Supercapacitors Serving as Power Supply in Tiny Sport Sensors
Field Testing Through Heart Rate Monitoring in Endurance Trail Runs

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Abstract: In professional and in non-elite sport activities, people today are using various electronic monitoring tools quite commonly. Sportspersons often are embedded into a personal body sensor network, which traces different parameters of their physiological activity. Especially heart rate sensors are used broadly, but often all kinds of meters, e.g., for counting foot steps and pedal turning, are also utilized in parallel. As technical construction, it has commonly established that these sensor devices are autonomously operated as very tiny computer systems from built-in lithium battery cells. Replacing such sensor batteries from time to time is expensive, the mechanical handling of this process is not very easy due to the small sensor housings, and it has to be reminded that use of throwaway batteries represents a waste of resources. In this work, an alternative power supply for sports sensors is investigated, which bases on the use of so-called supercapacitors. Construction concepts, advantages of the approach related to handling and manufacturing, and the possible application ranges are thoroughly discussed, while the study is complemented with practical experiments from endurance running sports.

1 INTRODUCTION

Improving health by controlled physical activities plays an important role in our modern and aging societies. Performing personal sports on regular and moderate base from early living days represents a valuable key for preserving an extended period with fewer health problems already at middle age (Oguma and Shinoda-Tagawa, 2004) up to higher ages (Jefferis et al, 2014). Both categories of physiological activities are today usually monitored with the help of electronic devices and tools for achieving optimal response (Arts and Kuipers, 1994). The simplest variants of such monitoring units are pedometers or smartphones with corresponding software tools (Tudor-Locke and Basset, 2004).

A higher or more professional elaboration level is achieved, when sports computers with built-in or RF-linked sensors are employed (Malkinson, 2009). One of the most well-known samples of this multi-device monitoring are chest straps with an autonomous sensor module for detecting heart beats from skin surface electrodes and producing continuously measures of the heart rate (HR), which are sent to other control units for display, evaluation and recording. Fig. 1 shows three different HR devices, two of them communicate through the so-called Bluetooth LE standard (Bluetooth SIG, 2017), while the third unit (device S) broadcasts its measures through ANT+ radio (Dynastream Innov. Inc., 2011). The latter can be received by many sports computer systems and by some smartphones with special RF electronics, while Bluetooth LE is readable by most modern smartphones. It has been reported earlier (Weghorn, 2015) that the electrical power consumption of the ANT+ system is lower compared to the Bluetooth LE solution.

Similar sensors exist for different other physiological measures, which are likely to be observed and traced during sports and health exercises. For instance, tread rate in foot stepping, wheel and pedal turning rate in cycling and other information may be of relevance and interest in such applications. Accordingly, many sensor types are available on the market and a training person can be embedded into an extended wireless body network, which consists of one central control unit and several autonomous sensor elements.

Since such sensors are constructed as tiny wireless computer modules, they do require also an electrical power supply. For this, commercial

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devices use lithium battery cells (B in Fig. 1), which have to be replaced and disposed as hazardous waste, when they are emptied. This manual exchange is not very easy, because the mechanical parts are tiny and some systems need considerable force and torque for opening and closing the battery mould covers. Fig. 1 shows above each sensor its back case part for the battery cell; for sensor S very small screws have to be handled, which is already inconvenient and complicate for younger people and may render impossible for older people or health patients with reduced sensitivity. Another negative aspect of inconvenience is, that these batteries are rather expensive.

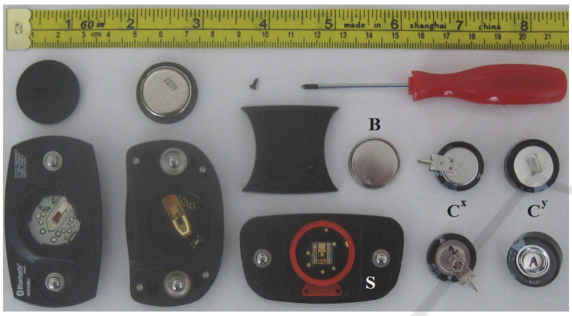

Figure 1: In here at bottom left, three different heart rate sensors are visible from backside. Above each sensor, its cover for the supply battery is shown, the middle one has to be fixed with four tiny screws. On bottom right, rear and top view of supercapacitors samples are sown, which are possibly feasible for replacing the lithium sensor batteries.

In the tiny sensor devices rechargeable batteries like in wristbands are not in use, because such a technology would increase size and price of the systems. Furthermore, wrong maintenance like deep discharge for a longer while damages accumulators and make the entire unit worthless, because the accumulator usually cannot be exchanged.

Coin-type accumulators are available in the same housing like the batteries, but with ten times lower capacity, what means the manual exchange for recharging would be required even ten times more often. Derived from commerce of simple time watches, development has concentrated therefore on reducing power consumption of the sensor devices. The energy load of a single-use battery cells allows a continuous operation of the sensors for few days, but in real practical use cases this long operational time is not really required for physical exercises. In medical investigation, in health and sports monitoring, workouts and exercises quite typically last in the order of one hour (USD Labor, 2009).

