This is a post-peer-review, pre-copyedit version of an article published in **IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society**. The final authenticated version is available online at: https://doi.org/10.1109/IECON.2018.8591487

Smart weighing scale with feet-sampled ECG

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***Abstract*—In a smart home, health and well-being monitoring could be embedded in everyday devices providing pervasive computing. A weighing scale is an example of such a device at home, typically used to measure weight, body composition (e.g. body water/fat percentage), etc. In this paper, we analyzed the potential use of a weighting scale to measure ECG from electrodes located on a floor tile. In particular, we used both simulations and real measurements to analyze the possibility of such measurements in reference to previous works. We originally created a simple finite element model to analyze the role of the vector cardiogram projected on the leg-to-leg lead. We also used real measurements from 11 health volunteers in sitting and standing positions. As a result we showed that the quality of the recorded ECG signal from feet is highly related to the electrical vector orientation of the individual's heart. We additionally compared the detected QRS complexes from hands- and feet-sampled ECG for sitting and standing positions. Results showed that for sitting position the difference was only for 3.6% QRS complexes, while for standing position about 24.9%.**

Heart rate, bathroom scale, ambient assisted living

I. Introduction

Aging society, especially in the developed countries, involves an increased requirements of a medical care. In turn, it involves an increased number of people to be employed in the home care services.

One of a possible solution to this situation is to build an unobtrusive care systems incorporated into changeable environment of caretakers [1]. This can be achieved in two ways, firstly by designing the wearable devices (e.g., smart textile, smart watches, etc.) together with a person or, secondly, embedding the devices in a user's local environment. Additionally, in case of health related problems a continuous monitoring of some vital parameters can improve efficiency of the care. In consequence, it enables an early health risk detection and undertaking a prevention procedure.

In the latter case it would mean the incorporation of medical diagnostic services into home devices. Today, there is a lot of modern Internet- of-Thing (IoT) devices that can communicate to each other, display messages to the user etc., so there is also a space for the health diagnostic devices working as a part of home IoT infrastructure. Additionally, by incorporating of the medical diagnostic functionality in already existing devices one can make it completely transparent and unobtrusive to the caretaker [2], [3].

One of the most popular devices used at home is a bathroom scale. Modern scales can measure body weight and also estimate body composition by means of bioimpedance measurement. Typical scale is in a form of a flat platform demanding to stand on it, preferably barefoot. It has been stated that a rapid (one day) body weight change could associated with a cardiovascular problem and thus it is a valuable information. Typical ECG signals are measured by means of several electrodes located on limbs or a chest. There are known solutions to measure ECG signals when weighting by means of additional electrodes kept in hands and incorporated into scales. Some of them are exposed on extension pads [2], [4], [5] while another have retractable electrodes [6].

The construction of weighing scale enables the measurements of other health-related signals and parameters. The electrical heart activity (measured by ECG) stimulated the mechanical hart actions. The mechanical response is preserved in vessels pulsations or a whole body acceleration (BCG - ballistocardiograph) [7]. By combing ECG and BCG it is possible to detect and evaluate each cardiac contraction [4], [8], [9]. Alternatively, the impedance changes (ICG) can be measured ([10]–[12]) using electrodes attached to each foot or even for a single sole of a foot [13]. For example, in [14] a combination of ECG, BCG and ICG was used for the estimation of cardiac contractility.

The use of additional handles to measure ECG from hands produces high quality signals but such method is not very comfortable for a weighing scale in a bathroom. Therefore, the ECG measurements methods feet were initially investigated in [4] and [15]. In [16] authors proposed a method for the estimation of blood pressure using ECG and BCG measurements. They showed, that the feet-sampled ECG is possibly but highly noisy.

In this paper, we used both simulations and real measurements to analyze the possibility of such measurements in reference to previous works. We originally created a simple finite element model to analyze the role of the vector cardiogram projected on the leg-to-leg lead. We also used real measurements from 11 health volunteers and compare the results for practical QRS detection problem.

his work was partially supported by European Regional Development Fund concerning the project: UDA-POIG.01.03.01-22-139/09-00 -"Home assistance for elders and disabled - DOMESTIC", Innovative Economy 2007-2013, National Cohesion Strategy and by Statutory Funds of Electronics, Telecommunications and Informatics Faculty, Gdansk University of Technology.

