Towards a Smart Non-Invasive Fluid Loss Measurement System

Article *in* Journal of Medical Systems · April 2015

DOI: 10.1007/s10916-015-0206-6 · Source: PubMed

Nagender Suryadevara

S.C. Mukhopadhyay
Macquarie University

J Med Syst (2015) 39:38
DOI 10.1007/s10916-015-0206-6

Towards a Smart Non-Invasive Fluid Loss Measurement System

N. K. Suryadevara · S. C. Mukhopadhyay · L. Barrack

Received: 10 October 2014 / Accepted: 27 November 2014

Abstract In this article, a smart wireless sensing non-invasive system for estimating the amount of fluid loss, a person experiences while physical activity is presented. The system measures three external body parameters, Heart Rate, Galvanic Skin Response (GSR, or skin conductance), and Skin Temperature. These three parameters are entered into an empirically derived formula along with the user's body mass index, and estimation for the amount of fluid lost is determined. The core benefit of the developed system is the affluence usage in combining with smart home monitoring systems to care elderly people in ambient assisted living environments as well in automobiles to monitor the body parameters of a motorist.

Keywords Wireless sensor networks · Physiological parameters · Elder care · Smart home

Introduction

The main objective of the investigation is to measure the dehydration of a person using external body sensors. The wireless dehydration measuring system was based on Texas Instruments' EZ430 Chronos Microcontroller. The microcontroller embedded in a wrist-watch can be worn around the user's wrist. It can also wirelessly communicate with a computer through a Radio Frequency (RF) communication USB dongle. The watch can also act as a central hub for nearby wireless sensors.

The following section present a detailed explanation of what dehydration is, how it is measured, and then look at some devices currently used for measuring it externally [2, 3]. It will then focus on the proposed method of measuring dehydration and the sensors used. The sensing system development will be explained in detail, and also how they interface with a microcontroller. The experiment that was designed and conducted to test the dehydration measuring method will then be discussed along with results and findings.

Background

Dehydration is the loss of fluids in the human body at a rate that the body cannot compensate for [5]. Fluid levels in the body can decrease in a variety of ways, including perspiration from physical activity, waste removal in the urine, breathing, and sicknesses like diarrhea or vomiting. There are two general types of dehydration that can occur. One being through loss of water alone, the other is through the loss of fluids and salts at the same time. These two conditions are known as dehydration and hypovolemia respectively [4]. These two mechanisms are often confused with each other; both blanketed under the term dehydration. Dehydration means that there is not enough fluid in the spaces between cells for the process of osmosis to regulate the concentration of salts in the body. To increase the volume of extracellular fluid in the body, salt-free water, not saline that is the treatment for dehydration, needs be ingested. Hypovolemia is a much more specific measure of dehydration as it focuses on decreased blood plasma volume [10]. This decreased blood plasma volume causes low blood pressure, high heart rate, and increased respiration as the body tries to deliver the same effective blood supply to the body [9].

This article is part of the Topical Collection on *Systems-Level Quality Improvement*

N. K. Suryadevara · S. C. Mukhopadhyay (✉) · L. Barrack
School of Engineering and Advanced Technology, Massey University, Palmerston North, New Zealand
e-mail: S.C.Mukhopadhyay@massey.ac.nz

Published online: 17 February 2015

Current methods of measuring dehydration

A search into the current methods for determining to what extent a person is dehydrated was conducted, and the findings are described below.

Skin turgor test

The most simple and least accurate test that was found was the skin turgor test, or pinch test. Skin turgor is a measure of how resistant to change in shape a person's skin is. The skin on the back of the hand is pinched into a tented shape, held for a number of seconds, and then released. If a person has enough fluid in their body, the skin will return to its pre-pinched state. If a person is mildly dehydrated, the skin will remain tented and slowly return to its pre-pinch state [8]. The Fig. 1 shows its applicability.

Urine specific gravity

One of the most practical and cost efficient clinical measurement methods is to measure the specific gravity of urine [11]. This is a measure of the ratio of the density of the urine and the density of water. It specifically measures the concentration of dissolved salts in the urine. Values greater than one means the urine is denser than water. As the measured specific gravity value rises, the person is becoming more dehydrated as the amount of salts relative to the amount of fluid in the urine increases. This change can be detected in two ways, a urine reagent strip, or a refractometer. The reagent strip is immersed in urine where a change will occur on the strip. This change can then be interpreted using the strip manufacturer's instructions. Urine refractometer uses the refraction of light through the urine and compares that to the refraction of light through water to give the specific gravity reading [11]. The Fig. 2 shows urine specific gravity measuring system.