Using switching capacitors as power cell theoretically provides much better convenience for electronics design than batteries, but this was not possible since the electro-chemical capacitors with sufficient energy storage amount haven't been available for long time. Around two decades ago, so-called supercapacitors, which are also named ultracapacitors, could be developed on base of upcoming nanotechnology (Conway, 1999) and since then, capacitor parts caught up to the desirable high storage of one Farad and more. Today after many years of further evolvement, supercapacitor (SC) application is well-known in sports, e.g., as power supply for boosting temporarily Formula 1 race cars as term of an ultra high power and extreme current cell (Lu, 2013).

Another recent application field for SCs is the replacement of backup batteries for configuration memory on computer boards (SC samples are C^x and C^y in Fig. 1). This scenario is very similar to what is required for operating sport sensors, since they need also a high capacity value, which is sustaining very long time a rather small electrical current. Out of the four fundamental SC types, this variant represents a prospective candidate for replacing the throw-away lithium battery cell in autonomous sports sensors with a self-sustaining electronic part.

Inspired from this existing knowledge and the new technologies, the work here discusses first the general properties of modern supercapacitors with respect to the targeted application frame in sports sensing; next the substitution idea particularly is used for the most common sensor of HR detection in endurance training for a real-world evaluation of the approach. Following this, the derived findings and possible concepts for further applications and improvements are critically reflected in their relevant details.

2 PROPERTIES OF FEASIBLE SUPERCAPACITORS

From practical experience through a longer period of on-going investigation about handheld sports tools and sensors, it had been estimated as initial working base, that a SC part in the order of one Farad should provide sufficient energy for at least one or even few hours of sport sensor operation. This estimate bases on the practical experience, that a 230 mAh lithium battery can be used approximately one week full week (Weghorn, 2015). The error bar of this assumption is rather high, because controversially the advertisements and promotion material for the sensors and their technologies promise much longer operational times. Due to the small voltages and the very small supply current it is not possible to measure the sensor energy consumption directly with high precision, especially not during longer physical workouts. Therefore, an indirect methodology was applied in the further investigation for the determination of a sufficient power supply capacity.

2.1 Initial Parts Selection and Laboratory Setup

At first, two different supercapacitor types had been selected from a quality manufacturer for passive electronic parts, which are matching the targeted use of low voltage combined with low current. Other important criteria were also, that these parts are available from stock and that the size of the parts is comparable to the size of lithium battery cells. Part C^x is specified as SC with 5.5 Volts maximum and a capacity of 1.5 F, while C^y - despite it has got a bigger housing - comes with the same voltage rating and 1.0 F. For the evaluation of statistical variation in specified ratings and parameters, sample sets were purchased from professional suppliers for electronic parts. The data sheets specify for the storage capacity possible differences from -20% up to +80%, but this wide range is expected to emerge reduced, since the body sensors are used in a much narrower temperature band than allowed in the total specification ratings.

Fig. 2 shows the laboratory board setup for conducting the basic experiments. The circuit allows to charge the SC probe through a protection shunt at a defined voltage and to discharge it through a defined load. The load in the test circuit was dimensioned, so that the discharge from 5V down to 3V takes in the order of one hour, since this should be similar like to the minimal estimated working time of a health or sports sensor. This test circuit maps to the following replacement construction for the battery cell: a linear voltage regulator downscales the SC voltage band to the valid sensor supply voltage, which lies between 2.7V and 3.3V as yielded by lithium battery cells during their life span.

2.2 Determining SC Storage Capacity

For each of the two different SC parts C^x and C^y five samples were tested with the laboratory setup in a charge/discharge cycle. In this first experimental run the variation in capacity should compared be under conditions similar to the use inside a sport sensor. Table 1 shows the corresponding results, and it indicates that the experienced variation of the capacity between different part samples is much lower than specified in the data sheets.

