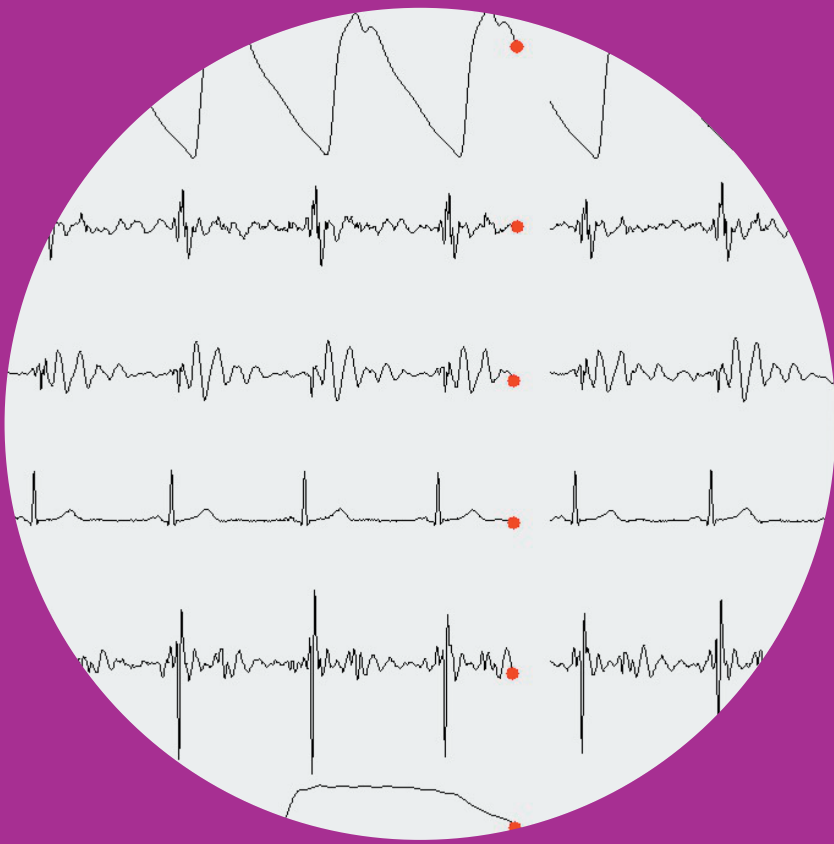
Department of Electrical Engineering and Automation

Seismocardiography: Practical implementation and feasibility

Mikko Paukkunen



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Seismocardiography: Practical implementation and feasibility

Mikko Paukkunen

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Abstract

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Abstract

Today, a rather comprehensive view of the state of the cardiovascular system can be obtained in the clinical environment. The already established methods, such as electrocardiography, phonocardiography, and impedance cardiography, are relatively inexpensive methods and produce information about the electrical phenomena, sound waves, and impedance variations produced by the function of the cardiovascular system. Cardiovascular magnetic resonance imaging, echocardiography, nuclear cardiology, and X-ray computed tomography, on the other hand, are relatively expensive and labor-intensive methods that produce images of the cardiovascular system and provide information about the perfusion and metabolism of the myocardium and also the blood flow.

Seismocardiography (SCG) is a newly revived inexpensive method where local vibrations due to cardiovascular function are detected non-invasively from the sternum. These vibrations provide information about the mechanical function of the cardiovascular system that can be used as an independent diagnostic cue or as a complement to the contemporary methods. Thus far, SCG has been proposed to be a useful tool in ischemia detection. SCG is also proposed to function as a relatively simple method for assessing myocardial contractility. While the bulkiness of the sensors and limited computing capacity hindered the feasibility of SCG in the clinical environment, the advances in computing power and accelerometer technology have now enabled practical SCG implementations.

In this thesis, the feasibility of SCG and the means to successfully implement a practical system for detection of SCG signals were studied. Two different SCG measurement systems were implemented and their performance was evaluated. The present implementations featured improved acceleration measurement sensitivity and a multimodal approach to the detection of SCG and auxiliary physiological signals. Also, the three-dimensional aspect of the SCG signals was more extensively utilized than in previous works. These enhancements improved SCG measurements and will increase the potential of SCG to be taken into clinical practice.

Keywords seismocardiography, electrocardiography, accelerometer, cardiovascular, three-dimensional

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Tiivistelmä

Sydän- ja verenkiertoelimistön tilasta saadaan kliinisissä olosuhteissa hyvin kattava kuva. Sähköisiä ilmiöitä, ääniaaltoja ja impedanssimuutoksia voidaan mitata vakiintuneilla menetelmillä kuten elektrokardiografialla, fonokardiografialla ja impendanssikardiografialla melko edullisesti. Sydämen magneettikuvauksella, ultraäänikardiografialla, isotooppikardiografialla ja tietokonetomografialla saadaan kuvia sydän- ja verenkiertoelimistöstä sekä tietoa sydänlihaksen aineenvaihdunnasta ja perfuusiosta ja veren virtauksesta. Nämä menetelmät ovat kuitenkin kalliita ja työvoimavaltaisia.
Seismokardiografia (SKG) on äskettäin elpynyt edullinen mittausmenetelmä, jossa sydämen aiheuttamia paikallisia värähtelyjä mitataan kajoamattomasti rintalastalta. Nämä värähtelyt antavat sydän- ja verenkiertoelimistön mekaanisesta toiminnasta tietoa, jota voidaan käyttää täydentämään muilla menetelmillä tehtyä diagnoosia. Esimerkiksi iskemian havaitsemisessa ja sydänlihaksen supistuvuuden arvioinnissa on saavutettu lupaavia tuloksia. Aiemmin toteutettujen SKG-järjestelmien anturit olivat kuitenkin suurikokoisia eikä laitteistoissa ollut riittävästi laskentatehoa. Nykyisin käytännöllisen SKG-laitteiston toteuttaminen on mahdollista.
Tässä työssä tutkittiin SKG:n toteutuskelpoisuutta sekä tapoja, joilla käytännöllinen järjestelmä SKG-signaalien havaitsemiseen voidaan toteuttaa. Lisäksi tässä työssä toteutettiin kaksi erillistä mittausjärjestelmää sekä arvioitiin niiden suorituskykyä. Toteutetuissa mittausjärjestelmissä kiihtyvyysmittaus oli muita järjestelmiä herkempi, ja lisäksi järjestelmissä käytettiin monimodaalista lähestymistapaa SKG-signaalien ja muiden fysiologisten signaalien mittaamiseen. SKG-signaalin kolmiulotteisuus otettiin myös huomioon laajemmin kuin aiemmissa aihealueen julkaisuissa. Edellämainitut kohennukset paransivat SKG-mittauksia, ja ne tulevat parantamaan SKG:n valmiutta kliinisiin sovelluksiin.