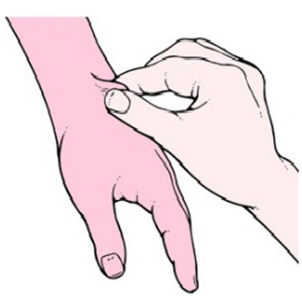


Fig. 1 Demonstration of the pinch test

Plasma osmolality

To get the most accurate measurement of dehydration, the plasma osmolality test should be used. The test works the same way as the urine osmolality test, but a blood sample is taken instead of urine. As blood is constantly circulating around the body, it gives a perfect instantaneous measurement of dehydration. Again, the fact that an osmometer and a trained technician are needed to administer the test means its cost and complicated operation make it impractical for most people. The Fig. 3 shows a typical osmometer.

Core temperature measurement

A study conducted found that "Dehydration also appeared to reduce the core temperature a person could tolerate, as core temperature at exhaustion was about 0.4 ° C (0.7 ° F) lower in the dehydrated state" [1]. This is not describing the complete relationship between dehydration values, but it shows there is some relationship.

Existing dehydration measuring solutions

Cantimer is a company who are in the process of developing a polymer that will expand and contract when in the presence of certain substances in bodily fluids. This expanding polymer will actuate a micro strain gauge that will produce a changing resistance that can be measured and equated to a hydration level. The device is not publicly available now as it is still in its prototyping phase [13].

Measuring bioelectrical impedance

There is a current patent for a device that judges whether a person is dehydrated according to changes in their bioelectric impedance, as well as the body temperature [12]. The device appears complicated to set up and use as well as being bulky.

A new dehydration measuring system

A smart wireless sensing dehydration measuring system has been designed and developed. The Fig. 4 shows the developed system.

Skin temperature

The skin is the body's largest organ. It has many functions apart from keeping everything on the inside. The

Fig. 2 Urine specific gravity measuring equipment

skins ability to sweat and regulate body temperature shows that it is definitely relevant to this project as there is a relationship between core temperature and skin temperature [14]. It is predicted that as the body loses its ability to sweat, the core temperature, as well as the skin temperature will increase over time.

Galvanic skin response

Galvanic skin response (GSR) is the change in the ability for the skin to conduct electricity [7]. This change is considered to be from emotional stimuli such as fright or nervousness. The change in electrical conductance comes from the response of sweat glands in the skin. This is however not the primary function of the sweat glands. Their job is to regulate the body temperature. It is possible to measure this change in conductance using two electrodes and passing a small current over the skin. It was decided that this would be a good parameter to observe. The Fig. 5 shows the placement of the electrodes to measure the GSR.

Fig. 3 One kind of Osmometer

Heart rate

The heart rate responds to dehydration by increasing the frequency at which it beats. This increase is to compensate for the decreased plasma volume, and lower blood pressure.

Electronic system design

The circuits were designed to be small, simple, and use as little power as possible.

Skin temperature sensor

There are many ways of measuring temperature. Mercury thermometers, infrared thermometers, thermocouples, and thermistors are just some of the currently available methods [15]. A quick search into temperature measurement chips came up with a DS600 temperature sensor chip. It can measure temperatures from −20 °C up to 100 °C in 0.5 °C steps so it has more than enough accuracy for this application. Its operating voltage ranges from 2.7 to 5.5 V. The chip is actually used upside down, so the legs had to be carefully bent to touch the pads on the backside of the chip. It provides an analogue output which can be directly converted into a temperature using the Eq. 1

$$\mathrm{Temp}(^{\circ}\mathrm{C}) = \mathrm{Vout}{-}5096.45(\mathrm{mV}) \tag{1}$$

