Development of a test bench for the characterization of movement artifacts in smart textile systems

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Introduction

Electrocardiography (ECG) is a method for measuring and recording the electrical excitation of the heart. Since the development of the ECG in 1903, it has been an essential instrument of medical diagnostics. Most of the ECG systems currently established on the market are equipped with adhesive electrodes. The adhesives used for fixating and the electrode gel used to minimize electrical resistance create discomfort for the user and can lead to skin irritation over long periods of time. Therefore they restrict the possible duration of long-term ECG examinations to a few days [1].

For longer investigations, textile electrodes are a suitable alternative as they cause less skin irritation due to the absence of adhesives and electrolyte gel. However, in the case of textile electrodes, the increased contact resistance and the additional capacitance in the electrode-skin-interface (s. Figure 1), which result in higher signal disturbances caused by the relative movement between the electrode and the skin, are still the biggest limitation.

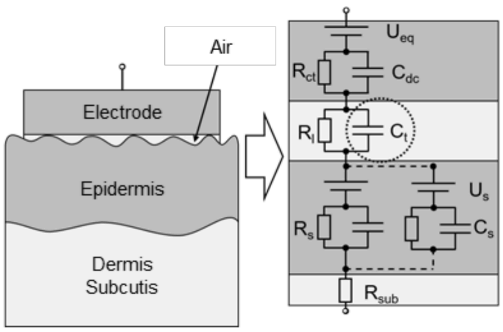

Figure 1: Electrical model of electrode-skin-interface for textile electrodes [2].

The sensitivity to such motion artifacts from different textile electrodes is difficult to compare, as there are no standardized test methods yet. Recent literature describes different test benches [2] [3] [4] [5], but these are either not suitable for reproducible measurements of motion artifacts or are associated with very high costs.

The aim of this work is, therefore, to provide a cost-efficient test bench for the characterization of textile ECG electrodes with regard to their susceptibility to signal interference caused by movement in the electrode-skin-contact. In addition to fluctuations in contact pressure, this also includes translational movements of the electrode on the skin. The test bench should enable the comparison of electrode geometries, manufacturing processes and materials and thus support the development of more precise and efficient textile electrodes.

Materials and Methods

The design project was carried out using the VDI 2221 procedure in order to achieve a cost-efficient and precise design. The overall system was divided into subsystems and their respective interfaces, which allow mounting textile electrodes, adjusting contact pressure and simulating movement patterns (s. Figure 2 and 3).

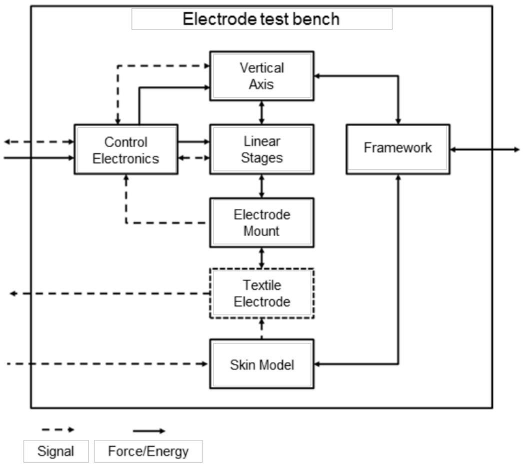

Figure 2: Overview of subsystems.

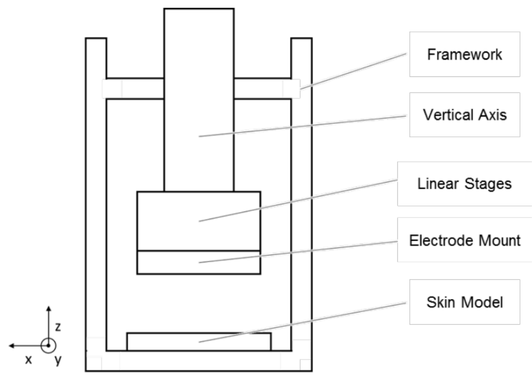

Figure 3: Assembly of subsystems.