Avainsanat seismokardiografia, elektrokardiografia, kiihtyvyysmittaus, sydän- ja verenkiertoelimistö, kolmiulotteinen

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Contents

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[P2] Paukkunen, M., & Linnavuo, M. (2014). Precordial Vibrations: Seismocardiography – Techniques and Applications. In M. Khosrow-Pour (Ed.), *Contemporary Advancements in Information Technology Development in Dynamic Environments* (pp. 201–220). Hershey, PA.

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[P4] Paukkunen, M., Linnavuo, M., Haukilehto, H., & Sepponen, R. (2012). A System for Detection of Three-Dimensional Precordial Vibrations. *International Journal of Measurement Technologies and Instrumentation Engineering (IJMTIE), 2*(1), 52–66.

Author's contribution

In [P1], the author participated in the literature review as well as in the writing of the manuscript. In [P2], the author alone wrote the parts that directly concerned seismocardiography, and participated in writing the rest of the content. In [P3] and [P4], the author designed and implemented the hardware and software, participated in writing the manuscripts, and designed and participated in carrying out the *in vivo* measurements.

Symbols and abbreviations

g	gravitation constant (9.81 m/s^2)
i	the index of a heartbeat
N	the number of samples in a segmentation window
R	the number of averaged heartbeats
t	time
t_N	end time of a segmentation window
t_o	start time of a segmentation window

1-D	one-dimensional
3-D	three-dimensional
AC	aortic valve closing
AO	aortic valve opening
AS	atrial systole
BCG	ballistocardiography
cMRI	cardiovascular magnetic resonance imaging
ECG	electrocardiography
ECHO	echocardiography
IC	isotonic contraction
ICG	impedance cardiography
IM	isovolumic movement
Li-Ion	lithium-ion
MA	maximum acceleration of blood in the aorta
MEMS	microelectromechanical systems
MC	mitral valve closing
MO	mitral valve opening
PC	personal computer
PCG	phonocardiography
PPG	photoplethysmography
RE	rapid ejection of blood into the aorta
RF	rapid filling
SCG	seismocardiography
USA	United States of America
X-CT	x-ray computed tomography

1. Introduction

1.1 Global burden of cardiovascular diseases

The global burden of disease has been shifting gradually from communicable diseases in children to noncommunicable disease in adults (Lim et al., 2013). In particular, cardiovascular diseases affect a large number of people worldwide. Ischemic heart disease, for instance, is the single largest cause of death in the developed countries and one of the leading causes of death in the developing countries as well (Gaziano, Bitton, Anand, Abrahams-Gessel, & Murphy, 2010). In 2008, 7,249,000 deaths due to cardiovascular diseases (12.7% of total deaths) were recorded worldwide (Finegold, Asaria, & Francis, 2013). In 2009, about 800,000 cardiovascular disease-related deaths occurred in the USA alone, while the total direct and indirect cost of cardiovascular diseases was approximately 312 billion dollars (Go et al., 2013). Thus, cardiovascular diseases cause a significant financial and health burden.

Promoting a healthy lifestyle and pharmacological treatment of risk factors may both prevent fatal and non-fatal cardiovascular events (Aldana, 2001; Chiuve et al., 2008; Weintraub et al., 2011). However, if primary prevention fails, secondary prevention is needed to make managing the disease as effective as possible. In the USA, an effective nationwide cardiovascular surveillance system has been suggested to be of use (Sidney, Rosamond, Howard, & Luepker, 2013). With respect to the practical implementation of cardiovascular disease screening systems, the development of cost-effective measurement tools is an important subject. Non-invasive methods are generally preferred due to their cost-effectiveness and lower associated risks when large numbers of people are examined. In the following section, some prevalent non-invasive cardiovascular function assessment methods are overviewed. Additionally, an emerging cardiovascular function assessment method called seismocardiography (SCG) is described.

1.2 Non-invasive detection of the function of the human heart

Today, the heart and the cardiovascular system are standard observation targets in human. The function of the heart and cardiovascular system can be monitored by a variety of methods. Visual inspection, auscultation and palpation are the oldest and also technologically the simplest methods. Combining anamnesis and visual, auditory and sensory cues, an experienced physiologist can diagnose a great number of abnormal cardiovascular conditions.

Although cardiovascular system palpation and auscultation are both well-established techniques (Tavel, 1996; Walker, Hall, Hurst, & Kurtz, 1990), technological developments have brought upon new windows to cardiovascular dynamics. A variety of methods for assessing cardiac function have been suggested throughout the 20th century (see Figure 1). While cardiac auscultation and palpation are still routinely used in clinical practice, the more modern and technologically advanced non-invasive cardiovascular function assessment techniques are increasingly prevalent.

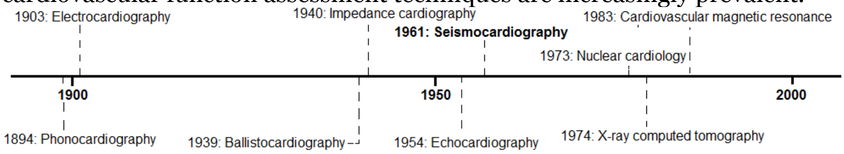

Figure 1. Important events in non-invasive cardiovascular assessment techniques.

1.2.1 Echocardiography

Echocardiography (ECHO) is an imaging method based on ultrasound. The first diagnostic attempts using ultrasound were made in the late 1940s by Karl Theo Dussik (Edler & Lindström, 2004). However, it was only in 1954 when Inge Edler and Hellmuth Hertz reported the first echocardiographic recording in a man (Edler & Hertz, 2004). At present, the images produced with ECHO are routinely used in diagnosis and follow-up of cardiovascular diseases.