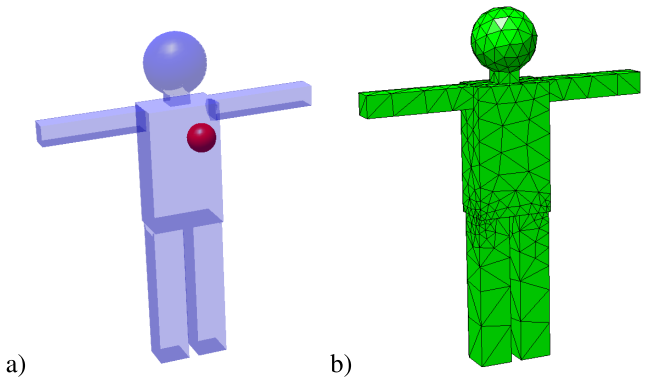

Fig. 1. Simplified model used for numerical calculations and resulting FEM mesh

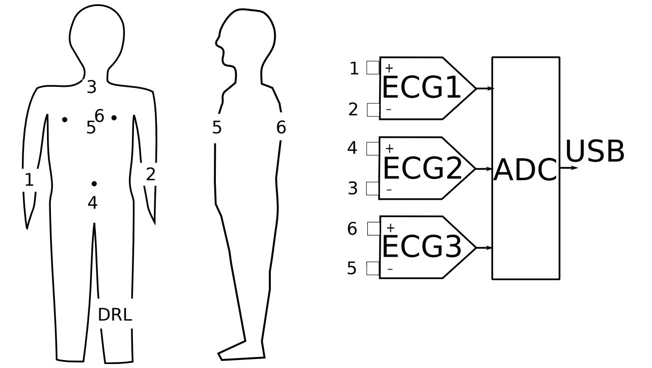

Fig. 2. Measurements of the heart vector - electrode placement and a basic experimental stand

II. Materials and Methods

Measurements of the ECG signals are recorded from the electrodes located on the chest, close to heart-muscle. Cardiac related potentials on the skin can be measured from different locations. Modern operational amplifiers allow obtaining high input impedance, high gain and still reasonable SNR that such measurements are possible.

A. Heart related potential on the legs - finite element study

As the classical bathroom scale is in the form of flat platform to stand on it during measurement it would be convenient to allow cardiac signal to be recorded from feet. We are trying to analyse how much cardiac signal measured from the feet is attenuated in comparison to measurement with electrodes located on chest.

Heart muscle from electrical point of view is regarded as a current dipole. In general, the dipole changes both the direction and amplitude. With the dipole a potential distribution is associated and it could be measured on a body surface.

To examine an influence of the dipole direction change (both personal and interpersonal) a simplified human body model was created. We approximated it by homogeneous body consisting of simple objects (Fig. 1). Cardiac muscle was approximated as a ball in which the current dipole was located. The potential distribution was then calculated for different orientation of the current dipole.

The complete model consisted of 6261 tetrahedrals and potential was calculated for 10152 nodes. The distribution of potential was calculated for 360 different orientations of the dipole.

B. Instrumentation used

In order to record ECG signals the custom made ECG amplifier board was designed and manufactured. Board utilizes several operational amplifiers to achieve an appropriate amplification, filtering and feedback (DRL approach). Utilisation of discrete components with universal operational amplifiers allows amplification and bandwidth customisation. Designed board is powered by single (not symmetrical) power supply. It was optimized to accept power voltage between 2 and 6V making it perfect signal source to any microcontroller's analog-to-digital (ADC) converter. ECG was recorded simultaneously from the hands and feet. For measurement of ECG signals from hands we have selected amplification of 2500 (68dB)) and formed bandwidth from 0.05Hz to 70Hz with 50Hz notch filter. Gain of amplifier for measurement ECG signals from feet was equal to 17500 (85dB) while bandwidth was reduced to 0.5Hz-30Hz.

As an ADC converter a SIGLENT SDS 1102CML digital storage oscilloscope (DSO) was used preliminary and then the STM32F401 microcontroller located on the STM32F401-DISCO board. Data from DSO were recorded on the USB mass storage device and transferred to PC by reconnecting circuit. Despite the high sampling frequencies accessible with the DSO it has only 8-bit quantization level and has limited buffer length. In order to increase a resolution of the ADC we used STM32F401-DISCO board. The STM32F401 microcontroller was equipped with 12-bit ADC and moreover it offered USB on-the-go interface. It enabled to achieve a fast data transmission to the PC using the USB link. We have implemented the USB CDC device and configured ADC to sample data with the frequency of 1.5kHz for each data channel. We were using up to 3 analog data inputs. A custom Qt based application was created in order to capture and visualize the data.