Vertical Axis, Linear Stages, and Electrode Mount

The mechanical components were divided into three modular components (s. Figure 4). The vertical axis module covers the function of adjusting the electrodes contact pressure to the skin model. For this purpose, a column guide, a spindle drive and a stepper motor were determined as suitable solutions. The linear stages are designed to generate the horizontal movements that a tex-tile electrode must withstand when worn by the patient on a daily basis. Similar to the vertical axis, one column guide, one spindle drive, and one stepper motor were used. The electrode holder module was designed to fulfill the function of attaching the textile electrodes to the signal measurement circuitry and to incorporate the sensors for the contact pressure determination. In order to allow comparable measurements with other classical ECG electrodes, standard snap fasteners were used for contacting the electrodes. The contact pressure measurement was realized by attaching a pressure sensing foil beneath a corresponding stamp mounted on the electrode holder.

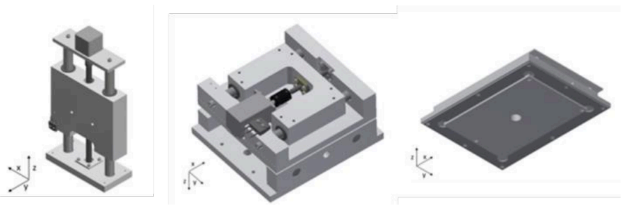

Figure 4: CAD-Models of Vertical Axis (left), Linear Stages (middle), and Electrode Mount (right).

Control Electronics

An Arduino Mega 2560 Rev3 based on an ATmega2560 8-bit microcontroller from Atmel was used as microcontroller, to handle the sensor, motor and user interface communication (s. Figure 5).

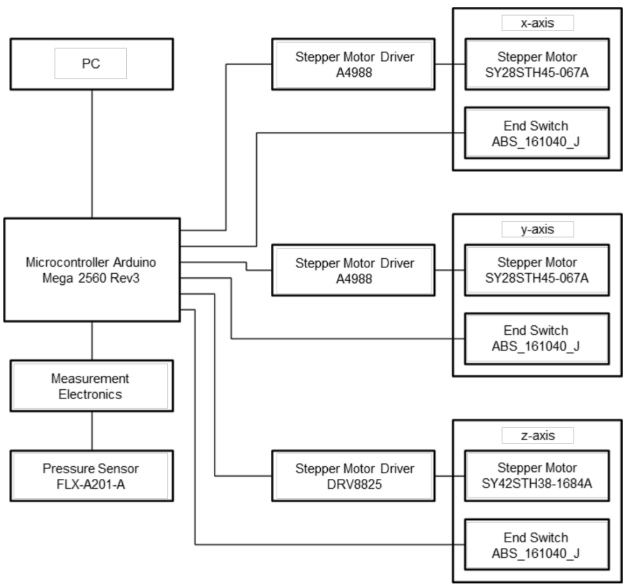

Figure 5: Overview of control electronics.

Based on the required forces to generate contact pressure values of up to 3 kPa and movement velocities of up to 10 mm/s two different stepper motors were used. For linear stage motors, the A4988 Stepper Motor Driver Carrier Black Edition from Pololu was used. It is based on the Integrated Circuit (IC) A4988 from Allegro MicroSystems, LLC and can supply 1.2 A current at an operating voltage of 8 V – 35 V. The stepper motors of the linear stages have a nominal current of 0.68 A and are to be operated at a voltage of 24 V. The stepper motor of the vertical axis has a rated current of 1.6 A, which is too high for the stepper motor drivers of the linear stages. Therefore, the DRV8825 Stepper Motor Driver Carrier from Pololu, based on the IC DRV8825 from Texas Instruments, was used here. It delivers up to 1.5 A without additional cooling and up to 2.2 A with cooling. Since the required current is only slightly higher than the value possible without cooling, it is sufficient to provide the IC with a heat sink. No active cooling is required.

To quantify the pressure a measuring foil from Tekscan with a measuring range up to 445 N was used (FlexiForce® Model A201, Tekscan). According to the recommendation of the manufacturer, an operational amplifier MCP 600x from Microchip Technology Inc was applied as measurement controller. The output signal of the operational amplifier is freed from high-frequency interference by means of a low-pass filter before it is processed by the microcontroller's ADC. This step is necessary to avoid interference due to the emission of the stepper motors and aliasing effects. The low pass is designed in such a way that the cutoff frequency is at 2000 Hz and thus below the step frequency of the motors but above the frequency of the pressure control.

Skin Model

The skin model was made on the basis of an electrolyte solution and the gelling agent agar-agar (Agar Agar E 406, Golden Peanut GmbH, Germany). Agar agar is therefore primarily responsible for mapping the mechanical properties of the human body, while the electrolyte solution, in turn, generates the electrical conductivity of the skin model.