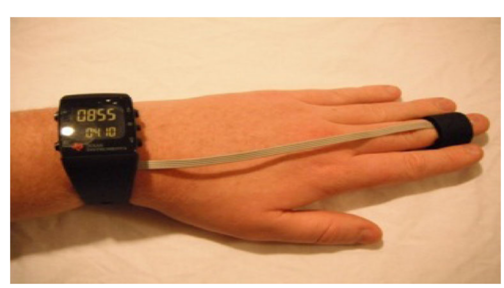


Fig. 4 A new dehydration measuring system

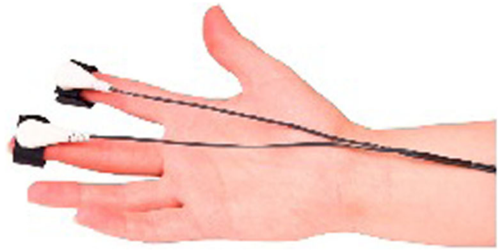


Fig. 5 Measuring GSR using two finger electrodes

$$Vout = Vcc\frac{R_2}{R_1 + R_2}$$

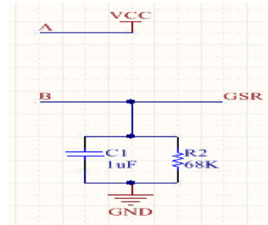


Fig. 7 Schematic diagram of GSR sensor

The microcontroller can read the analogue voltage on the input pin and from there the conversion process is simple. The Fig. 6 shows the schematic diagram of the temperature sensor.

Galvanic skin response sensor

The GSR sensor is a voltage divider circuit. Figure shows A and B are the electrodes. The human body acts like a large resistor, so the output is dependent on the voltage divider equation. This means that Vout and R1 are inversely related, therefore when the resistance of the skin decreases Vout increases [6]. The Fig. 7 shows the schematic of the GSR sensing system.

$$Vout = VccR2R1 + R2$$

Heart rate sensor

The heart rate sensor was the hardest and most interesting sensor of all. After reviewing a few methods of measuring heart rate, it was decided that a method called Photoplethysmography (PPG) would be used as there are many examples available. PPG uses an infrared light source to illuminate the finger on one side, and a phototransistor placed on the other side of the finger that detects small variations in the transmitted light intensity. The variations in the intensity are related to changes in blood volume inside the finger tissues as the heart pumps blood through it. The signal starts of noisy and low amplitude so it needs to be amplified. It also has a relatively large DC offset. The first high pass filters removes the DC component of the signal with a cut-off frequency of 0.72 HZ calculated using the Eq. (2):

$$fc = 12\pi RC \tag{2}$$

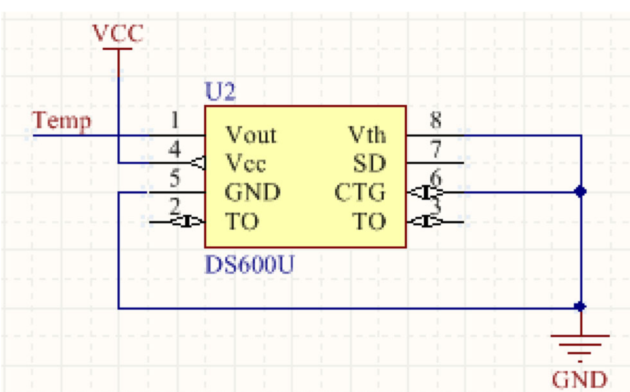


Fig. 6 Schematic diagram of DS600 temperature sensor

The signal is then filtered and amplified by an active low pass filter with frequency cut-off set to 2.34Hz and a gain of 100. This is then replicated in the second stage giving a total gain of 10,000. The non-inverting buffer then lowers the output impedance signal which is useful once the signal is fed into the microcontroller. The Fig. 8 shows the schematic of the heart rate sensor.

Printed circuit board design

The GSR and heart rate sensors were individually tested, then tested at the same time on a bread board before the PCB design process had started. This was to verify they operated as expected, and didn't interfere with each other. The main goal while designing the PCB was to keep it all small. The back plate of the Texas instruments watch was measured and that size was set as the outline of the board. The most complicated thing about the PCB was trying to solder a MicroSOP IC onto its miniscule pads, especially when the pads have to be cut apart using a razor. The Fig. 9 shows the prototype of the designed system.

Microcontroller

As previously stated the microcontroller in the Texas Instruments watch could not provide the required hardware inputs needed as they were all utilized. It was for this reason that an Arduino microcontroller was substituted as a simulation tool, just to prove the device works.