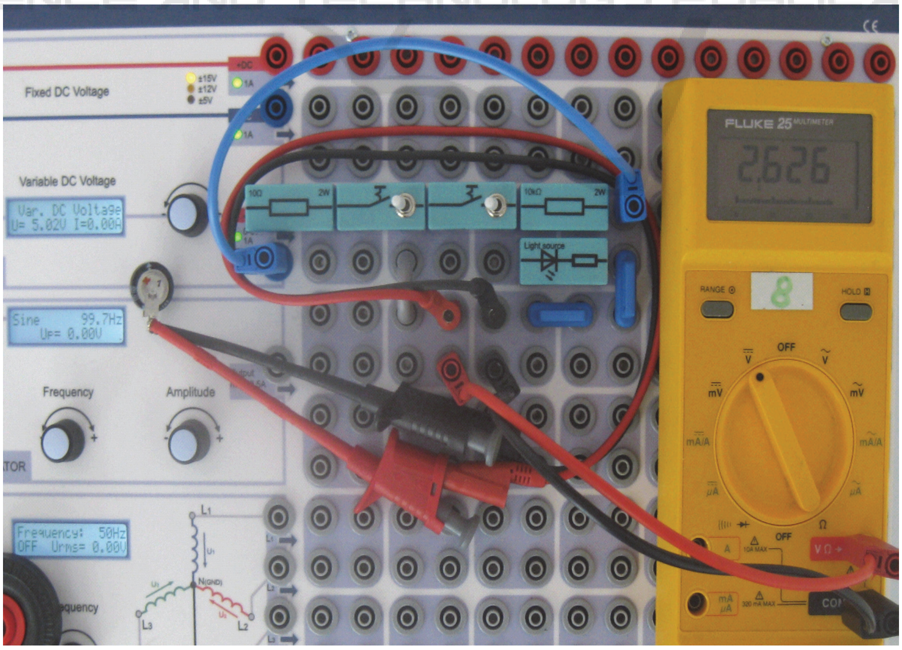

Figure 2: Laboratory board for charging and discharging the supercapacitor probe. A digital voltmeter measures precisely the probe output.

Although the discharging is non-linear according to the fundamental rules, this can not explain high difference between the discharging slope within the defined voltage steps completely. The reason more is, that supercapacitors behave in some aspects considerably different to electrolytic capacitors, since they do stand only low switching frequencies and their internal resistance increases with charging load. As observed in the experiments, it is not sufficient to connect SC for a short while to the desired charging voltage, following the definition of how to measure SC capacity, it would even more be required to keep the target charging voltage up for half an hour. Since this is not realistic for the intended application frame here, charging was terminated after an acceptable time for a sports user. The consequence is, that the discharge rate is over-proportional high in the first phase as seen in the middle row in Table 1, because the SCs were not charged completely.

Table 1: Discharging time results for the ten SC samples: each probe was charged up to 5.00V, then this load voltage was sustained for a further minute, after which the discharging was initiated. From there, the time delay was measured in seconds for a voltage drop of each probe down to 4.00V and then further down to 3.00V.

SC probe	Δt for 5.00V → 4.00V	Δt for 4.00V → 3.00V
C_1^x	534s	1155s
C_2^x	555s	1164s
C_3^x	490s	1117s
C_4^x	491s	1123s
C_5^x	478s	1105s
C_A^y	456s	880s
C_B^y	422s	854s
C_C^y	457s	865s
C_D^y	422s	876s
C_E^y	394s	856s

Next, two reference measurements of the absolute capacity had been performed for SC type C^x and C^y. For obtaining precise values, the SC probes were charged in the beginning to a higher voltage for an increased waiting time.

Following this, the slope of the discharge curve was measured at a lower voltage frame, i.e. after the over-proportionally fast discharge phase. In addition, a plain resistive load was used. Table 2 shows all experimental parameters and the deduced results. The determined reference capacities are much lower than the specified values from the data sheets.

Table 2: Experiment of determining the absolute capacity value for reference.

item/event	mode	C_3^x	C_C^y
$V_{SC}(t_0=0)$	defined&set	5.00V	5.00V
R_L = 10k selected	measured resistance R_L	9.93kΩ	9.93kΩ
@$V_{SC}(t_1)$ = 4.50V	measured time t_1	05:16:05	08:44:22
@$V_{SC}(t_2)$ = 4.00V	measured time t_2	05:35:40	09:01:08
t_2 - t_1	calculated	1175s	1006s
C	calculated	1.00 Farad	0.86 Farad

From these reference values in Table 2, the mutual measures in Table 1 can be calibrated as difference from the nominal capacity, which would be C^x = 1.5 F and C^y = 1.0 F, like this is stated in their data sheets. Table 3 lists the derived results for the measured capacities, which arise systematically too low. The difference appears considerably smaller for C^y, for which most measures are even within data sheet specification. Interestingly, the housing of C^y is bigger than the one of C^x while the latter claims having 50% higher capacity.

Table 3: Calibrated capacitor values in reference to the nominal data sheet values for the upper and for the lower discharge voltage frame.

SC probe	deviation 5.00V → 4.00V	deviation 4.00V → 3.00V
C_1^x	-27%	-31%
C_2^x	-24%	-31%
C_3^x	-33%	-33%
C_4^x	-33%	-33%
C_5^x	-35%	-34%
C_A^y	-14%	-13%
C_B^y	-21%	-15%
C_C^y	-14%	-14%
C_D^y	-21%	-13%
C_E^y	-26%	-15%

2.3 Self-discharge Behaviour

According to the concept, that the SC should supply a health sensor for the very next use period in a physical workout, which lasts typically around one hour, the sensor would have to be charged each time before this use. The question arises, how convenient this can be handled; one relevant factor for answering this is, how much delay is allowed directly after SC charging before using the sensor. When sensors are inactive, they consume only reduced energy; storage cells in general - regardless which technology - suffer from own self-discharge. Both effects have to be regarded to optimize the entire use cycle starting with any kind of preparation.