1.2.2 Cardiovascular magnetic resonance imaging

Cardiovascular magnetic resonance imaging (cMRI) is a cardiovascular imaging method based on nuclear magnetic resonance which was first described in the 1930s and 1940s. 1983 has been designated as the year when the clinical potential for cMRI was first widely addressed. Applications of cMRI include detection of coronary artery disease as well as assessment of structural and congenital heart diseases. (E. van der Wall, 2013a)

1.2.3 X-ray computed tomography

X-ray computed tomography (X-CT) is an imaging modality where x-rays are used to create slice images of a subject. The first practical CT implementation was done by Hounsfield in 1972. In the same year, the first clinical CT images were produced revealing a cystic frontal lobe tumor. (Kalender, 2006) In 1983, Higgins was one of the first to report the potential of X-CT in cardiovascular imaging (E. van der Wall, 2013b). Today, the main application of X-CT is coronary angiography and, more specifically, the detection of coronary atherosclerosis (E. van der Wall, 2013b).

1.2.4 Nuclear cardiology

Nuclear cardiology is a method where radioisotopes are injected into the vascular system and the emitted radiation is recorded externally. Although pioneering work on nuclear cardiology had been presented earlier (Dilsizian & Taillefer, 2012), Zaret's report in 1973 is considered a landmark in nuclear cardiology (E. E. van der Wall, 2013). Zaret found that the anatomic location of an infarct was possible to be displayed with myocardial perfusion imaging. At the moment, nuclear cardiology is typically used in the assessment of myocardial metabolism and perfusion (E. E. van der Wall, 2013).

1.2.5 Electrocardiography

In electrocardiography (ECG), the electrical functioning of the heart is studied. Einthoven's electrocardiogram (Einthoven, 1903) is widely considered to be the origin of ECG. Today, ECG is a standard examination method in the clinical environment. ECG is also feasible for use in remote monitoring (Martínez, Everss, Rojo-Álvarez, Figal, & García-Alberola, 2006).

1.2.6 Phonocardiography

Phonocardiography (PCG) is a method for detecting the sounds produced by the heart and blood flow. The first practical PCG system was described by Einthoven in 1894 (Lukkarinen, 2012). Similarly as in auscultation, PCG is most commonly measured non-invasively from the chest, but with a microphone. PCG enables post-processing of the data, which makes the interpretation of the signal less dependent on the person performing the examination. Also, PCG adds inaudible frequencies and sound intensity to the observations, enabling even phonospectrography (Lukkarinen, 2012).

1.2.7 Impedance cardiography

Changes in the fluid content of the chest induce changes in thoracic impedance. This phenomenon can be measured using impedance cardiography (ICG). Although ICG emerged in 1940, it didn't immediately enter the clinical practice (Bour & Kellett, 2008). ICG is considered a relatively simple method (Bour & Kellett, 2008; Jensen, Yakimets, & Teo, 1995), which makes it a potential method for routine use. Besides basic cardiac monitoring, ICG has also been proposed to be a tool for assessing cardiac output (Jensen et al., 1995; Keren, Burkhoff, & Squara, 2007).

1.2.8 Ballistocardiography and seismocardiography

Ballistocardiography (BCG) and seismocardiography (SCG) are both methods for studying the mechanical vibrations that couple to the body and are produced by cardiovascular activity. BCG is a method where the cardiac reaction forces acting on the whole body are measured. SCG, on the other hand, is a method where the local vibrations of the precordium are measured. (Tavakolian, Ngai, Blaber, & Kaminska, 2011)

Neither of these methods has achieved routine clinical use. BCG was under intensive research around the mid 20th century but failed to reach clinical relevance due to challenges such as cumbersome and expensive instrumentation (Inan, Etemadi, Wiard, Giovangrandi, & Kovacs, 2009). However, BCG is experiencing a revived interest, presumably due to technological developments in the late 20th century (Giovangrandi, Inan, Wiard, Etemadi, & Kovacs, 2011).

SCG has also received increasing attention (see Figure 3). A major factor contributing to the increasing attention are the advances in accelerometer technology. While BCG is suggested to be useful in, for example, stroke volume approximation, SCG has been suggested to be useful in measuring cardiac time intervals (Tavakolian et al., 2011).

1.3 Towards a comprehensive view of cardiac function

Contemporary measurement methods yield multimodal information about the heart. ECG, PCG, ICG, SCG, and BCG offer information about the electrical phenomena, sounds, impedance variations, local vibrations, and recoil forces produced by the function of the cardiovascular system. cMRI, ECHO, and X-CT on the other hand, produce images of the cardiovascular system. Nuclear cardiology can be used to study the perfusion and metabolism of myocardium. Combining the strengths of these modalities, a rather comprehensive view of the cardiac function can be obtained. Figure 2 summarizes the previously introduced non-invasive methods that can be used in studies of cardiac function and structure. At the moment, SCG seems to be the least studied of the methods, so when aiming towards a comprehensive view of cardiac function and structure, SCG should be further researched.

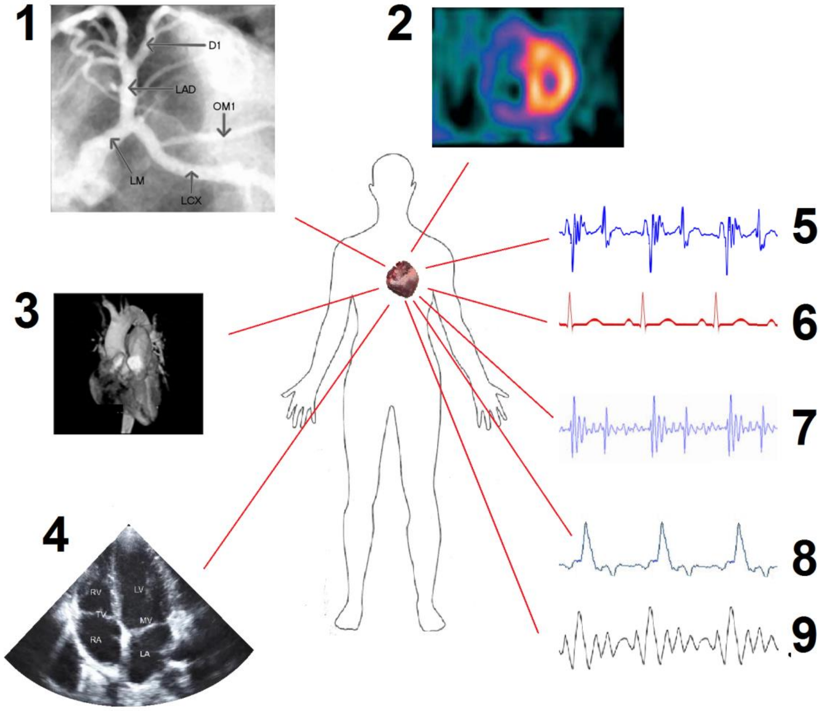

Figure 2. A comprehensive view of cardiac function and structure. The following numbering is used: 1 is X-CT, 2 is nuclear cardiology, 3 is cMRI, 4 is ECHO, 5 is SCG, 6 is ECG, 7 is PCG, 8 is ICG, and 9 is BCG.

