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Hydration management system for sports and health care applications – Fundamental considerations and early development

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Abstract: Dehydration can cause serious health problems. The optimal amount and the right time to drink varies individually and depends on many factors, i.e. anthropometric data, current stress levels or environmental influences. Therefore, we aim to develop an intelligent hydration management system for sports and health care applications based on sensor technology to determine fluid intake, linked to current vital, performance and environmental parameters. This allows the calculation of individual requirements and drinking recommendations for an optimal fluid and electrolyte balance. In the current study, we evaluated three sensor principles for determination of drinking volumes and analyzed boundary conditions for an automated test stand to simulate tube-based drinking.

Keywords: hydration management, dehydration, sensor systems, drinking volume, test stand.

1 Introduction

Consuming less fluid than the body loses leads to dehydration (DH), which can cause serious health consequences. In Germany, about one in three people is dehydrated at least occasionally, and more than one in ten is dehydrated four or more days a week [1]. Individual fluid loss should always be replaced by at least 80% to avoid DH [2]. For example, Sawka et al. (2009) recommend a fluid intake of 0.4-0.8 l/h during intense physical exertion [3]. However, drinking too much can lead to overhydration. The optimal amount and right time to drink is individually different and depends on many factors such as physical and mental condition (age, morbidity etc.), current stress levels and environmental influences.

Although drinking is uncomplicated, at least for a healthy person, various reasons lead to underhydration. Short-term DH can and long-term DH will lead to health problems. DH of only 2% of total body water can result in significant impairment of physical, visual-motor, and cognitive performance [4]. Judelson et al. (2007) describe a 10% reduction in endurance performance with DH [5]. Logan-Sprenger et al. (2015) even found a 13% reduction in performance in cycling [6].

There are numerous patents on sensor-based drinking systems, but only a few involve drinking recommendations based on multiparametric data analysis. Commercial systems presented by Cohen et al. (2021), such as the Hidrate Spark drinking bottle (HidrateSmart LLC, USA), that indicates recommended drinking times by light signals, do not allow access to the sensor data obtained, as there is no open programming interface [7].

Our long-term goal is to develop an intelligent hydration management system for sports and health care applications based on sensor technology to determine fluid intake, linked to current vital, performance and environmental parameters to calculate individual requirements and provide drinking recommendations for optimal fluid and electrolyte balance.

For the development of the hydration management system, we initially select and test three sensor principles for determination of drinking volumes: a capacitive measuring principle on a drinking bottle as well as a liquid flow sensor and a self-developed setup with two liquid level sensors for integration in a drinking tube, **Figure 1**. In the current study we aim to select and evaluate a suitable sensor system. To this end, the three sensor principles are tested in initial experiments. Furthermore, it is to be assessed what properties of a test stand are needed to simulate drinking in order to practically test the sensor system. For this purpose, the pressure curve in a drinking tube is determined during the drinking process, which should ideally be reproduced by the test stand.

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2 Materials and methods

2.1 Sensor systems for determination of drinking quantities

For the measurement of drinking volumes, we initially selected three sensor principles. For capacitive measurement of the changing fill level in a bottle, the out-of-phase liquid level technique according to [8] was applied by creating a double-sided circuit board which was fixed onto a plastic bottle (wall thickness: 1 mm), **Figure 1a**. The FDC1004QEVM evaluation module (Texas Instruments Inc., USA) with the FDC1004EVM GUI software was used for data assessment. The software is able to control a FDC1004Q capacitance-to-digital converter chip, to display the measured capacitive values and to export the data. Initial tests were performed with distilled water at room temperature using the oversized bottle shown (100% sensor range ≙ fill height difference of 80 mm).

For a second measuring principle, a liquid flow sensor FS1027-DL (Renesas Electronics Corp., USA) based on a calorimetric principle was selected due to its application range of 0 to 10 l/min flow (in water) and the inner diameter of 10 mm, **Figure 1b**, suitable for a 10 mm tube, which is a typical diameter for drinking tubes. A program for measuring the fluid flow as an analog voltage was implemented on an Arduino UNO (Arduino S.r.l., Italy).