Therefore, the self-discharging effect also was measured for the SC samples. In the corresponding experimental series, C^y was excluded, because its size slightly too big, so that it wouldn't directly fit into the sensor without major rework of the housing. From this stage of the fundamental investigation should evolve specifically to the final application, therefore the capacitor samples were charged for an extended time to the start voltage of 3.3V, which is what a fresh lithium battery cell would feed to the sensor. Table 4 lists the discharging measures in time; the digital voltmeter was connected always only for a short time when collecting the sample points, so any discharging distortion by the voltage measurement itself was avoided.

Table 4: Measuring voltage drops invoked solely by self-discharge of the SCs.

	C_1^x	C_2^x	C_3^x	C_4^x	C_5^x
@ t_0=0	3.30V	3.30V	3.30V	3.30V	3.30V
t_0 + 1h	3.14V	3.26V	3.30V	3.21V	3.19V
t_0 + 12h	2.87V	3.16V	3.26V	3.01V	2.93V
t_0 + 1d	2.79V	3.11V	3,.23V	2.94V	2.84V
t_0 + 1.5d	2.74V	3.07V	3.20V	2.90V	2.78V

Concerning self-discharge, the variation between different SC samples appears high. Another snapshot is seen in Fig. 2, which shows the voltage of C_1 three days after starting the experiment in Table 4. From the other results it can be derived, that it is advisable to early use the sensor after charging, if a SC is used as power supply cell, since the nominal supply working range for sensors ends at 2.7 Volts.

2.4 Interpretation of Results and Derived Selection Strategy for SC Components

For intermediately summarizing at this point the general results on supercapacitors, it can be stated, that the measured variation in capacity appears much lower than specified in the data sheets. On the other hand, self-discharge rate varies extremely between individual samples. Some parts have got almost no self-discharge effect, while others discharge themselves within one day down so far, that they can not be used as sensor supply after this time.

This leads to the recommendation, that a user has to charge the sensor supply capacitor directly before the workout. The specified capacitor values from the data sheets are far above than what can be achieved in practical use. This certainly is rooted in the defined measurement methods for the ratings, e.g. charging a capacitor for 30 minutes may be useful for achieving highest capacity counts in advertisement sheets, but it is totally unrealistic in practical application.

Hence, parts selection should compensate this by choosing intentional too high values; from the experiments here, 50% oversize seem a method of feasible dimensioning. Certainly, quality control in sensor mass production will be specially required for their power cell, if supercapacitors parts are used.

3 PRACTICAL USE OF A SC POWER CELL IN HR SENSORS

In the next phase of this investigation, the practical application in terms of replacing the lithium battery of a heart rate sensor by a supercapacitor was prepared. Based on the findings, which were collected so far, the following was decided: at first, an ANT+ HR sensor was selected for the rework, because of its low power consumption (unit S in Fig. 1) in comparison to other units; secondly, since SC part model C^x is only barely bigger than the lithium battery (B in Fig. 1), it was chosen for the concrete re-work for limiting the required mechanical adoption in the sensor housing. This was performed in two stages, first without and then including an additional voltage regulation electronics.

3.1 Direct Supply Connection for First Proof of Concept

During the analysis of the battery mould in the sensor cover it turned out, that the selected SC could directly replace the lithium cell battery with few modifications in the sensor housing and at the soldering lugs of the SC (Fig. 4a). Therefore, the sensor was connected directly as supply to the electrical sensor supply inputs in the fist practical use tests. The consequence is that the exploitable voltage range of the SC had to be limited to a frame between 3.3 Volts down to 2.7 Volts. One further discharge test with these new limits showed that type C^x can provide more than 60 minutes sufficient supply voltage at the expected discharge current of the used HR sensor. In the following work, several use tests have been performed in this simplified way and the implementation of the regulator circuitry in the test sensor was postponed to a later experimental phase.

The SC part sample of type C^x with the smallest self-discharge rate was selected, so that the power consumption of the sensor in sleep mode could also be determined and qualified accurately. In a first laboratory experiment, the SC was charged to the maximum allowed input supply voltage with the board in Figure 2. Then it was installed inside the closed cover of the HR sensor. With a proprietary smartphone App and a sports watch in parallel the operation of the sensor was observed, while it was worn for the next hour by an experimenter. During this phase, only lab working activities, but no strain sport actions, were performed, Table 5 list in its first row the measuring results for this cycle.

Table 5: First documented test runs of the HR sensor supplied from the SC cell: the columns show the voltage just before installing the SC in the sensor and the voltage immediately after removing the SC.

use mode	overall time frame	just before	directly after
normal work, no physical strain	09:08-10:17	3.29V	2.99V
slow jogging on natural trail	10:38-11:43	3.31V	3.03V

The measured voltage drop of 0.3 Volts in the first practical use of more than an hour suggested that the SC-supplied sensor is directly feasible for a first field test. For this, an endurance training was performed in terms of a controlled slow jogging for one hour at a constant speed of 6.5 mph (lower row in Tab. 5). In this experiment, the HR sensor was connected to a wearable sports computer, from which the recorded running data can be transferred to software running on a personal computer, in order to display the results in bigger screen collections and plotting graphs.