C. Estimation of heart vector versus posture

Measurement of the ECG signal with electrodes located on the feet was related to the cardiac vector projected on the line between hips. In order to measure ECG vector and its changes a non-standard electrode placement (three leads) on the chest was used. We have used 3 identical ECG bipolar measurement channels connected directly to the ADC provided by STM32F401-DISCO board. The electrodes were placed on the chest so the leads were orthogonal each to other in X,Y,Z coordination system. Results obtained from the data could be directly used in calculation of the vectorcardiogram and thus the heart vector.

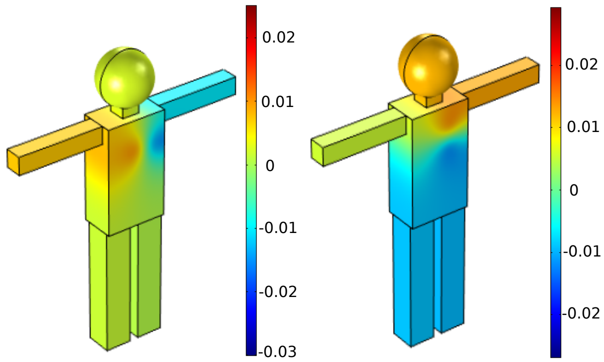

Fig. 3. Calculated potential distribution for different angles of cardiac-related current dipole

In this experiment an influence of person's heart position on the measured data was investigated and following properties of measurement system could be evaluated.

D. ECG measurements from scale

We have prepared experimental set-up consisted of scale base with located feet electrodes and additional stand with exposed hands electrodes. We have used two custom made ECG amplifier boards with different bandwidth and gain. Data from the ECG amplifiers were recorded by means of DSO and STM32F401-DISCO board.

We have asked 11 healthy volunteers (7 male, 4 female) to take part in the experiments. We assured medical class safety of measurement system by means of galvanic separation and battery operation where applicable. Prepared scale prototype was disinfected prior each use by means of clinical grade disinfection fluid. Volunteers were asked to do both, stand on a scale pad and to hold their hands on dedicated holder and perform similar task while sitting.

III. Results and Discussion

A. Finite element modelling

Examples of calculated potential distributions for selected two different angles of current dipole are presented in Fig. 3. A difference of voltage measured between hands and between feet was also calculated as a function of dipole orientation. Each potential was estimated as an average over hand or sole ending nodes.

Value of voltage versus dipole angle is shown in Fig. 4. Calculated relation between two voltages is shown in Fig. 12. Ratio of the measured voltages is not constant over dipole angle and moreover shows discontinuity. It follows from the fact that for a certain heart dipole orientation the voltage measured between feet is zero. An angle value is related to asymmetrical location ot the heart in the thorax.

B. Heart vector versus posture

In Fig. 6 a measurement stand is shown. It shows custom made ECG amplifiers connected to the STM32F401-DISCO board and by means of the USB to the laptop computer where

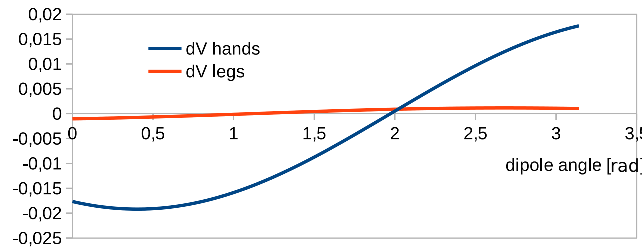

Fig. 4. Calculated difference of voltage between hands and feet versus angle of cardiac dipole

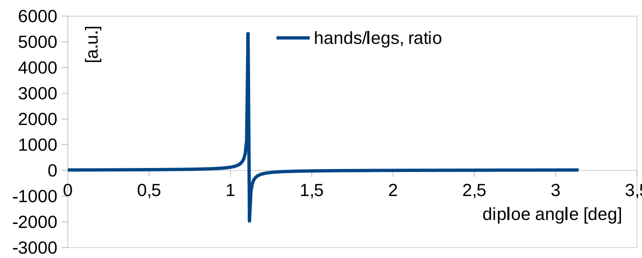

Fig. 5. Calculated ratio $\frac{V_{hands}}{V_{legs}}$ versus dipole angle

data are visualised and recorded. Example of recorded signals is shown in Fig. 7.

Raw data obtained for different subject with two body postures - sitting and standing were processed and vector cardiograms are collected in Fig. 8. Figure shows data for two different persons (P1 and P2) and two different positions.