Table 1 compares the merits of the described methods by providing an estimation of the cost, infrastructure demands, professional involvement, and applicability to home monitoring. Table 1 also provides a summary of the main applications of the introduced measurement methods. According to Table 1, it seems that SCG might be a feasible tool in terms of home monitoring due to its low cost, low infrastructure demands, and relative ease of use. To advance SCG to clinical use as well, the method needs to be evaluated for clinical feasibility, standardized, and further developed. Although SCG has received increasing interest (see Figure 3), many issues still remain. These issues vary from technical challenges, such as choosing the axis of measurement, to profound physiological questions of what is the origin of the SCG waveforms. This thesis aims to study the past and current technologies used in SCG and develop solutions for the issues encountered.

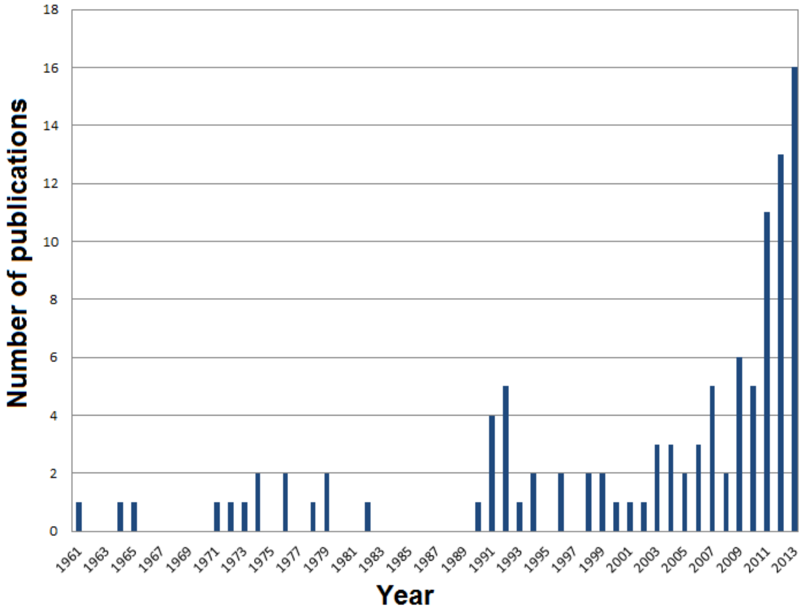

Figure 3. An approximation of the number of publications on seismocardiography between the years 1961 and 2013. The databases used in the search were PubMed and Scopus. The keyword used in the search was “seismocardiogra*”.

Table 1. A comparison of non-invasive cardiovascular assessment methods. Explanation of the variables: cost is the approximated combined cost of the equipment and labor needed to use the method; infrastructure demands are used to depict the associated infrastructure, such as a separate examination room, that are needed to use the method; professional involvement is the estimated need of professionals to use the method correctly; applicability to home use is an estimation of the suitability of the method to be used in a non-clinical situation without medical staff; and clinical feasibility is an estimation of the feasibility of the method when the subject is examined in a clinical environment. All parameters are estimated, and, for every parameter, each method is assigned one of the following values: low, moderate, or high. If a method is not applicable in a given environment, its value in the table is N/A.

Name of the method	Cost	Infrastructure demands	Professional involvement	Applicability to home use	Measured phenomena
BCG	Low	Moderate	Low	High	Movement of the whole body due to recoil forces of cardiac function
ECHO	Moderate	Low	High	Low	Blood flow and the anatomic structure of the heart
ECG	Low	Low	Low	Moderate	Bioelectrical functioning of the heart
ICG	Low	Low	Moderate	Mod	Impedance variations due to changes in blood volume in the chest
cMRI	High	High	High	N/A	Anatomic structure of the heart, blood flow, and perfusion
PCG	Low	Low	Moderate	Moderate	Cardiac sounds
SCG	Low	Low	Moderate	Moderate	Precordial vibrations due to cardiac function
Nuclear cardiology	High	High	High	N/A	Blood flow, metabolism and perfusion
X-CT	High	High	High	N/A	Anatomic structure of the heart and perfusion

1.4 Introduction to seismocardiography

Seismocardiography (SCG) is the non-invasive measurement of cardiac vibrations transmitted to the chest wall by the heart during its movement, as described by Zanetti and Salerno (D. Salerno & Zanetti, 1990). SCG was first introduced around the mid 20th century (Baevsky, Egorov, & Kazarian, 1964; Bozhenko, 1961) and later revived by Zanetti and Salerno (D. Salerno & Zanetti, 1990). Using Zanetti's SCG technique, some promising clinical applications were suggested. These include the observation of changes in the SCG signal due to ischemia and the use of SCG in cardiac stress monitoring (Jerosch-Herold et al., 1999; D. M. Salerno et al., 1991; D. M. Salerno & Zanetti, 1991).

The origin of SCG can be traced back to the 19th century when Gordon (Gordon, 1877) reported observing a heartbeat while standing on a scale. Despite Gordon's early observations, it was Isaac Starr's pioneering work in the field (Starr, Rawson, Schroeder, & Joseph, 1939) that can be seen to have begun a new era in non-invasive cardiac vibration measurement. Starr studied ballistocardiography (BCG) in which the reaction forces of cardiovascular activity acting on the whole body are measured. While some promising results were achieved (Pollock, 1957), BCG never reached clinical use. Newer applications of BCG include embedding the measurement into everyday objects such as chairs (Junnila, Akhbardeh, Värri, & Koivistoinen, 2005; Junnila, Akhbardeh, Barna, Defee, & Värri, 2006; Koivistoinen, Junnila, Värri, & Koobi, 2004; Lankinen, 2009; Ritola, 2002), beds (Lindqvist, Pihlajamäki, Jalonen, Laaksonen, & Alihanka, 1996; Vehkaoja, Rajala, Kumpulainen, & Lekkala, 2013), and scales (Inan et al., 2009; Ritola, 1997).