The whole system worked during the exercise without problems and in a way as known from the normal HR sensor use. In this run, there was some additional preparation time for dressing and moving between laboratory space and the running path outside the building. Again this experiment showed that the simplest concept easily supplies the HR sensor for one full hour while consuming only half of the available capacity. In other words, the ANT+ HR sensor can be operated in this configuration for at least two hours plus several minutes for setup and preparation times.

According to these first positive results, a longer sensor test with a complete use cycle was prepared. Since one of the two chest strap connectors on the sensor housing (unit S in Fig. 1) is directly connected to Ground level on the sensor board, only one other electrical access point to the positive pole of the SC was required. This was established by drilling a hole into the back cover case above the battery mould. After this, the SC could be firmly enclosed into the sensor housing, since charging and voltage measurement was now available through access from outside. Few undocumented experiments with slight overcharging, observation and validation of the SC-supplied HR sensor had been conducted in the following working phase.

After all, participating a public street run over half-marathon distance was prepared in terms of complete and quite regular handling cycle by a sports person using and wearing the modified sensor unit. The running event took place in 50 mi distance from the laboratory environment, therefore typical activities like traveling to the event place, registering for the run and changing clothes was part of this extended field experiment. Table 6 protocols the relevant steps in this experiment.

Table 6: Protocol for the stages in attending a street running competition with the SC-supplied HR sensor.

time	mode/action	measure
09:15am	charging for 1 min	3.40V
09:30am	test after settling time	3.37V
11:30am	quiescent discharge test	3.35V
11:40am	activation + walk to start	
12:01am	race start	
01:42pm	cross finishing line	
01:50pm	entering sensor sleep mode	2.27V

Unfortunately, correct HR recording failed already 10 minutes after the run was started. After leaving the race place and when the sensor entered sleep mode, an unexpected deep discharge of the SC had to be detected. In the following phase of the investigation, it was found that humidity collected inside the sensor caused the partial failed of the half-marathon experiment. Several additional field tests on nature trails and inspections of the sensor unveiled, that the sealing of the sensor casing has to be improved in the further work. Despite this unexpected problem, the entire phase of the event participation, which started with sensor charging, then continued with preparation of the event

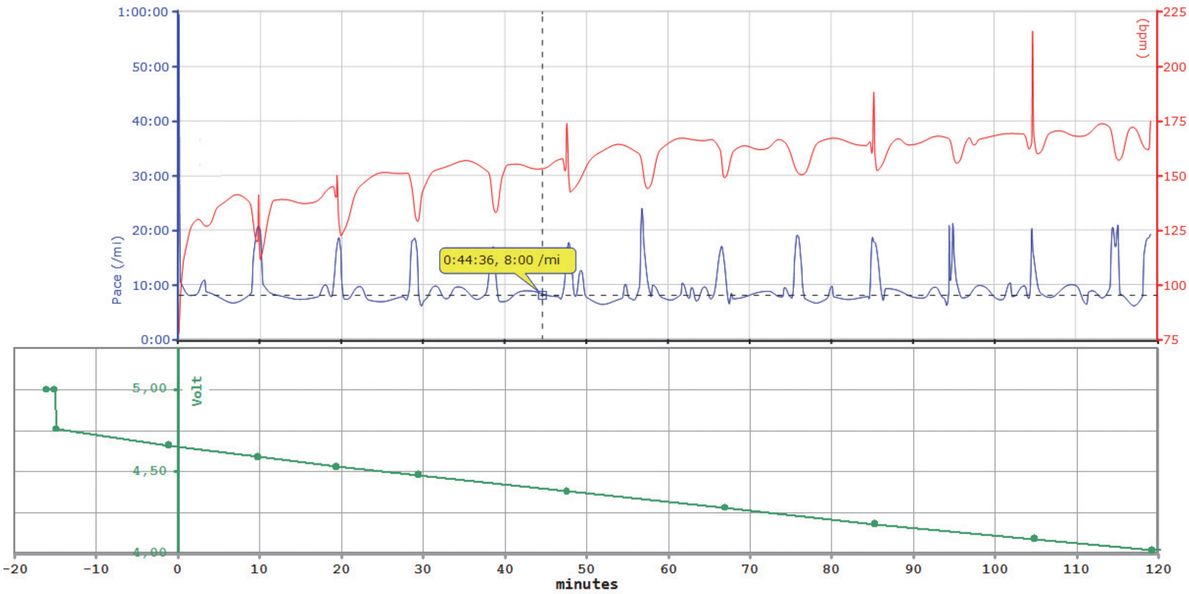

Figure 3: A half-marathon was covered by the run-walk-run method as reflected in the middle function plot, which displays the moving pace in units of minutes per mile. The lower curve shows the SC voltage, which was measured in the one minute walking breaks. This plot starts 15 minutes before the run with one minute charging at 5 Volts. The upper functional graph shows the HR curve, which suffers from distortion peaks induced by the voltage measurements.

attendance and running the first mile, has shown, that the SC capacity can supply a complete handling cycle when attending such a sports event of two hours duration. The SC discharge, which was contributed by the HR sensor in sleep mode, is found being negligible, hence no particular expedition with the sensor in sleep mode is required, even when conducting a two-hour workout with this very simple power cell concept.