C. ECG measurements on the real scale model

The scale model was built to perform experiments. Scale platform has 4 metal pads made of perforated stainless steel. In parallel we have prepared stand for the hands in order to measure reference signal (see Fig. 9).

Examples of recorded signals are shown in Fig. 10. When examined person was standing an electromyographic (EMG) signal was more pronounced. An attempt to apply QRS detection algorithms on the acquired signals was done. QRS episodes detected in signal retrieved from hands and feet were compared. Eleven adult volunteers (mean age 41 14), both, in standing and sitting position were examined. All participants were informed about the details of the experiment and informed consent was obtained from each volunteer. The experiments were performed with agreements to rules specified by the regional, institutional Bioethical Commission. Recorded data were processed by means of signal filtration and correlation function with the expected ECG signal model. During experiments patients safety was assured by means of galvanic isolation and medical-grade power supply of the acquisition system. Then, the Pan-Tompkins QRS detection algorithm was applied to detect QRS episodes. The automatically detected locations of QRS complexes where compared to manually indicated locations of QRS complexes (a reference). ECG signal fragments lasting 20 seconds were used in the analysis. As a

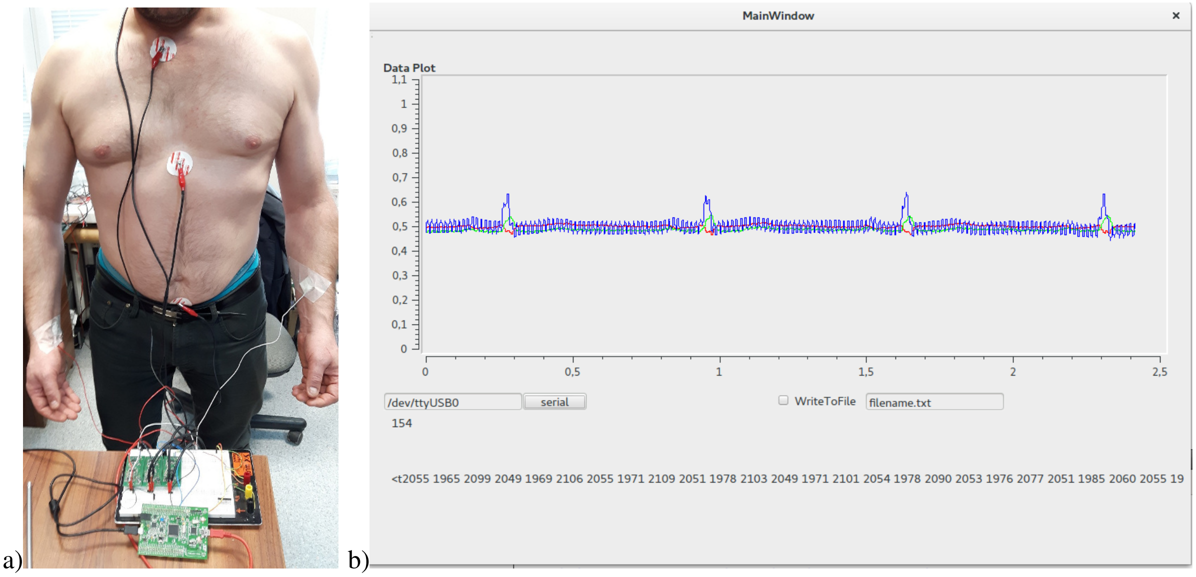

Fig. 6. Set-up for cardiac vector measurement a) and accompanied application b)

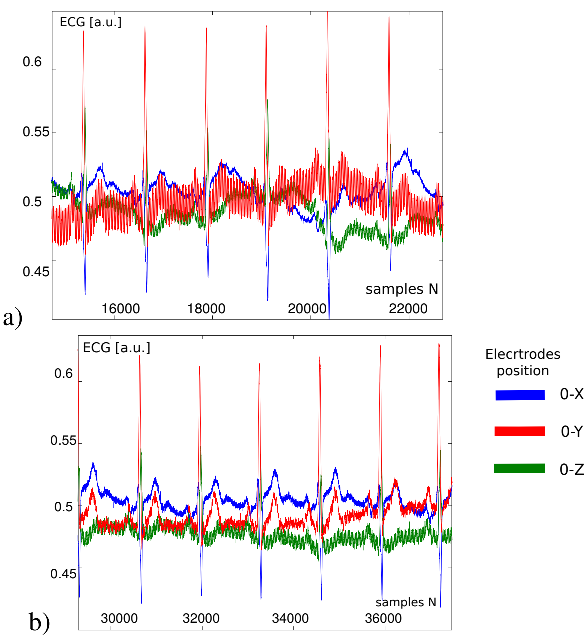

Fig. 7. Results of ECG for standing position a) and sitting position b) for the same subject