For the construction of a skin model based on agar agar, Beckmann et al. [2] recommend the administration of 7 g pure agar agar on 100 ml electrolyte solution, to create a sufficiently stable but still highly flexible structure. As the resulting skin model turned out too stiff in comparison to the skin the value was reduced to 5 g. The conductivity of human skin at body temperature on living tissue was measured by Gabriel et al. [6] over a frequency range from 10 Hz to 20 GHz. The medically relevant signal components of the ECG signal are in the lower frequency range up to 100 Hz. To achieve a matching conductivity characteristic to the properties of the skin a saline solution (0.5% NaCl) was used as a basis for the skin model.

Test Setup

For the simulation of an electro-cardiac signal through the skin model a signal generating device (HeartSim) from Laerdal GmbH & Co. KG (Stavanger, Norway) was used. The ECG signal was fed into the agar agar block via a classical adhesive ECG electrode. The signal recorded by the textile electrode is measured by means of a BioRadio from Great Lakes NeuroTechnologies (Valley View, Ohio, USA) and transmitted to a laptop for display. The devices are connected to each other and to the electrodes in the test bench according to Figure 6.

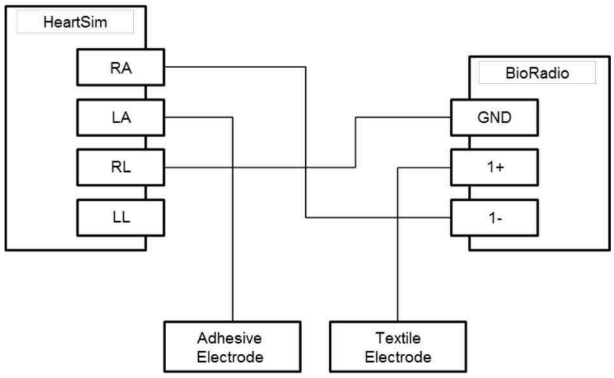

Figure 6: Test setup for the simulation and measurement of artificial ECG signals.

Results

Figure 7 depicts the final design of the developed electrode test bench, for investigating the ECG signal transmission of textile Electrodes under controlled movements.

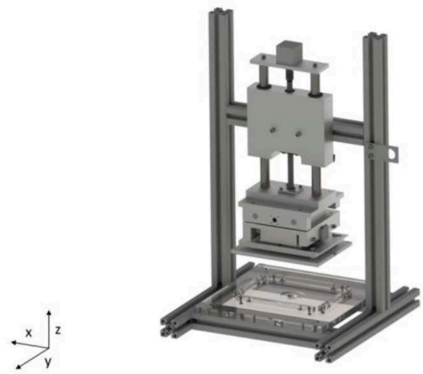

Figure 7: Design of complete electrode test bench.

Influence of movement on signal quality

For the validation of the test setup, preliminary measurements were conducted using the above-described test setup to generate artificial ECG signals. The ECG signals were recorded with textile, moss-embroidered electrodes during circular movements with different radii (1 mm to 4 mm) and velocities of 1 mm/s and 16 mm/s (s. Figure 8). It is apparent that the influence of the movement's radius varies with its velocity. At 1 mm/s the signal quality decreases slightly with increasing radius but all typical ECG characteristics are easily identifiable, even at the greatest radius of 4 mm. However, with a movement speed of 16 mm/s the influence of the movement's radius is significantly higher. While the QRS complex is clearly observable in all three measurements, the T- and in particular the P-deflection becomes less visible with increasing radius.

Movement artifacts

When using textile electrodes that aren't adhesively fixated to the skin a major challenge is the increased emergence of motion artifacts, which exceed the original ECG signals amplitude and render the data unreadable. Therefore it is eminently important to investigate their influence on the signal quality. Figure 9 shows two ECG signals that are interfered by abrupt motion artifacts, one recorded at standstill and one at a speed of 8 mm/s. The motion artifacts were evoked by manually agitating the test bench at the illustrated points in time. In standstill, the interference with the signal only lasts for about one-quarter of a second compared to half a second to one second during movement. Furthermore, the motion artifacts evoked during movement of the electrode entail additional repetitive artifacts, which interfere with the signal about one and a half seconds later.