1.4.1 Measurement techniques

During the history of SCG, the accelerometers have become gradually smaller. For example, the usability of Zanetti's work, which required the use of an acceleration sensor weighing 0.8 kilograms, is, however, questionable by modern standards. Recent developments in acceleration sensors have resulted in gradually smaller and thus less obtrusive transducers, which is perhaps one of the reasons why so many research groups are now studying SCG.

In 1957, Mounsey described a measurement setup which included an electrochemical accelerometer with a flat frequency response in the range 0 to 3000 Hz and linear response for forces about 0 to 0.015 g and greater (Elliott, Packard, & Kyrazis, 1954; Mounsey, 1957). The accelerometer was based on electrical changes at the surfaces of contact of a mercurysulfuric acid interface (Elliott et al., 1954). Zanetti's approach used a bulky piezoelectric accelerometer weighing almost one kilogram (D. Salerno & Zanetti, 1990). The accelerometer had a linear response between 0.3 and 800 Hz with a sensitivity of 1.0V/g (D. Salerno & Zanetti, 1990). Current 3-

D SCG systems use lightweight accelerometers based on microelectromechanical systems (MEMS) technology, for example. The use of miniature accelerometers with surface area of approximately 0.25 cm^2 is presented, for example, in the research of Pandia et al. (2012) and Dinh et al. (2011).

1.4.2 Waveforms

A typical SCG signal contains several recurrent waveforms with distinctive systolic and diastolic components (J. Zanetti, Poliac, & Crow, 1991). Depending on whether the SCG transducer is AC or DC coupled, the SCG signal might feature low-frequency baseline fluctuation. This fluctuation is caused by the changes in the inclination of the sternum. Some research proposes that only frequencies up to 20 Hz contain significant information (Tavakolian et al., 2011). The assertion is based on the hypothesis that the artefacts in the higher frequencies are caused by different mechanisms than the artefacts in the lower frequencies. The waveforms' amplitudes are not usually quantified. In the author's unreported studies, the SCG waveform maximum magnitudes have been observed to be of the order of 0.1 m/s^2.

Some of the SCG signal's recurrent waveforms have been proposed to occur simultaneously with specific events of the cardiac cycle. These events are the peak of the atrial systole (AS) (Crow, Hannan, Jacobs, Hedquist, & Salerno, 1994), mitral valve closure (MC) (Akhbardeh et al., 2009; Crow et al., 1994), isovolumic contraction (IVC) (Akhbardeh et al., 2009), aortic valve opening (AO) (Akhbardeh et al., 2009; Crow et al., 1994; Gurev et al., 2012), the peak of rapid systolic ejection (RE) (Akhbardeh et al., 2009; Crow et al., 1994; Gurev et al., 2012), aortic valve closure (AC) (Akhbardeh et al., 2009; Crow et al., 1994; Gurev et al., 2012), mitral valve opening (MO) (Akhbardeh et al., 2009; Crow et al., 1994), and rapid filling (RF) (Akhbardeh et al., 2009; Crow et al., 1994). Also, points representing isotonic contraction (IC) and isovolumic movement (IM) have been identified (Crow et al., 1994). Although Crow et al. (1994) identified the AS, IC, and IM points, these points have not been applied widely in SCG analysis. The IC point has later been suggested to correspond to the maximum acceleration of blood in the aorta (MA) (Gurev et al., 2012).

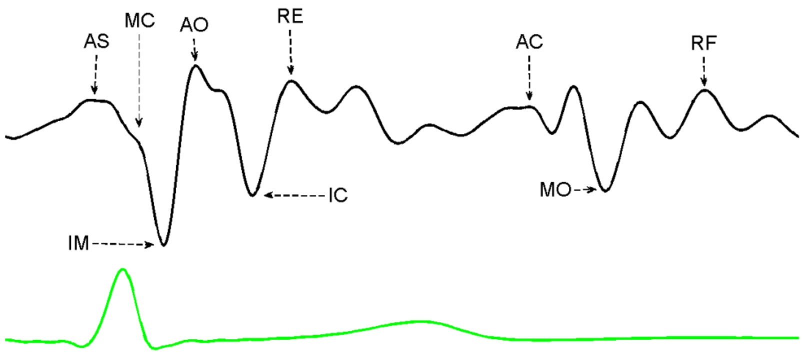

Figure 4. Annotation of seismocardiographic waveforms using the annotation scheme proposed by Crow et al. (1994). The black line is the seismocardiogram and the green line the electrocardiogram. The following abbreviations are used: AS = atrial systole, MC = mitral valve closure, IM = isovolumic movement, IVC = isovolumic contraction, AO = aortic valve opening, IC = isotonic contraction , RE = peak of rapid ejection, AC = aortic valve closure, MO = mitral valve closure, RF = rapid filling. Akhbardeh et al. (2009) refers to the IM point as the isovolumic contraction point (IVC). Gurev et al. (2012) proposed that the IC corresponds to the maximum acceleration of blood in the aorta (MA).

A diverse nomenclature for naming the modalities and waveforms of SCG has existed since the field has emerged. Even some of the first works in the field of SCG recording used divergent nomenclature. Mounsey (1957) called his technique precordial BCG while Bozhenko (1961) and Baevsky et al. (1964) called their techniques SCG. To date, no unanimous agreement has been reached about the naming convention. However, the general consensus seems to move towards the division proposed by Tavakolian et al (2011), where SCG is considered a vibration measurement method that measures the vibrations locally in the precordial area, whereas BCG is considered a measurement of the vibrations of the whole body. A recent manifestation of the nomenclature issue described above can be found in the literature (Neary, MacQuarrie, Jamnik, Gledhill, & Busse, 2011; Tavakolian, Vaseghi, & Kaminska, 2008; Vogt, MacQuarrie, & Neary, 2012), where SCG recordings are referred to as BCG and vice versa.

In addition to the name of the method itself, the nomenclature used to describe SCG waveforms is not uniform. For example, some research uses the established BCG waveform nomenclature to describe SCG recordings (McKay, Gregson, McKay, & Militzer, 1999; Neary et al., 2011), which might be confusing, as the BCG and SCG are essentially different methods (Tavakolian et al., 2011) and the waveforms are considered to be of different origin (Migeotte et al., 2012). Zanetti and Salerno (1990) annotated the SCG waveforms with respect to corresponding cardiac events rather than based on old BCG annotations, and the tradition has since been continued in some of the current research.