TABLE I
QRS DETECTION COMPARISON FOR RECORDED SIGNALS

Volunteer	Manual	Pan-Tompkins (hands)	Pan-Tompkins (legs)	Correctly detected	incorrectly detected
V1 sitting	19	19	19	19	0
V2 sitting	19	17	17	17	0
V3 sitting	20	20	19	19	0
V4 sitting	21	21	27	16	11
V5 sitting	17	17	17	17	0
V6 sitting	22	22	22	22	0
V7 sitting	25	23	23	23	0
V8 sitting	21	20	20	20	0
V9 sitting	19	17	17	17	0
V10 sitting	22	21	21	21	0
V11 sitting	18	18	19	18	1
V1 standing	19	19	19	18	0
V2 standing	22	21	32	17	15
V3 standing	20	20	19	15	4
V4 standing	21	20	31	15	16
V5 standing	22	21	32	17	15
V6 standing	19	19	20	18	2
V7 standing	26	24	38	21	17
V8 standing	21	20	22	20	2
V9 standing	19	18	19	18	1
V10 standing	21	21	24	20	3
V11 standing	18	18	27	18	9

result of the analysis the number of correctly and indirectly detected QRS complexes was calculated. Fig. 11 illustrates the method how QRS complexes were labeled as correctly detected, incorrectly detected or missed. Results of the analysis are presented in Table I. For sitting position the difference between the detected QRS complexes from hands- and feet-sampled ECG was only 3.6%, while for standing position about 24.9%. However, it is also important to underline that much more false alarms were observed for the ECG signals recorded in standing position: 36.7% than in sitting position (5.4%).

In Fig 12 a) the ratio of automatically detected QRS episodes to manually detected versus body posture is shown. It shows that automated algorithm performs worst for standing posture as it is influenced by the EMG signals. We have also compared ratio of detected QRS complexes between hands electrodes and sole ones. Results are shown in Fig.‘12b). Again for standing position one can notice weaker performance (smaller ratio and greater standard deviation).

In Fig. 12a the ratio of automatically detected QRS episodes to manually detected episodes is shown (for both investigated body positions). It shows that the standard algorithm