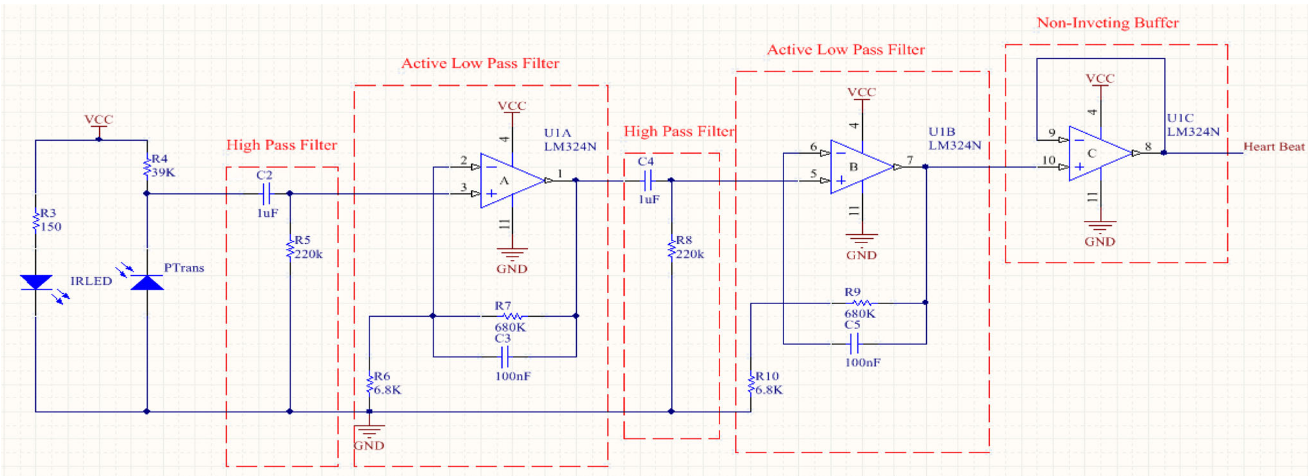


Fig. 8 Schematic diagram for heart rate sensor

Problems where encountered trying to get the microcontroller to do three things at once. For example, the method initially used to measure the heart rate was to time between pulses. This resulted in blocking code that would not allow the microcontroller to do anything else. To solve this problem an interrupt method was used. When a rising edge is encountered, it sets off an interrupt service routine which starts a timer that can run without blocking the rest of the code. Once another rising edge is encountered, the timer returns how long it was running for. The inverse of the period is taken to get the frequency and then divide by sixty to get the heart rate in beats per minute.

```
Elapsed = millis()-start; //gets the full period (in ms)
beat=1/((elapsed/1000)/60);//calculates heart rate in BPM
```

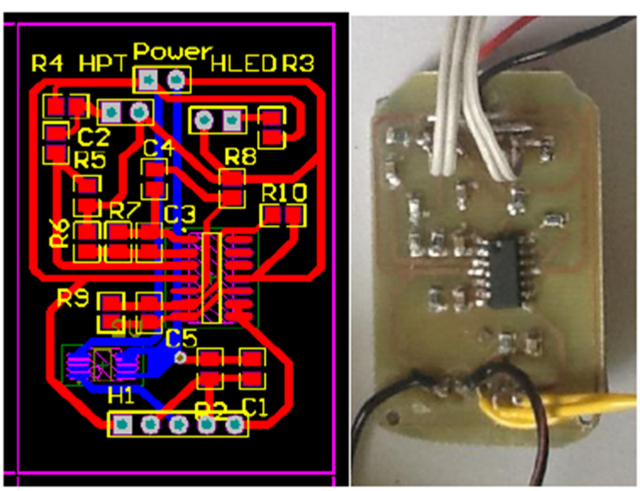


Fig. 9 The Altium board with the actual board on the right

In the case of the temperature sensor it is a simple task of reading the analog input pin, converting the ADC value to a voltage, then converting the voltage to a temperature.

```
therm = analogRead(A1); // input on Analog pin 1
volt1 = therm* (5 / 1.024);// conversion to Voltage
temp = ((volt1-509)/6.45); // temperature calculation
```

The GSR sensor follows the same process but stops at converting the voltage to a temperature.

```
rawgsr = analogRead(A0); // input on Analog pin 0
GSR = rawgsr * (5 / 1.024);// conversion to Voltage
```

Writing to the LCD screen is a simple case of setting the cursor position and then telling the Arduino what needs to be written there. The Fig. 10 shows the display of the three measured values.

Fig. 10 Display of the three measured parameters

To obtain an estimation for the percentage of fluid lost, it is a simple matter of plugging the previously calculated values into the regression Eq. (3).

$$\text{fluid} = -1.95403 + (0.0554441 * \text{BMI}) - (0.0228502 * \text{temp}) + (0.0084186 * \text{beat}) + (0.000370397 * \text{GSR}); \quad (3)$$

The Fig. 11 shows the estimated fluid loss measured and displayed on the microcontroller.

