes were hydrated and covered using waterproof and breathable plaster. In total, 24 single-chamber MFCs were built and prepared as described below.

The inoculation was performed by activated anaerobic sludge, collected from the Cam Valley wastewater treatment works, Wessex Water, Saltford, UK. Tryptone 1% (w/v) and yeast extract 0.5% (w/v) (Fisher scientific) were added into 200 ml of sludge. Firstly for one week, the sludge was fed in continuous flow at a slow flow rate (27 μl min⁻¹), using a Watson Marlow 205U peristaltic pump (Watson Marlow, UK). This was performed for the purpose of inoculation, but assisted by slow flowing in order to prevent blockages in the MFCs. Subsequently, a new anolyte composed of 200 ml of deionized water, 1% (w/v) tryptone and 0.5% (w/v) yeast extract were driven into the MFCs with the flow rate of 45 μl min⁻¹ for another week. Urine, collected from individuals and pooled together, was used to feed the bacteria in the MFCs with the same flow rate. It was replenished with fresh urine once a day, for the duration of the experiments.

At first, the MFCs were left open circuit, before they were all connected to 5 kΩ resistors. Following from this, polarisation experiments were performed every week, with the use of the Resistorstat device[16]. Briefly, the cells were left in open-circuit conditions for at least 5 min, prior to starting the polarisation run with a 1 MΩ value (multiple resistive loads connected separately to each MFC). Subsequently, the values of the resistances were sequentially reduced to reach the lowest (short circuit) condition. In total, 38 different values were set as external loads, which were connected for 5 min each, with the purpose of establishing quasi steady-state values. Data were collected using a multi-channel Agilent 34972A, LXI Data Acquisition/ Switch Unit (Farnell, UK). For the long term, fixed load experiments, the MFCs were connected to the resistor, found to produce maximum power during the polarisation experiment.

After a 10 d period of maturation, the MFCs were connected together electrically, in the following manner: pairs of MFCs were connected to one tube, fed by the same common anolyte, which were connected in electrically in parallel, using external wires. Six such tubes (i.e. 6 MFC pairs) were inserted in each sock (foot). The polarisation experiments were conducted on each of these MFC pairs. After 3 d, the 12 pairs (6 pairs per sock) were connected in series, thus forming a stack of 24 MFCs, and a polarisation experiment was carried out, in order to measure the total output. This was done by manually connecting 32 different resistors to the stack, starting from 1 MΩ and sequentially coming down to 50 Ω as a close-to-short circuit value. Each resistor was connected for a period of 4 min, in an attempt to record quasi-steady state conditions.

This above was performed on the bench, following which the MFC tubular system was left to mature for a further two weeks, then integrated into the wearable sock support. A manual pumping system was designed and developed in order to circulate the anolyte through the MFCs, as shown in the schematic of figure 1(a).

This manual pumping system, inspired by the fish circulatory system, consists of a silicone tube (pumping-tube) with a 1 mm inner diameter and two check valves (SCV21053, The West Group Ltd, UK). The piece of tube with 1 mm inner diameter mentioned above, was placed directly under the heels, mimicking the role of a ventricle in the fish heart; this is henceforth referred to as the pumping-tube. A series of uni-directional valves were connected between the pumping-tube and two other silicone tubes with an inner diameter of 2 mm (reservoir-tube and carrier-tube). The latter tubes had the role of vessels, carrying urine both to the pairs of tubular MFCs (inner diameter of 1.8 mm) and the pumping-tube, respectively. These tubes have the ability of being distended and compressed like the vessel tubes. Therefore, in each sole, 6 separate pumps were considered for feeding 6 pairs of MFCs by means of 12 pieces of check valves. As with the aforementioned bench experiments, all the pairs were connected in situ to each other in series, to increase the generated voltage. The output energy of the system was stored in two super-capacitors (330 and 6.8 mF) connected together in parallel, which acted as an accumulator. The image of the developed wearable system is illustrated in figure 1(b).

In order to demonstrate the real potential of the wearable MFC generator for powering a self-sustainable system, a radio communication module was
implemented by the use of a RF transceiver (Easy-Radio type, ER400TRS), which operates at a frequency of 433–434 MHz. A PIC microcontroller (PIC24F16KA102) installed on the Microchip development board was used to manage the transmission process. The function of the communication circuit was initially tested using an external power supply. The flowchart of the programme ran by the microcontroller is shown in figure 2(a), which was checking the level of the power supply voltage every 10 s. Provided that the voltage was above 3.1 V, an exemplar message, i.e. ‘World’s First Wearable MFC’, was sent by the transmitter module. The microcontroller was left in sleep mode in order to reduce the power consumption during the idle period. This was interrupted every 10 s and the aforementioned function was performed. The receiver for this module, was connected to a PC for recording the transmitted message and displaying it on the screen of a PC. The block diagram of all the described components, emphasising the electrical connections, is shown in figure 2(b).