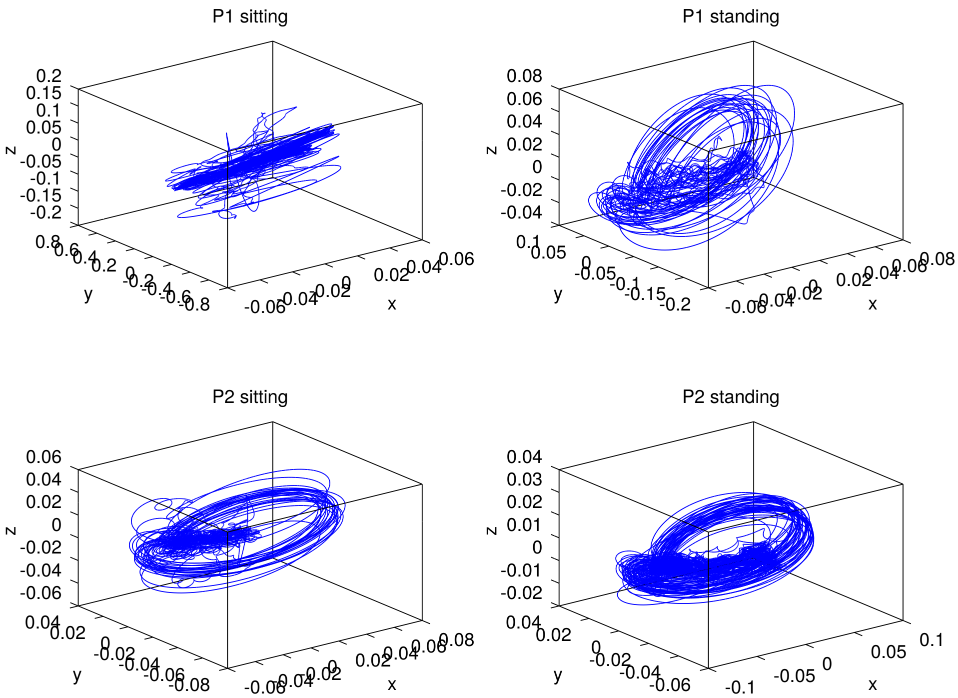

Fig. 8. Calculated vectorcardiograms for two person when sitting or standing

Fig. 9. Measurements of the ECG signal for different body positions

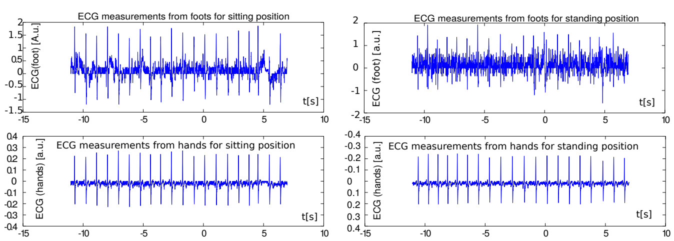

Fig. 10. ECG recordings taken from electrodes located on feet and hands for different body positions, the same subject

performs worse for standing posture than for sitting position as it is influenced by the EMG signals. We have also compared ratio of detected QRS complexes between hands electrodes and feet electrodes. Results shown in Fig. 12b also indicates worse results for standing position. (smaller ratio and greater standard deviation).

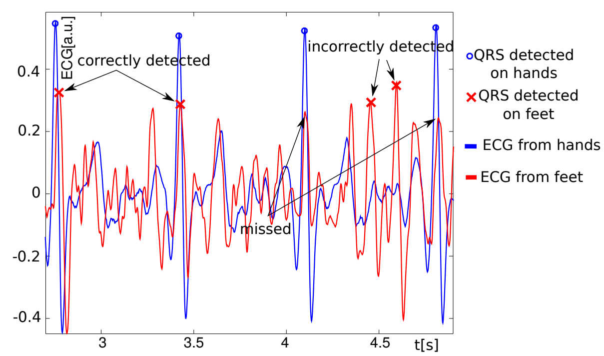

Fig. 11. Explanation of selection criteria for QRS detection validation of "feet" ECG

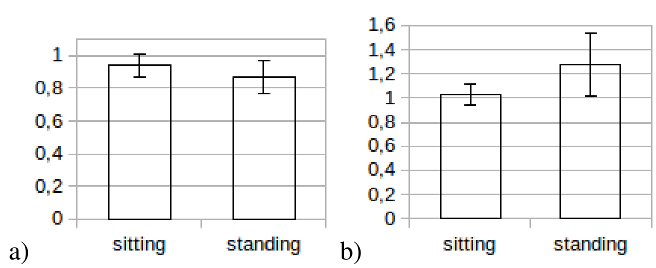

Fig. 12. Ratio of correctly detected QRS epizodes to manually detected ones a) and ratio of detected QRS epizodes using sole electrodes to hand electrodes. Botch charts have standard deviation marked

IV. Conclusion

Measurement of cardiac signals using electrodes located on the scale pads - via feet is possible but still several factors must be considered. First of all - there is demand for QRS detection algorithm improvement. Data are corrupted by EMG signals and despite an advanced time - based filtration the QRS detector performance is not satisfactory.

In order to achieve feasible measurements using sole electrodes measurement system must have greater amplification for the ECG amplifier. We have used 6 times greater amplification than for measurement using hands or chest. Additionally to reduce measurement noise bandwidth of the amplifier should be narrower.

The amplitude of QRS period measured on feet depends strongly on the heart location and orientation inside the chest. Additionally, a pose person examined alters the signal properties and thus the resulting figures. In general, a much better signal quality could be achieved for the person in sitting position due to two mechanisms. First, a dipole orientation could be modified in comparison to that during a standing pose and legs muscles are in rest state (EMG signal level is lower).

The measured vectorcardiograms are showing individual character for each examined person however the obtained curves were position and posture dependent. The individual cardiac muscle location influences ECG signal quality obtained from the feet measurement.

Due to individual character of measurements it is possible to distinguish between persons standing on the scale. The scale can recognize person on the basis of their weight, detected heart-rate and obtained signal quality. Information about signal quality can be concluded by means of vectorcardiography measurement performed once prior to scale installation. However this will require further study. Once person is recognized it is possible to measure eg. body mass index (BMI) on the basis of previously stored person's height.

Measurement with use of limited number of volunteers showed very individual system performance - especially for measurements in standing position. Authors believe this might be caused by individual skin impedance and EMG from posture muscles. This should be investigated further on more volunteers with extended age range and body composition (e.g. skin thickness).

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