The final device

The watch platform was kept to stay true to the roots of the project that this was to use the EZ430 Microcontroller watch. It can be worn on the wrist with the GSR electrodes contacting the skin on either side of the wrist. The skin temperature sensor contacts the top of the wrist. The heart rate sensor LED and photo transistor is worn on any finger and held in place with a Velcro strap. Caution must be taken to not tighten this strap too much as that throws the reading out. The Fig. 12 shows the developed prototype.

Experimental data collection

The aim of the experimental process was to collect data that could be used to develop an equation that related BMI, GSR, heart rate, and skin temperature to dehydration.

Initial experimentation

The device used to measure the heart rate, GSR, and skin temperature wirelessly transmits data to a computer at a rate of one set of measurements per second and stores the data in a very large text file for later analysis. The form of each data packet is: timestamp, skin temp ADC value, heart rate (BPM), GSR value.

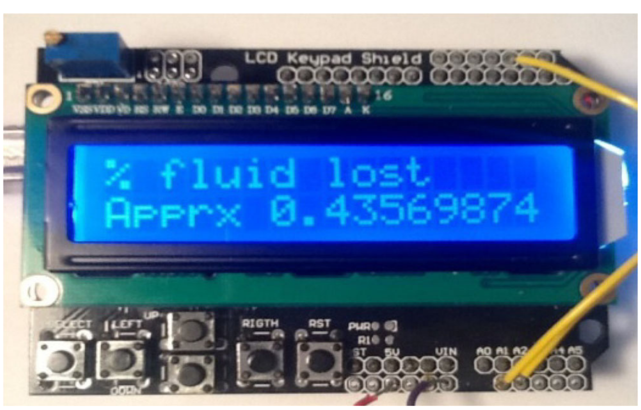


Fig. 11 Display of estimated fluid loss

The first round of experimental testing was to be very simple. Experimental participants had their height and weight measured so that their body mass index (BMI) could be calculated using the Eq. 4

$$\text{BMI} = \text{Weight (kg)Height2 (m)} \quad (4)$$

The participant then placed their hand on the device shown in Fig. 7 to have their heart rate, GSR, and skin temperature measured. The participant was then given a large drink of water and after five minutes their heart rate, GSR and skin temperature where all measured again.

The results obtained from this experiment showed completely random data so the experiment was scrapped and a new experiment was designed.

Second experiment method

The second experiment was to be far more comprehensive. It had to somehow produce dehydration like symptoms, and reduce the fluid level in the body. It was decided that physical activity would be the easiest and safest way to reduce fluid levels.

The process was to:

1. Measure the participant's height and weight so their BMI could be calculated.
2. Have the participants place their hand on the device shown in Fig. 4 and take initial readings for heart rate, GSR, and skin temperature.

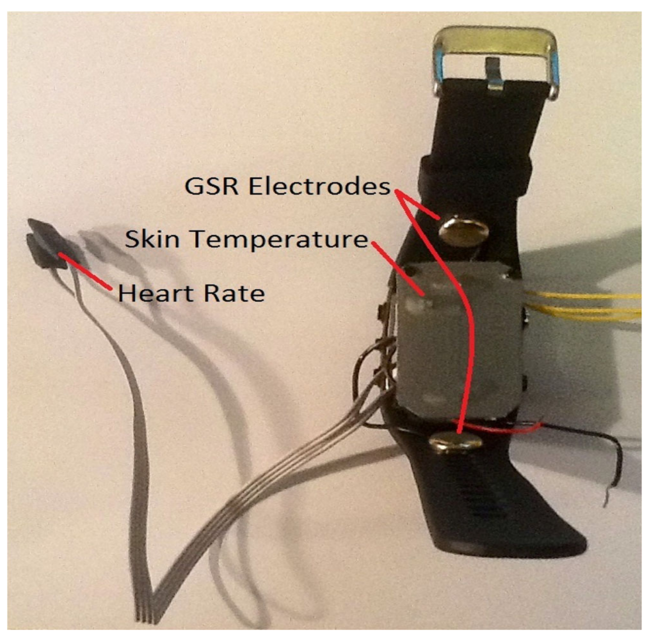


Fig. 12 Assembly of the final system

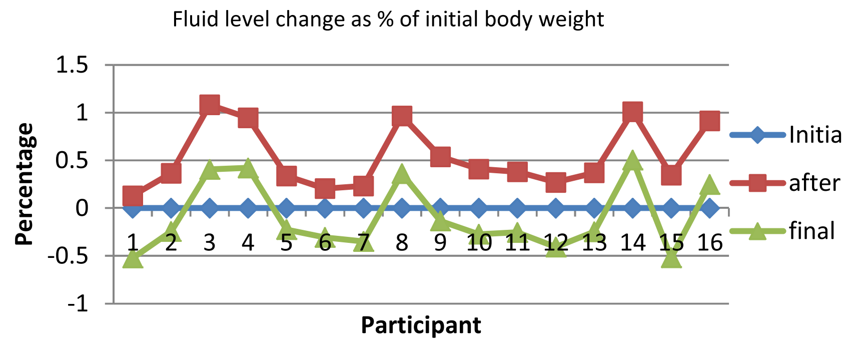


Fig. 13 Graph showing change in fluid level as a percentage of initial body weight