3.2 Regulated SC Power Supply and Extended Field Test

For the final working stage in this context, a SC was implemented firmly together with a linear voltage regulator circuit (Fig. 4b) into the battery mould of the HR sensor's back case (Fig. 4a). Charging and measurement access was enabled through a connection wire, which was fixed on the front of the cover case as this side is not touching the skin. The housing was closed mechanically and the system was made watertight properly with electronic tape. After the first test runs, it turned out that as well the plus contact on the front side had to be electrically insulated, because this contact point also started to distort HR measurements as soon as the touching clothes of the experimenter became moist from sweat. Accordingly, the charge access pin was modified further, so that it can be contacted by a test prod, but it is protected against unintended electrical contact of other items like wet shirts. As regulator IC a type was selected, which has got low voltage drop and ultra low power dissipation. Despite this and according to its specification, the voltage regulator increased the self-discharge rate of the power supply, while it expanded the usable voltage span of the SC from 2.8 Volts up to theoretically 5.5 Volts. Under the assumption, that in practice a wired USB cable charger provides 5 Volts only, this value was applied as upper charging voltage limit in all further tests.

The following experiments (Tab. 7) yielded, that the discharge rate of the regulated power cell is again approximately 0.3Volts/hour for the SC with one Farad true capacity. The self-discharge rate of the expanded supply system with regulator IC was observed being increased by approximately 1/3. For the final test shown in Fig. 3, a natural trail run was decided, which should cover half-marathon distance and should last two hours. During this workout, the decaying capacitor voltage was measured with equipment, which was carried in a rucksack. For practicability of the voltage measurements during the test trail, the run-walk-run method was applied, which is proposed and advertised by a runners coach, who is successfully active since many decades in this sports field (Galloway, 2017).

In this mode, the moving speed alternates between quicker running for one mile and relaxation phases for one minute at walking speed, which causes dynamics in the corresponding HR trace. In the strain pauses, the voltage measurements were performed. Since the Ground contact of the sensor is also used as skin electrode for HR detection, the connection of the digital voltmeter disturbed the very sensitive HR monitoring. This is reflected as spurious distortion peaks in the HR curve in Fig. 3. The preparation of the trail run started 1/4 hour earlier with charging the SC for a minute with 5 Volts. Immediate measurements after the charging showed, that the SC can not sustain the end voltage, which refers to the fundamental property of supercapacitors that their internal resistance is increasing with accumulated charge. This implies that a connection of the loading voltage for just one minute is not sufficient for injecting the full electrical load. Nevertheless, also the partial load is already sufficient for longer workouts as seen here.

Table 7: Tests of the HR sensor supplied from the SCC with voltage regulation.

use mode	lab work	trail run
charging method	@3.4V for one minute	@5.0V for one minute
active time frame	04:43-05:43	10:38-11:43
voltage at use start	3.29V	4.39V
voltage after use	2.95V	4.01V

Together with this final trail running experiment, the findings about the new power supply can be summarized as follows: 1) The usable voltage range, which can be practically harvested from the SC supply, is reduced, especially under the assumption of USB cable charging for a limited time; 2) the sensor should be used early after charging; 3) a one minute charge load for a one Farad SC is capable of operating an ANT+ HR sensor for reliably more than six hours. Overall, the construction renders feasible for typical workouts in sports and health exercises, since these use to last around one hour as discussed above.

3.3 Further Aspects on Design Convenience

The selected capacitors have got a slightly bigger size and a higher weight than a lithium battery cell, while their price is similar or even lower. All these differences are not high, but still consequence modifications of the sensor housing. If the complete SC voltage band is exploited and the sensor operation time is specified to the typical value of one hour plus - reasonably - 200% extra reserve, a smaller and cheaper SC can be used, especially in ANT+ devices. This means, that the sensors could be constructed more slim and lightweight, which would provide a further handling benefit.

4 DISCUSSION OF RESULTS AND COMPLEMENTING CONCEPTS

The experimental results and the proof-of-concept in several field tests have shown here that the lithium battery cell in sports and health sensors can be replaced by an appropriately selected supercapacitor. Already with a very simplified, direct connection of the one Farad SC power cell an operational time of more than two hours can be achieved for the most typical unit of a heart rate sensor. When adding a voltage regulator in the supply path (Fig. 4b), the usable voltage range can be increased from (3.3-2.7)Volts to (5.0-2.8)Volts, which stands for a factor of approximately 3.5 and by that an operational time with one single charge of at least seven hours. This certainly will be enough for most personal applications, only in extreme cases like attending an Ironman Triathlon this supply capacity wouldn't be sufficient.