The introduction of 3-D SCG measurements has complicated the nomenclature by introducing multiple axes of measurement. Traditionally, the dorso-ventral axis has been called SCG (D. Salerno & Zanetti, 1990; Tavakolian et al., 2011). The prevalent practice, which is also used in this study, is to call the sinistro-dexter, superior-inferior, and dorso-ventral axes the x, y, and z axis, respectively (see Figure 8). However, some exceptions to the rule are present in the current literature (Vogt et al., 2012).

1.4.3 Applications

Although SCG in general has not been deployed in the clinical environment, some promising applications have been suggested. For instance, SCG has been proposed to be of value in assessing the timing of different events in the cardiac cycle (Crow et al., 1994; Gurev et al., 2012; Tavakolian, Blaber, Ngai, & Kaminska, 2010). Using these events, assessing, for example, myocardial contractility might be possible (Tavakolian et al., 2012). SCG has also been proposed to be capable of providing enough information to compute heart rate variability estimates (Laurin, Blaber, & Tavakolian, 2013; Ramos-Castro et al., 2012). A more complex application of cardiac cycle timings and SCG waveform amplitudes is the computing of respiratory information from the SCG signal as proposed by Pandia et al (2012, 2013).

Another promising use of SCG is supporting other measurements. For example, SCG has been proposed to function as a feasible method when monitoring cardiac activity during magnetic resonance imaging (Jerosch-Herold et al., 1999; Naemura & Iseki, 2003). Recently, also applications for the gating of cardiac imaging and therapy have been proposed (Tavakolian et al., 2013; Wick et al., 2012). Some research also implies that SCG is a useful adjunct to ECG in coronary artery disease and ischemia diagnosis (Becker et al., 2013; Korzeniowska-Kubacka, Bilińska, & Piotrowicz, 2005; Wilson, Bamrah, Lindsay, Schwaiger, & Morganroth, 1993). In animal tests, SCG has shown promise for detecting myocardial ischemia while using ECG only as a timing reference.

1.5 Study objectives

As stated in the preceding section, a variety of different measurement setups for SCG that use accelerometers of very different sizes has been reported in the literature. For example, Zanetti and Salerno (1990) reported using a bulky and almost 1-kilogram accelerometer whereas Pandia et al. (2012) used miniature accelerometers with negligible mass. Although the reference measurements vary between measurement setups, ECG is acquired to serve as a timing reference in almost every SCG measurement setup. The variety in the SCG measurement setup implementations suggests that there is no consensus on how SCG should be measured in order to obtain meaningful data. In addition, even though several advanced diagnostic applications that use SCG have been proposed (Becker et al., 2013; Korzeniowska-Kubacka, Bilińska, & Piotrowicz, 2005; Wilson, Bamrah, Lindsay, Schwaiger, & Morganroth, 1993), the mapping of cardiac cycle events to SCG events is not clear. To gain knowledge on whether SCG is a feasible method for detecting cardiac vibrations, the response of SCG signals to changes in, for example, posture should be studied.

To address the concerns regarding how SCG should be measured, what kind of equipment should be used to implement an SCG measurement system, and whether SCG is a feasible method for detecting cardiac vibrations, the following objectives are set for this study:

1) To study the means to implementation of a practical system that can be used in SCG research.
2) To implement a practical system for SCG measurements and evaluate its performance.
3) To study the feasibility of SCG.

2. Materials and methods

2.1 Measurement equipment

2.1.1 Measurement equipment for three-dimensional seismocardiographic signal and auxiliary parameters

General design

The measurement system consists of 3D-SCG, ECG, PPG, and respiration measurements. Figure 5 depicts the block diagram of the system. In order to facilitate test subject safety, the system is galvanically isolated by powering the electronics and the host PC with rechargeable batteries. The electronics are powered with a Li-Ion battery (800052, Enix Energies, UK). The host PC is powered with a generic laptop PC battery.

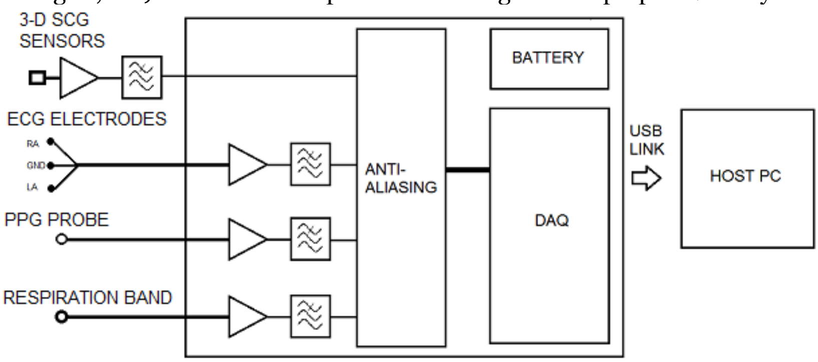

Figure 5. Block diagram of the measurement system for 3-D seismocardiography. [P4]

Bandwidth requirements and anti-aliasing

Under normal circumstances, an adequate upper cut-off frequency for BCG is around 40 Hz (Khandpur, 2004). However, in SCG measurements, the majority of the power of the signal is suggested to be observed at less than 20 Hz (McKay et al., 1999; Tavakolian et al., 2011). An adequate cut-off frequency for PPG is around 50 Hz in normal conditions (Khandpur, 2004). While the ECG bandwidth may reach even up to 150 Hz (Webster, 2009), the main components contributing to the QRS complex are below 100 Hz (Thakor, Webster, & Tompkins, 1984). Normally, a person breathes at most 50 breaths per minute (Khandpur, 2004), which corresponds to a frequency of less than 1 Hz. With respect to the bandwidth requirements of the measured signals, a 100-Hz anti-aliasing cut-off frequency is a suitable choice. The anti-aliasing filters are identical 8th-order Bessel low-pass filters, all of which have a rated cut-off frequency of 100 Hz and attenuation of at least 96 dB at 800 Hz. The Bessel filter was chosen for its constant group delay. The filters are implemented with operational amplifiers (AD8630, Analog Devices, USA) coupled in the Sallen-Key topology.