3. Allow the participants to undertake some form of physical activity without taking on fluids.
4. Measure the participant's weight, heart rate, GSR, and skin temperature after their physical activity.
5. Give each participant a drink of 500 ml of water.
6. Finally, measure their heart rate, GSR, and skin temperature.
7. The amount of fluid loss as a percentage of initial body weight could then be calculated using the varying body weights.

To make the data collection process as streamlined as possible, Royal New Zealand Air Force (RNZAF) Base Ohakea Physical Training Instructors where contacted to determine whether or not the experiment could run in conjunction with one of the daily physical training sessions run in the gym at RNZAF Base Ohakea. Fortunately, they were more than happy to be part of the project. This meant a relatively large sample size of 16 people who would all complete 30 min of intense mostly cardio physical activity.

Experimental hypothesis

A fluid loss in the region of 2 % body weight was desired as this is generally considered the onset of mild dehydration.

It was expected that heart rate, GSR, and skin temperature would all peak after the workout, and then drop back down to somewhere near the pre workout level initially measured. However, due to the highly responsive nature of the GSR it was expected that the results were to be somewhat erratic.

Participants

The experiment was conducted with the help of sixteen individuals from the Avionics department at Base Ohakea. There where fourteen males and two females all with varying levels of fitness, but fit enough to pass the operational fitness test the Air Force has its members undertake. This consists of thirty push- ups, and a five kilometre march carrying twenty extra kilograms of weight.

The relevant physical characteristics of this group where height=179±10 cm, mass =89.1±31.2 kg, and BMI of 26.98 ±6.705.

The workout

The physical activity that the participants endured is known as circuit training. The participants move around the "circuit" stopping at each activity and doing that activity as hard as the can for four minutes. The circuit was designed by profes-

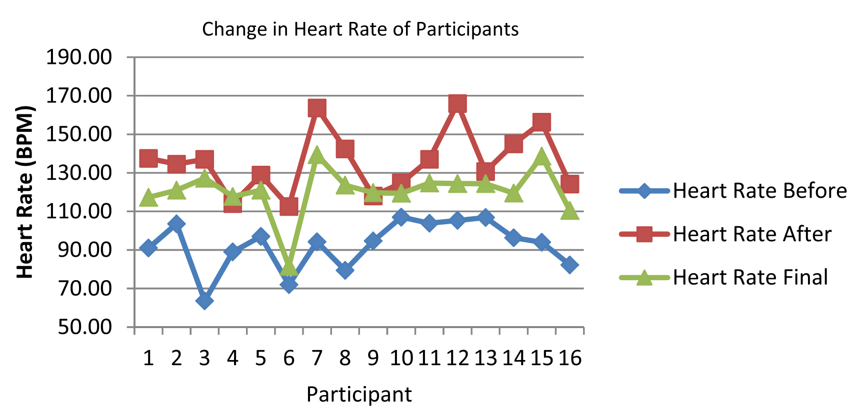
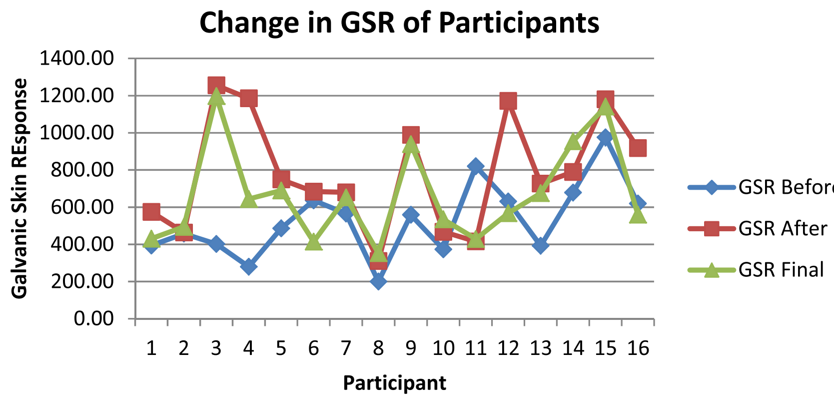


Fig. 14 Graph showing the change in heart rate of participants throughout experiment

Fig. 15 Graph showing the change in GSR of participants throughout experiment



sional physical training instructors so the risk of injury to the participants was very low. The various stops included activities such as sit-ups, stationary rowing, star jumps, medicine ball throws, crab walks, bar lifts and burpees. The workout spanned approximately half an hour, and it was obvious from the expression on the participant's faces that they were working hard.