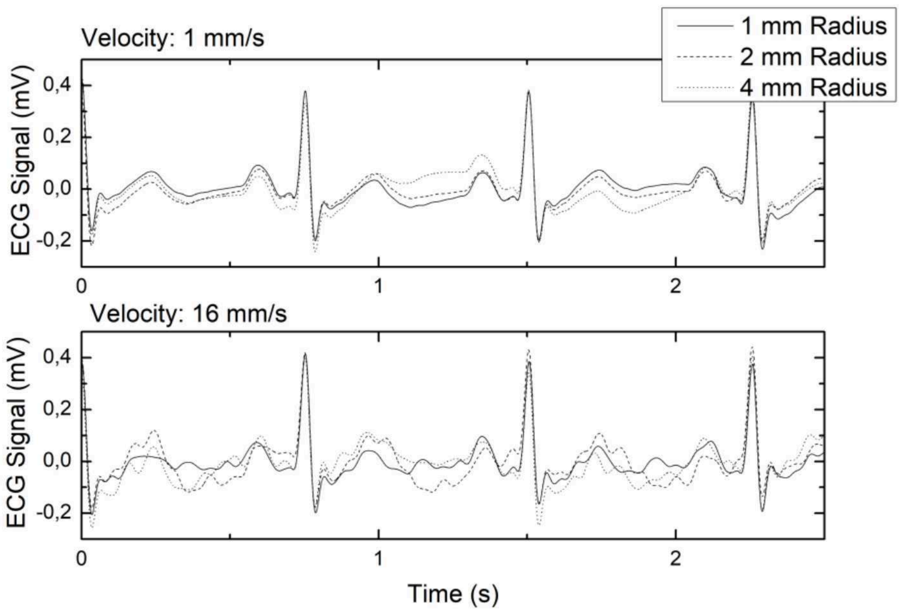

Figure 8: Influence of movement on the ECG signal quality measured with moss embroidered electrodes.

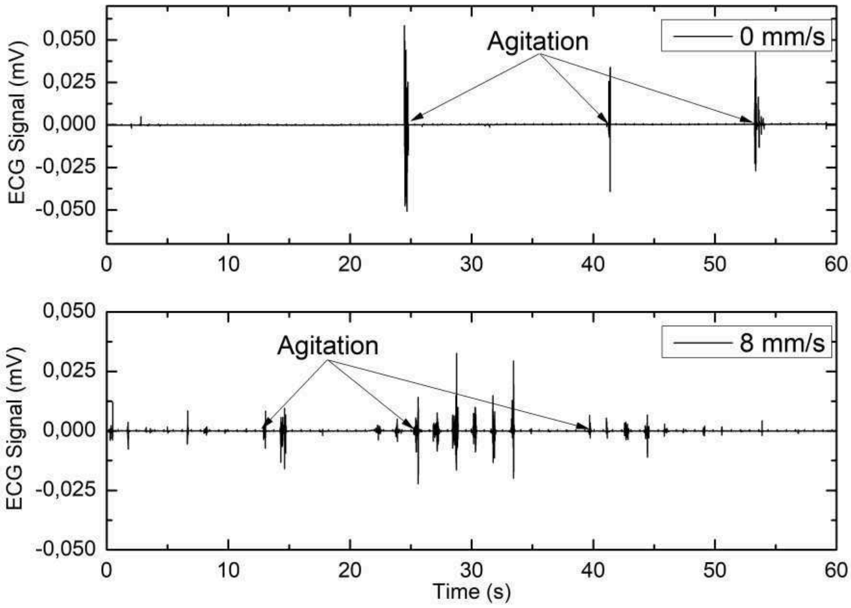

Figure 9: Interference of movement artifacts in ECG signal transmission evoked through agitation of the test bench during standstill (top) and movement (bottom).

Discussion and Conclusion

In this work, a newly developed, functional test bench for textile electrodes was presented. First preliminary measurements were conducted, showing that the test bench meets the necessary requirements to compare the effects of motion artifacts on the signal quality of the different textile ECG electrodes. Compared to current test benches used for the characterization of textile electrodes [2] [3] [4] [5] a cost-effective design was achieved while enabling the possibility to reproducibly simulate movement patterns on an artificial skin model.

As for now, the test bench is able to reproduce uniform circular movements with adjustable radii, velocities and contact pressures. Future work will further enhance these features and focus on the addition of more complex movement patterns. Furthermore, the detection of other influence factors on the performance of the textile electrodes as the current state of elongation, moisture level, and temperature will be implemented.

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