3-D seismocardiography measurement

All three axes of acceleration are measured with a dedicated accelerometer (SCA610-C21H1A, Murata Electronics Ltd., Finland). To facilitate 3-D measurements, the three accelerometers are orthogonally mounted accelerometers in one package. The cross-axis sensitivity of the accelerometers is 4% and the output noise density is 80 $\mu g/\sqrt{Hz}$. The accelerometers were measured at Murata Electronics' laboratories and were shown to have the -3dB point at 47 Hz.

The output of the acceleration sensor is amplified using an instrumentation amplifier stage (INA337, Texas Instruments, USA) which amplifies the difference between the raw acceleration sensor signal and its DC component, which is extracted using a single-pole RC low-pass filter. The gain of the 3D-SCG circuit is 24 dB and the passband (-3dB) of the circuitry including the anti-aliasing filters is from 0.12 Hz to 95 Hz.

Respiration measurement

The respiration signal is measured with a 10-cm long 10-kΩ DC-excited slide potentiometer (EVAJQLR15B14, Panasonic, Japan) attached to the subject with a non-stretching band. One end of the band is fixed while the other end is attached to the slide of the potentiometer. The slide is returned to its initial position using two springs. The sensitivity of the measurement is approximately 0.5 V/cm. The passband of the circuit is the same as the passband of the anti-aliasing filters.

ECG measurement

The ECG signal is measured with three lead wires using a basic unshielded commercial cable and electrodes (Blue Sensor L, Ambu®, Denmark). The ECG signal is amplified as follows. First, an instrumentation amplifier (INA326, Texas Instruments, USA) followed by a single-pole RC low-pass filter is used for preamplification. Then, an operational amplifier (OPA2335, Texas Instruments, USA) is used to amplify the difference between the signal from the first stage and a reference voltage (LM4120AIM-1.8, National Semiconductor, USA). High-pass filtering is implemented by feeding the signal from the instrumentation amplifier stage back to the reference voltage pin of the instrumentation amplifier via an operational amplifier coupled as an integrator (OPA2335, Texas Instruments, USA). The gain of the ECG circuit is 60 dB. The passband (-3 dB) of the ECG circuitry including the anti-aliasing filters is from 0.4 Hz to 70 Hz.

PPG measurement

The PPG sensor is a generic PPG finger probe (Oxytip+, GE Healthcare Finland, Finland). The PPG measurement is made using a single light source (visible red light) that is excited with a DC source (LM317L, National Semiconductor, USA). The output of the finger probe's photodiode is first amplified with an operational amplifier (OPA337, Texas Instruments, USA) coupled as a transimpedance amplifier. The signal is then amplified similarly to the 3D-SCG signals, as described earlier. The passband of the PPG circuit including the anti-aliasing filters is from 0.15 Hz to 65 Hz. The gain of the PPG circuit is 165 dB.

Analog-to-digital conversion and communication

The measured signals are sampled with a 16-bit simultaneous sampling analog-to-digital converter (USB- 1608FS, Measurement Computing Corporation, USA). The sampling rate is 2000 samples/s. The analog-to-digital converter is connected to the host PC with a wired USB link. The visualization and storing of data is implemented in a custom virtual instrumentation software (LabVIEW® 2009 9.0 32-bit, National Instruments, USA).

2.1.2 Portable measurement equipment for the superior-inferior axis of the seismocardiographic signal

The measurement system is based on the 3-D SCG acquisition hardware described in the preceding section. The aim of developing this system was to give more emphasis to portability and ease-of-use. The measurement system consists of superior-inferior SCG, ECG, PPG and respiration measurements, and also includes as data acquisition and communication units. The differences compared to the 3-D system are wireless communication, a different respiration sensor, a different analog-to-digital conversion, a different method of mounting the SCG sensor, and the use of only one axis of measurement.

Figure 6 shows the block diagram of the system. The respiration signal is measured using a strain gauge. The DC-excited strain gauge is coupled in a full bridge configuration and amplified with an instrumentation amplifier (INA326, Texas Instruments, USA). The breathing sensor is attached with an inflexible band that has a piece of elastic band attached to allow breathing. The accelerometer is attached between the respiration band and the chest. Thus, no skin contact or preparation for the SCG sensor is needed. All signals are sampled with a microcontroller's (ATMega328P, Atmel, USA) internal ADC with 8-bit resolution at the rate of 1000 samples/second. The sampled data is sent to the host PC via a Bluetooth module (Parani-ESD200, Sena Technologies, USA).

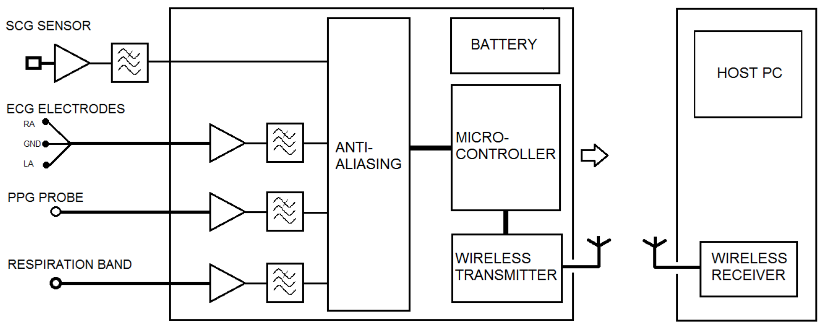

Figure 6. Block diagram for the 1-D seismocardiography measurements.

2.2 Signal processing

Segmentation of the seismocardiography signals

In the present approach, the heartbeats are detected using the peak of the ECG R wave (lead I). The SCG signal is segmented to windows of equal length starting and ending at a specific point with respect to the corresponding ECG R wave peak. Figure 7 depicts the segmentation of three consecutive heartbeats from the SCG z axis with emphasis on the vicinity of the peak of the ECG R wave. The segmentation procedure is repeated for each measured SCG axis.