3. Results and discussion

The power curves of the 12 MFC pairs, when fed with fresh urine at the flow rate of 45 μl min⁻¹ have been previously reported in Taghavi et al [15], where the variations in the performance of the MFCs are also discussed. The power and polarisation curves of the entire stack are also shown in figure 3. It shows the average output signal when the 12 pairs are connected in series. The maximum achievable power is about 110 μW, which was generated when a load of 30 kΩ was connected. The system was limited by the slow flow rate, an increase of which would have increased
the risk of leakage. This was the main reason for designing the manual pumping system, in order to at least have uniform flow across all MFCs. It was estimated that under a walking speed of 45 steps min$^{-1}$ by each foot, the average flow was ca. 100 μl min$^{-1}$. This number was considered as a normal gaiting for each leg, assuming the value of 90 steps min$^{-1}$ as an average walking speed for a person. Each pair of MFCs was fed by pumping the fuel from a single foot, i.e. half of the total steps, so each foot pumps the fuel into the tubular MFC at the speed of 45 steps min$^{-1}$ or 100 μl min$^{-1}$.

Foot pumping occurs while gaiting during the two phases of heel STRIKE and heel OFF. The design of the foot pump follows the existing single circuit circulatory system of fish. Unlike the cardiac muscles, working involuntary, the frequent compression of the pumping chamber in the generator is provided by gaiting. Therefore, a soft material with the ability of stretching is required to mimic the heart chambers and the function of vessels or capillaries (figure 4(a)). In this way, tubes made of silicone rubber were chosen as the main pumping chamber and reservoirs and carriers. Similarly, these units were labelled as reservoir-

![Figure 3](image3.png)  
**Figure 3.** Power and polarisation curves of all the 12 pairs of MFCs where are connected in series; the experiment was performed after two weeks of maturation before assembling into the wearable support and manual pumping system; the error bars show the standard deviation of 4 acquired data points, recorded over 4 min, for each resistance value.

![Figure 4](image4.png)  
**Figure 4.** Schematics of the bio inspired pumping system; (a) the tubes were filled when the heart-tube was left under the foot pressure; (b) urine flows from vein-tube to heart-tube as the pressure is released; (c) urine flows through MFCs for compensating the differential pressure between vein-tube and aorta-tube; (d) squeezing heart-tube flows urine to the aorta-tube; (e) the system comes back to the first condition by flowing urine from aorta-tube to the vein-tube trough the MFCs.
tube and carrier-tube for the purpose of carrying fresh and used urine respectively. In fact, fish heart consists of other chambers connected to the main muscular part of the heart (ventricle). For example, an atrium and a conus arteriosus are working as two accumulators for the entrance and exit of blood from a ventricle, respectively. The muscular structure of these chambers, besides acting as check valves, assist the ventricles with circulating the fluid [17]. In other words, contraction of the ventricle moves the blood into the conus arteriosus and then to the aorta. In contrary, expansion of the ventricle in addition to contraction of the atrium allow blood to flow into the ventricle. In the present system, for the sake of simplicity, and since a high speed fluid circulation was not necessary, pressure and suction created by the main part (pumping-tube) were used for driving urine out of/into the MFCs.

The two steps required for pumping urine were performed by sequential squeezing and releasing of the pumping-tube, which led to pumping the urine into the carrier-tube and to creating suction from the reservoir-tube, respectively. Figure 4(b) shows the first step, where all the connections were made, when the pumping-tube was subject to a foot pressure. Therefore, as shown in figure 4(c), heel OFF, i.e. the first phase of gaiting, drives the fluid from the reservoir-tube down to the pumping-tube. Check valves lead the fluid flowing only through the reservoir-tube due to the differential potential generated by the released pumping-tube, resulting the foot pressure. The compensation of the differential pressure in the closed tubing system, consequently, leads to move urine through the MFCs from carrier-tube to the reservoir-tube (figure 4(d)). In contrast, as shown in figure 4(e), heel STRIKE, i.e. the second phase, compressed the tubes, and thus the fluid flowed into the carrier-tube, through the check valve on the opposite side. By continuing the flowing of urine in the MFCs, the reservoir-tube is refilled and returns to the first situation (figure 4(f)). As the toe OFF phase of one foot and heel-ground contact of another one happen at the same time, the identical cycle repeats for the second foot until the time that the first heel strikes the ground again.