It has to be noted that this efficiency applies in such extend to ANT+ sensors, the more universal systems with Bluetooth low Energy would reach - due to their higher power consumption - only in the order of 2.5 hours total operational time, which is also sufficient for 80% of non-elite sports people (USD Labor, 2009). The electrical power consumption of other sensors are very similar to the HR units, because most energy is required for their RF transmissions. The voltage regulation has to be performed in the experiments here with an additional semiconductor circuit, because the sensor unit represents a black box with non-transparent internals, which cannot be modified.

For a final product on the market, the sensor manufacturers can simply integrate the expanded regulation into the device without additional effort in electronics, since stabilization of supply voltage has to be implemented anyway always. When using instead of linear regulation so-called voltage pumps, the supply band could be expanded towards much lower SC output voltages, which would then factorize the working time by another value of approximately 1.5. Hence, with this improved supply electronics, also BT sensors can reach a very reliable operational duration.

Using a supercapacitor as power cell of a sensor provides a series of advantages for construction and manufacturing, for usability and for environment. The SC would be implemented firmly inside the sensor housing, therefore no mechanisms are required for manual exchange by the user. Considering, e.g., sensor S in Fig. 1, six mechanical parts could be omitted in the design, which are in detail the four screws, the backside cover and a sealing ring. Furthermore, the sensor housing case could be simplified. This all saves development costs and even in fabrication by multiplication with a high count of produced units, the costs for raw material, production processing stages and production cycle time.

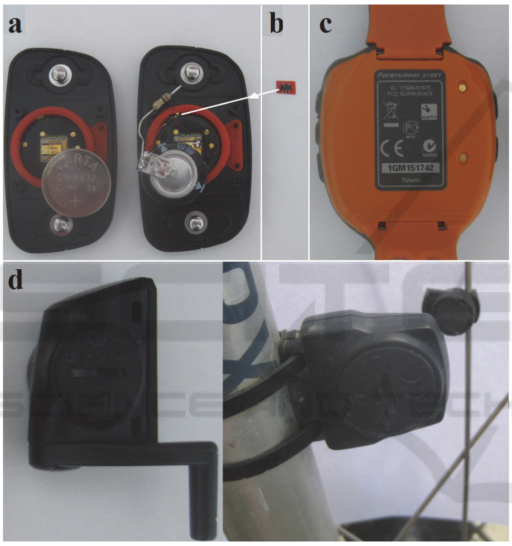

Figure 4: Collection of devices for discussion of charging concepts: a) backside mould of the open case of sensor S, and the installation of the SC plus required electronics b) voltage regulator IC installed left hand; c) commercial solution of contacting device for charging; d) pedal and wheel turning sensors as samples without regular contacts but battery mould.

The price of the lithium battery cell, which is usually contained in newly sold sensor packages, is even higher than the one for a SC. Either the selling price of the sensor could be reduced, which would represent a customer benefit, or the earnings statement for the vendor could be slightly improved. The cumbersome handling of changing batteries like discussed before could be avoided completely, which represents evidently an important benefit for the customer. Using a self-sustaining power cell is obviously more environment-friendly than any type of throw-away batteries, especially those wasting rare earth metals. Capacitors provide advantages even more compared to accumulators, because the number of charge/discharge-cycles is almost unlimited, and the capacitor cannot be destroyed by deep discharge. This all preserves a much longer use of SC-supplied sensors than when using theoretically micro accumulators, and therefore again an improvement of environment-friendliness.

One other important aspect hasn't been covered in the discussion up to here: The question how the SC can be charged prior to sensor operation appears also relevant for the degree of handling convenience. For HR sensors, which are equipped with electrodes for their sensor inputs anyway (Fig. 4a), the charging could be performed by a DC cable connection through these connectors as well. For other types (Fig. 4d), which do not have any electrical connectors to outside, any kind of plug adapter would be required, but for this technical solutions are known and widely in use like, e.g., for charging sports watches (Fig. 4c). For such cases, some additional technical effort would be incurred. Use of a charging cable would map perfectly to USB connectors, which are known worldwide as universal system for charging small units and which is partially even enforced by laws. A more modern solution would be inductively charging through an RF field; this would require additional components in the electronic circuitry of the sensor, but may keep the mechanical design of the its housing simple.

Contact-less charging represents a comfortable method, if the charge loading is limited to a reasonable time span, but even more modern would be a complete self-supply of electrical sensor energy as discussed for medical applications (Bachmann et al., 2012). Sourcing heat dissipation from the human body for generating the required electricity (Thielen et al, 2017) would be another prospective concept, in sports activities similar ideas would be possible with tapping mechanical acceleration forces.