Experimental results

The Fig. 13 shows the levels of dehydration that were achieved. After their workout, the combined average loss of fluid was only 0.53 % with a maximum value of 1.08 % and a minimum of 0.13 %.

This is less than what was desired, but is still a reasonable loss of fluid, as it does not account for the sweat that remained in the participants clothing. The ideal way of obtaining this measurement would be to weigh participants without clothing on. This is a source of systematic error as it is assumed most fabrics absorb approximately equal amounts of water.

The statistical analysis later in the report uses this fluid loss as the response, which is to be predicted by a combination of BMI, heart rate, GSR, and skin temperature. Figures 14, 15 and 16 shows approximately the expected outcome. The peak in heart rate after the workout was expected. However, it was expected that the "Heart Rate Final" line would lie approximately over top of the "Heart Rate Before" line.

This is not the case as the average final heart rate remains 30 beats per minute higher than the before measurements. This is most probably due to the fact that not enough time was given to the participants to allow their hear rates to get to the resting rhythm.

On first glance, it seems to show very erratic data but if the averages are examined, there is a definite trend. The average GSR value for "Before" is 529.2 this increases to 784.9 after the workout, finally dropping back down to 667.1.

According to the data collected the skin temperature continued to rise after the participants had been given their water. This could be to do with the core temperature being raised during the workout, which would take some time to settle back down after the experiment has finished. This is a plausible explanation, as it would take a fair amount of time to reduce the temperature of such a large object like the human body.

Statistical analysis of experimental results

Initially it appeared that the data that was collected was useful. However this couldn't be determined without

Fig. 16 Graph showing the change in skin temperature throughout experiment

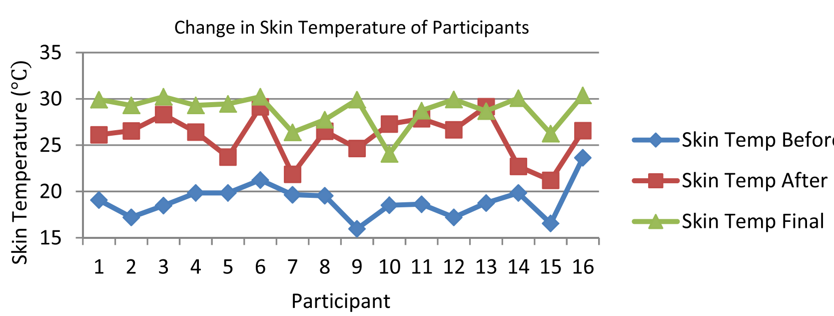


Table 1 Predictor *P* values

Source	P
BMI	0.0001722
SkinTemp	0.0628871
HeartRate	0.0028130
GSR	0.0529122

further statistical analysis. The most comprehensive way of doing this was to use a Minitab statistical software package. An initial general regression analysis was performed on the data. The predictor variables were BMI, skin temperature, heart rate, and GSR. The response was the percentage of fluid lost (or gained).

The human body is a very variable system so it was safe to say that we will work with a 90 % confidence interval where a 95 % confidence interval would normally be used.

The results of the analysis were that all predictor variables can be considered significant as they all have P values that are less than 0.1. This means that all predictor variables can be used in the regression equation to predict the fluid lost in the participants. Tables 1 and 2 shows the predictor and variance values.

The variance inflation factor is a measure of how related each individual predictor variable is to the other predictor variables. As all the variance inflation factors are less than 5, it is safe to assume that all predictors are independent and not related.

The regression coefficient confidence intervals are effectively saying "if all the data in the universe was present the actual value would lie somewhere between these two numbers". In the case of this data it was found that all the calculated coefficients where within the confidence interval, even at the 95 % level. Table 3 shows the regression coefficient intervals.