A third, newly developed sensor concept for determining the drinking volume is based on the principle of a transit time measurement between two SEN0509 (DFRobot Corp., China) liquid level sensors positioned on the drinking tube, **Figure 1c**. The measuring principle is based on time points where the change at the sensors (change from “wet” to “dry” and vice versa) defines the state of the system. In the program implemented on an Arduino UNO, the *millis* function is used for time recording, which enables a sufficient resolution in the millisecond range. The sensor principle requires a tube-based, preferably vertical setup without air bubbles and a continuous flow during the drinking process.

2.2 Initial test of the 2-sensor concept

The preferred sensor principle with two liquid level sensors, see **Figure 1c**, should be initially investigated for its suitability to accurately determine the volume of liquid consumed. A corresponding test arrangement according to **Figure 2a** was set up for this purpose. The sensors with an inner diameter of 4.5 mm were mounted between tubes with an inner diameter of 4.5 mm and a wall thickness of 1 mm, cf. **Figure 1c**. Using a syringe pump (Nemesys high pressure module, 50 ml stainless steel syringe, CETONI GmbH, Germany), distilled water was pushed into the vertically mounted sensor-equipped tube at a continuous flow rate and then withdrawn again. Flow rate was varied for the simulation of the drinking process (0.1, 0.5, 1, 2, 2.5, 3, 4, 5 and 6 ml/s); to simulate the backward flow of water under the influence of gravity, a constant flow rate of -2 ml/s was applied. Between forward and backward flow there was a dwell time of 3 s. For each flow rate, 30 cycles were run, with a pause of 5 s between the cycles. The flow rate for the forward flow is calculated from the time between switching sensor I and sensor II to “wet” and the volume of the tube between the two sensors. The time points for flow rate calculation of the backward flow are the switch to “dry” from sensor II and sensor I

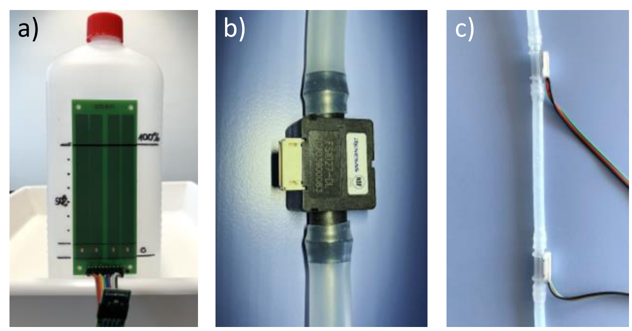

Figure 1: Sensor principles to determine drinking quantities: a) capacitive measurement of the fill level in a bottle with a double-sided circuit board, b) flow measurement using a liquid flow sensor with an inner diameter of 10 mm, c) flow measurement based on transit time determination between two liquid level sensors.

2.3 Determination of pressure profile in a drinking tube

Tests were carried out to determine the pressure conditions in a drinking tube, which a test stand for realistic drinking simulation must reproduce for testing fluid sensor systems. Three AMS 4711-0350-D-B bidirectional differential pressure sensors (Analog Microelectronics GmbH, Germany) with a pressure range of ±350 mbar were connected to the drinking tube at three different height levels using 3D-printed T-pieces, **Figure 2b**. The pressure values were recorded on three channels of a 4-channel oscilloscope PicoScope 6424E (Pico Technology, UK) with an input voltage range set to ±5 V. There was no offset compensation of the pressure values.
“Real” drinking was carried out in a self-experiment with two test persons (male/female). As a reference the fluid flow was generated with a magnetically driven gear pump setting a flow

rate of 1000 ml/min (GJ-N21.DGD61J, Micropump Inc., USA). Two different tube diameters were compared: 9 mm (wall thickness 1.5 mm) and 5 mm (wall thickness 1 mm). The tests were repeated three times for each combination of test person/pump and tube, so that a total of 18 measurement curves were recorded for each of the three pressure sensors. As the pressure values varied by ±3 mbar at absolute values in a range of -130 to 10 mbar, the *LOWESS* method (span: 0.5) in OriginPro 2018b (OriginLab Corp., USA) was applied to smooth the curves.