It shall be remarked at this concluding point, that the study here is aiming just for achieving fundamental findings and for demonstrating the applicability of a relatively new components technology in electronics to a new field of use. The development of certified and professional sensor products is deferred to companies, who want to implement such ideas into new product generations feasible for mass production and long-term use in health and sports sensing.

5 CONCLUSIONS

As it has been demonstrated and validated in the experiments here, supercapacitors sustain enough electrical power for operating wireless body sensors for a reasonable duration in sports workouts. Therefore, super capacitors can replace the commonly used lithium battery cell in terms of a much more environment-friendly part for typical use cases. In addition, mechanical sensor construction can be simplified, since no exchange of the power cell has to be regarded any more, and all cumbersome manual user handling of this can be completely avoided. Hence, the supercapacitor solution arises more comfortable and cheaper than using lithium batteries.

Physical workouts are limited for most people to a duration around one hour; during this time frame the one Farad SC easily delivers enough energy for operating sensors with ANT+ or Bluetooth LE, even if only a limited supply voltage range like the one of lithium batteries is exploited. Depending on the effort, which is invested in the power regulation electronics, an expanded voltage band can be harvested from the SC and the operational time can be factorized considerably, which means that, e.g., an ANT+ HR sensor can be used up to half a day without recharge.

SCs can be reloaded in practice for an unlimited number of repetitions, and they cannot be destroyed by deep discharge; hence, SCs provide also clear advantages over the possible, alternative use of micro accumulators. Since feasible SCs have got similar size and weight like the lithium battery cells, there remains no deterioration or restriction during their use as sensor energy supply.

Preparation of the sensor use, on the other hand, represents indeed an aspect of handling convenience, which has not been covered intensely in this study so far. Therefore, the concept work of this investigation will be continued by developing and testing improved discharge and recharge mechanisms like contact-less methods and voltage-pumping. The resulting increased duration for the sensor supply will be validated with further practical experiments, especially also for Bluetooth sensors with higher power dissipation, because Bluetooth reaches almost all modern smartphone devices and this may inspire more people for performing also healthy sports activities.

Up to here, this investigation has shown clearly the potential, that supercapacitors can be used as more comfortable, more cost-efficient and more environment-friendly power supply than the established solution of using throwaway lithium cells in sport sensors.

REFERENCES

Arts, F. J., Kuipers H., 1994. The relation between power output, oxygen uptake and heart rate in male athletes. *Int. J. of Sports Medicine*, Vol. 15, No. 5, pp228-231.

Bachmann C., et al., 2012. Low-Power Wireless Sensor Nodes for Ubiquitous Long-Term Biomedical Signal Monitoring. *IEEE Communications Magacine*, vol. 50(1), pp 20-27.

Bluetooth SIG, https://developer.bluetooth.org/DevelopmentResources/Pages/White-Papers.aspx, last access: April 2017.

Conway, B.E., 1999. *Electrochemical Supercapacitors, Scientific Fundamentals and Technological Applications*. Springer Science+Business Media, New York, USA.

Dynastream Innovations Inc., 2011. ANT message protocol and usage. http://thisisant.com, Rev. 4.5 (2011).

Galloway, J., Run Walk Run: It began in 1974. http://www.jeffgalloway.com/training/run-walk/, last access: July 2017.

Jefferis, B.J. et al, 2014. Protective Effect of Time Spent Walking on Risk of Stroke in Older Men. *Stroke*, vol. 45, pp 194-199.

Lu, M., 2013. *Supercapacitors: Materials, Systems and Applications*. John Wiley and Sons Inc., New Jersey, USA.

Malkinson T., 2009. Current and emerging technologies in endurance athletic training and race monitoring. In *TIC-STH 2009, Science and Technology for Humanity*. IEEE, Toronto, Canada, pp. 581-586.

Oguma, Y., Shinoda-Tagawa, T., 2004. Physical activity decreases cardiovascular disease risk in women. *American Journal of Preventive Medicine*, vol. 26(5), pp 407-418.

Thielen, M., et al., 2017. Human Body Heat for Powering Wearable Devices: From Thermal Energy to Application. *Energy Conversion and Management,* vol. 131, pp 44-54.

Tudor-Locke, C., Basset D.R., 2004. How many steps/day are enough? Preliminary pedometer indices for public health. *Sports Med.*, vol. 34(1), pp 1-8.

Weghorn, H., 2015. Usability and Engineering Aspects of Competing RF Technologies for Communication with Commercial Sports Sensors in Ubiquitous Applications - Experimental Comparison of Power Consumption and Use Cases for ANT+ and Bluetooth Low Energy Sensor Devices. In *icSPORTS 2015, 3rd International Congress on Sports Science and Technology Support*, SCITEPRESS, pp 263-270.

USD Labor, 2009. Sports and Exercise. *Spotlight on Statistics*, May 2009, https://www.bls.gov/spotlight/2008/sports/, last access: June 2017.