The regression analysis gave the Eq. 5 which is used in the microcontroller to predict the fluid level.

$$\begin{aligned}\text{Fluid} = {} & -1.95403 \\ & + 0.0554441\text{BMI} - 0.0228502\text{SkinTemp} \\ & + 0.0084186\text{HeartRate} + 0.000370397\text{GSR} \quad (5)\end{aligned}$$

Table 2 Variance inflation factors

Term	VIF
BMI	1.23052
SkinTemp	1.43857
HeartRate	1.71225
GSR	1.21816

Table 3 Regression coefficient confidence intervals

Term	Coef	95 % CI
BMI	-1.95403	(-2.88403, -1.02402)
SkinTemp	0.05544	(0.02827, 0.08262)
HeartRate	-0.02285	(-0.04698, 0.00128)
GSR	0.00037	(-0.00000, 0.00075)

Discussion and conclusion

The experiment was successful in detecting changes in heart rate, GSR, and skin temperature after the workout, and then at the end of the experiment. The parameter which contributes the most towards the estimation of the fluid lost is BMI. This is shown by BMI having the lowest P value. It is possible that not all participants are putting in the same effort during each activity. To make this experiment more accurate a constant type exercise would need to be done, walking on a treadmill, or cycling on a stationary bike for example. Looking at this experiment, the results obtained, and the analysis performed on the data, as well as the input from the professionals, there is a strong indication that it is possible to detect fluid loss in the human body using external sensors [16–18].

References

1. Asker, J., and Gleeson, M., *Sport nutrition-an introduction to energy production and performance*. Human Kinetics, Champaign, 2009.
2. Bhardwaj, S., Lee, D. S., Mukhopadhyay, S. C. and Chung, W. Y., "Ubiquitous healthcare data analysis and monitoring using multiple wireless sensorsfor elderly person", *Spec Issue Mod Sen Technol, Sens Transducers J*, ISSN 1726–5479, 90:87–99, 2008.
3. Bhardwaj, S, Lee, D. S., Mukhopadhyay, S. C. and Chung, W. Y., "*A fusion data monitoring of multiple wireless sensors for ubiquitous healthcare system*", Proceedings of the 2nd International Conference on Sensing Technology Palmerston North, New Zealand, pp. 217–222, 2007.
4. Bhave, G., Neilson, E., Volume depletion versus dehydration: how understanding the difference can guide therapy. 302–309, 2011.
5. Thomas, D. R., Cote, T. R., Understanding clinical dehydration and its treatment. *JAMDA*, 292–301, 2008.
6. Lykken, D. T., Venables, P. H., Direct measurement of skin conductance: a proposal for standardization. *Psychophysiology*, 656–672, 1971.
7. Houghton Mifflin Company, *The american heritage® dictionary of the english language*, fourth edition. houghton mifflin company, 2000.
8. Vorvick, L. J., Skin turgor. Retrieved April 17, 2013, from MedlinePlus: http://www.nlm.nih.gov/medlineplus/ency/article/003281.htm, 2012.
9. Marie-Jocelyne, M., SOGC clinical practice guidelines. *Hemorrhagic Shock* 1–8, 2002.

10. MedicineNet, Retrieved April 17, 2013, from MedicineNet.com: http://www.medterms.com/script/main/art.asp?articlekey=3871, 2012.
11. Minton, D. M., Best practice for clinical hydration. *Athl. Ther. Today*, 9–11, 2009.
12. Miyuki Tanita Corporation Shimomura, K. T., Patent No. EP1177763 B1: Europe, 2001.
13. Stewart, R. F., A. D.-S., 2009 Patent No. WO2009142742 A1: United States of America, 2009.
14. Savage, M. V. (1996). Control of skin blood flow in the neutral zone of human body temperature regulation. J. Appl. Physiol., 1249–1257
15. Suryadevara, N. K., Quazi, M. T, Mukhopadhyay S.C., *Intelligent sensing systems for measuring wellness indices of the daily activities for the elderly*: Proceedings of the IEEE 8th International Conference on Intelligent Environment(IE), Mexico, 347–350, 2012.
16. Suryadevara, N. K, Quazi, M. T., Mukhopadhyay, S. C., *Smart sensing system for human emotion and behaviour recognition*, Perception and Machine Intelligence, Springer Berlin Heidelberg:11–22.
17. Quazi, M. T., Mukhopadhyay, S. C., Suryadevara, N. K., Huang, Y. M, *Towards the smart sensors based human emotion recognition*: Proceedings of the International Conference on I2MTC-2012: 2365–2370.
18. Quazi, M. T. *Human emotion recognition using smart sensors*, 2012.