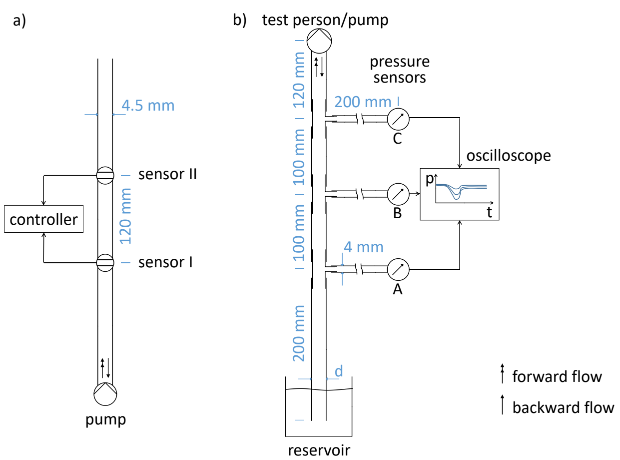

Figure 2: Test setups for the initial testing of the 2-sensor concept using a tube with an inner diameter of 4.5 mm (a) and for the determination of the pressure profile in a drinking tube with three pressure sensors A (bottom), B (middle) and C (top) and a variable drinking tube's inner diameter d (b).

3 Results and discussion

3.1 Determination of drinking quantities

The result of the experiments for the first sensor principle, the capacitive measurement, was a quadratic correlation between the actual fill level and the fill level calculated from the measured capacitances, **Figure 3a** (red markers). For the corrected curve, the values fit very well, **Figure 3a** (green markers), enabling the determination of the liquid volume. The equation applies for 0 to 75% and is limited by the selected geometry of the capacitive surfaces, which lead to an exceeded measuring range above 75%, see **Figure 3b**.

Initial tests with the second sensor principle, the liquid flow sensor, showed that the sensor requires a continuous flow completely filled with water. The large cross-section made this sensor unusable. Therefore, no measurements were recorded.

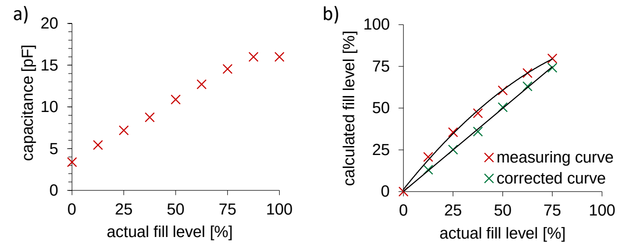

Figure 3: Results of representative capacitive measurement: a) correlation between capacity and fill level with an exceeded measuring range above 75% fill level, b) matching the actual fill level with the calculated fill level using quadratic regression of the measuring curve (red markers), resulting corrected curve (green markers).

The experiments with the third sensor principle, the 2-sensor concept, showed a very good agreement between the flow rate set with the syringe pump and the flow rate determined by the sensors and the associated Arduino program, so that a precise determination of the drinking quantity can be made on this basis. **Figure 4** shows the determined flow rates as a function of the set flow rates for the forward flow. The backward flow is 2.051± 0.002 ml/s for the set value of 2.0 ml/s.

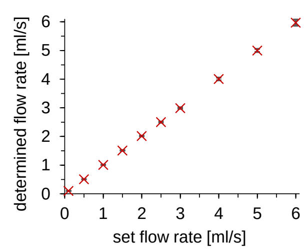

Figure 4: Correlation between the flow rate set with the syringe pump and the flow rate determined using the 2-sensor concept and the associated program for the forward flow with different flow rates.