Although the average flow rates of the manual and automatic pumps have been compared, the fluid driving mechanism of the two systems are different. Firstly, the electric pump creates a flow with constant velocity, and thus it can be considered as constant flow. Secondly, it is connected to the tube’s input, and so operates only by pushing the fluid through the tubes. However, the heart-inspired pump benefits from both pushing and pulling mechanisms at the two contraction and expansion phases. Therefore, it not only drives urine inside the carrier-tube and MFCs, but it also provides suction to the reservoir-tube and MFCs. This process brings about fluid flow within a lower pressure. Consequently, during the foot pump experiments, this pumping process decreased the risk of urine leakages, small quantities of which were only observed occasionally around connections during bench experiments under similar conditions. This can affect the performance of the system [15], which could be a reason why the circuit output voltage of the wearable system went up to 4 V, after assembling into the wearable support and fed by fresh urine via manual pumping, whereas it was 3.66 V for the bench stack under identical conditions.

Two super capacitors (6.8 and 0.33 F) were connected in parallel for storing the generated energy of the MFC stack. The capacitors were charged up to 4.1 V and connected to the Microchip® board with the transmission components. The rate of discharge was found to be 1 V (down to 3.1 V) every 465 s. After this time, as explained above, since the level of the powering source for the electronic board had decreased down to 3.1 V, the transmission stopped. This idle period can be considered as a start point for evaluating the MFC generator function. At that time, the MFCs were generating sufficient energy to reach the threshold voltage and meet the minimum requirement for charging the capacitors and transmitting the data. During this period, the microcontroller was woken up every 10 s and was checking the input power. If it was less than 3.1 V, the microcontroller would go back to sleep-mode without sending any wireless data. This experiment was performed with gaiting by the speed of 88 steps min−1 for 30 min, and the results are shown in figure 5. It is illustrated that, the communication module is able to send a meaningful message every 2 min on average, whilst fresh urine is pumped into the MFCs by the typical stepping speed (see the video in the supplementary data). In fact, neglecting the inherent leakage from the capacitors, the board consumes three different amounts of energy within three phases: the first is during the time that the processor goes to sleep-mode. The second is while it wakes up and checks the capacitor voltage level, and then goes back to the sleep without sending any data. The third and last occurs when the microprocessor confirms the voltage level, and allows the transmission unit to send the message. Therefore, 2 min of operation of the wearable power generation system is sufficient to meet all these requirements.

The heart in fish, pumps blood first to the gills where the gas exchange takes places, and then blood continues to the rest of the body. However, in our system, in order to simply show the possibility of the presented concept, no unit is considered for replacing urine with fresh fuel. In detail, it is calculated that the entire capacity of the fresh urine stored in each tube for a pair of MFC is ca. 1.8 ml. Assuming that the flow rate of the normal gaiting produces 45 ml min−1, as explained above, the single circulation of all the reserved fresh urine occurs within 40 min. This part, can be modified to bridge the gap for transferring this technology into real long-term applications. As an
example, the function of the gills in the fish circulatory system can be replicated by a reservoir containing fresh urine, equipped with a manual subsystem or integrated with the gaiting pump system, in order to slowly release the fuel and thus have a constant replenishment rate otherwise known as hydraulic retention time. It is worth noting that since evaluating long term stability of such a system would be an important factor in real applications, the temporal behaviour of an individual MFC, developed under similar conditions, has already been reported [10]. It is then possible to envisage wearable transmission systems that have a purpose of transmitting a person’s coordinates, in e.g. a case of emergency, which can operate when fed with just urine. A venture in this direction not only widens the range of applications that MFCs could be implemented in, but also introduces the concept of built-in “proof of life” capability, since the device will only operate if the person wearing it, urinates inside it. This is a direction of research that may unlock further possibilities in outdoor gear, military equipment, operations at sea, as well as survival kits.

4. Conclusions

A wearable electricity generator, powered entirely by a human, successfully ran a wireless transmission board. It was shown that it is able to send a message every 2 min to the PC-controlled receiver station. The soft MFCs were worn as a pair of socks and supplied by fresh urine using manual pumping. The pump was designed based on the inspiration of a single loop fish circulatory system. The involuntary heart muscles were substituted by soft tubes, placed under the heels, which produced the frequent fluid push–pull mechanisms by gaiting. Each two MFCs, positioned in series and wired in parallel, were separately connected to a single pump. Twelve couples of those MFCs were wired in series and used as the power supply for the electronics. 90 steps min\(^{-1}\) as a normal gaiting of human provides urine circulation with the flow rate of 45 μl min\(^{-1}\) in each leg for each MFC couple, where the whole open circuit output voltage of the system reaches 4 V.

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Supplementary data

A video showing the operation of the system.

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