3.2 Pressure profile in a drinking tube

The measurement curves for the pressure profile in the drinking tube, which serve as a basis for the configuration of a future test stand, show a plausible but very uneven progression during drinking for both test persons, even more so for the larger tube diameter, although the attempt was made to drink evenly, **Figure 5**. As expected, the curves for the pump-generated flow show a generally uniform pressure progression. The constant pressure differences of approx. 10 mbar between the sensors result from the height position of the sensors, each with a difference of 100 mm, and the respective water column above each sensor.

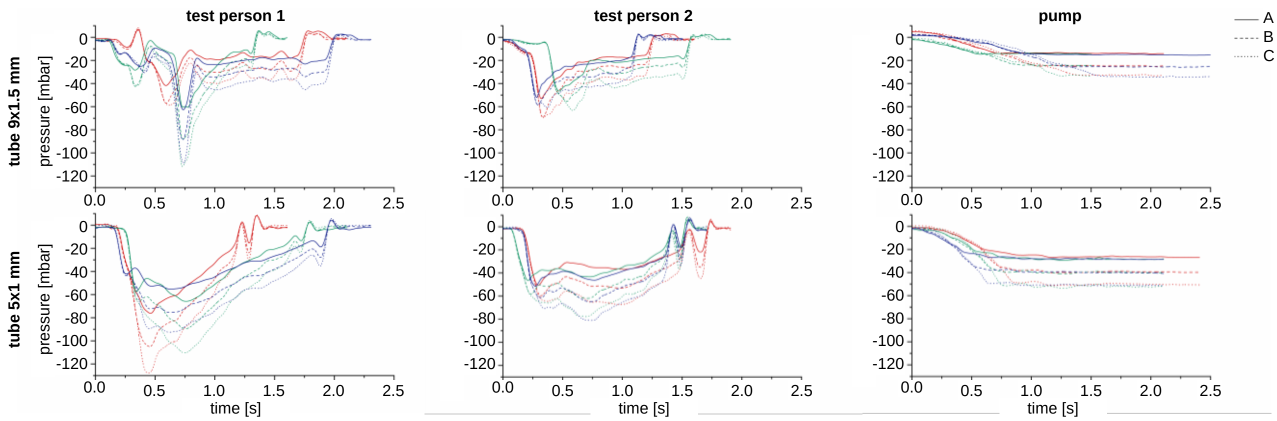

Figure 5: Pressure profile over time for pressure sensors A (solid), B, (dashed) and C (dotted line) in 9×1.5 mm (top) and 5×1 mm (bottom) tubes for drinking of test person 1 (left) and 2 (center) and pump-generated flow (right), three tests each (red, green and blue curves)

4 Conclusion and outlook

The fill level measurement with the tested capacitive principle could be performed successfully. However, the sensor principle is particularly disadvantageous for our planned applications, e.g. in cycling, as vibrations or a tilted bottle make it difficult to determine the exact fluid volume.

In initial tests of a liquid flow sensor, no continuous flow and complete filling with water was achieved. Therefore, no measurement of drinking volume was possible. Other variants, e.g. sensors with smaller diameters, could be evaluated in the future. However, direct liquid contact of the sensor is not recommended for reasons of hygiene and handling.

Initial tests of the newly developed 2-sensor principle with two liquid level sensors showed convincing results. Nevertheless, the advantageous simplicity of the setup requires certain restrictions, such as a preferably vertical setup and a continuous flow. The very cost-effective sensors, which work without direct liquid contact, are currently only available with an inner diameter of 4.5 mm. An integration into larger 3D-printed housings enables testing of other tube sizes. To combine both test setups presented, the sensor principle can be transferred to the 3D-printed T-pieces of the setup for pressure profile determination, so that the events can be synchronized via the fourth channel of the oscilloscope.

The highly variable pressure curves in drinking tests with different tube diameters demonstrate that the development of an automated test stand with a wide range of adjustable boundary conditions to simulate realistic drinking is expedient for a practical evaluation of sensor concepts to determine drinking volumes. This test stand will show whether the 2-sensor principle works in practice, including health care, occupational medicine and sport, to provide an intelligent hydration management system in the future. Functionality for many technical applications can already be assumed.

Author Statement

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