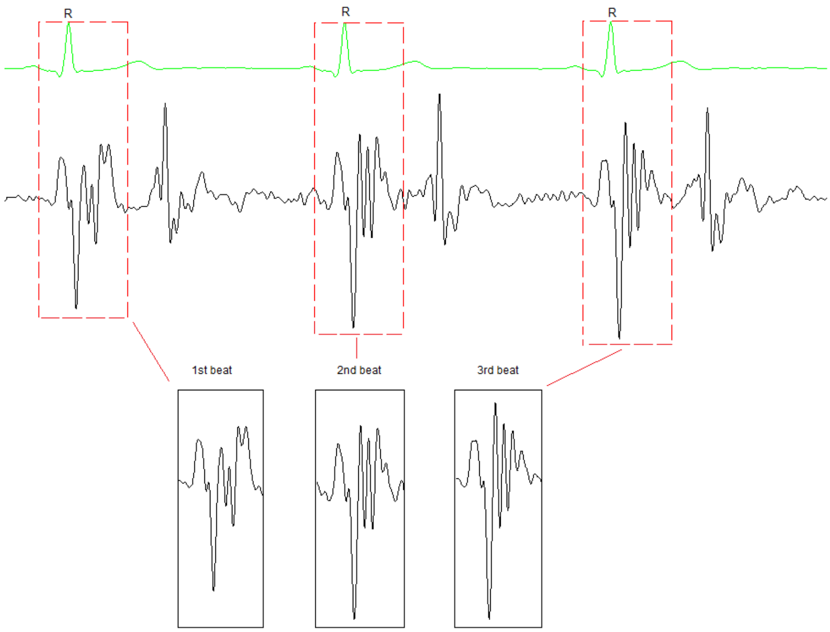

Figure 7. Three cardiac cycle segments extracted from the SCG z-axis signal. The green line represents the ECG lead II signal and the black line the SCG z-axis signal. The SCG signal is captured using similar equipment as in [P4], whereas the ECG signal is captured using a commercial ECG system (BC-ECG2, BIOPAC Systems Inc, US).

The segmentation can be applied either to a certain period of time or a certain number of heartbeats. After segmentation, each cardiac cycle can be presented as a set of segmented cardiac cycles defined as follows:

$$\mathrm{SCG}_{\mathrm{segmented}} = \{\mathrm{SCG}(t_0), \mathrm{SCG}(t_1), \dots \mathrm{SCG}(t_n),\ \mathrm{SCG}(t_N)\}, \qquad (1)$$

where t_o is the beginning of the segmentation window, t_N is the end time of the segment, and SCG (t_n) is a vector that consists of x, y, and z axis SCG at time t_n. The segmented heartbeats can be either used for beat-to-beat analysis or further processed to facilitate averaging-based analysis.

Averaging of the seismocardiography signals

The total average of a set of segmented SCG cycles at time t_n is computed as follows:

$$\mathrm{SCG}_{\mathrm{avg}}(t_n) = \frac{1}{R}\sum_{i=1}^{R} \mathrm{SCG}_i(t_n), \qquad (2)$$

where R is the number of ensemble averaged heartbeats and t_n is the nth sample of the selected segmentation window. Next, the ensemble averages are combined sequentially to produce a seismocardiogram that represents the average heartbeat within the selected segmentation window. An average seismocardiogram is defined as follows:

$$\mathrm{SCG}_{\mathrm{avg}} = \left\{\mathrm{SCG}_{\mathrm{avg}}(t_0), \mathrm{SCG}_{\mathrm{avg}}(t_1), \dots, \mathrm{SCG}_{\mathrm{avg}}(t_N)\right\}, \qquad (3)$$

where t_o is the starting time of the segmentation window and t_N is the end of the segmentation window.

2.3 *In vivo* measurements

2.3.1 Test subjects

Two sets of test subjects were measured to obtain the SCG and related data. The first set consisted of six subjects (six male, one female). The age of the subjects ranged from 25 to 58 years and their average weight was 72.2

kg. The average height of the subjects was 1.71 m. The second set of subjects consisted of four subjects aged 28 to 57 years (three male, one female). For the second set, the weight and height of the subjects was not recorded. All subjects were generally healthy and did not suffer from diagnosed cardiovascular conditions. The first set of subjects was measured with 3-D SCG, and the second set with 1-D SCG.

2.3.2 Placement of the sensors and electrodes

The SCG sensor was placed on the midline of the body of the sternum with the lower end of the sensor at the superior end of the xiphoid process. In the 3-D measurements, double-sided adhesive tape was used to secure the contact to the skin. In the 1-D measurements with the portable measurement system, the SCG sensor was secured by placing it under the respiration band. The ECG electrodes were attached to the wrists just next to the hand and the medial side of the right ankle while avoiding bone and thick muscle. The bipolar limb lead I was registered from the electrodes. The PPG signal was recorded from the right or the left index finger. In the 3-D measurements, the respiration sensor was placed approximately two finger-breadths caudad to the xiphoid process. In the 1-D measurements, the respiration band was attached so that the band secured the SCG sensor on the sternum. Figure 8 shows the mounting of the sensors and electrodes in the 3-D measurements.

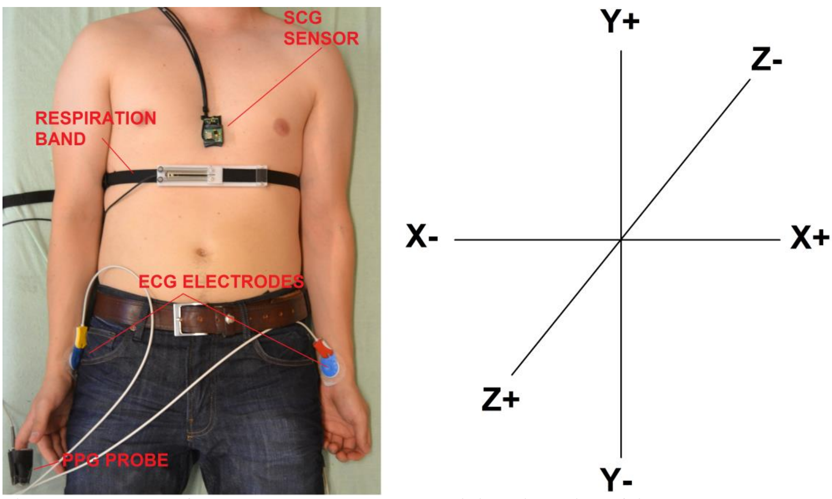

Figure 8. Test setup for 3-D SCG measurements and the orientation of the SCG axes.

2.3.3 Test protocol

3-D measurements in the supine position

The subjects were measured in the supine position for approximately ten minutes per session. These sessions were repeated three times. All the electrodes were replaced and sensors removed and reattached between each recording session. Each recording began with a five-minute baseline recording under spontaneous, quiet respiration conditions. After the baseline measurement, the subject was asked to take a deep breath and hold it for as long as was comfortable. After expiration, the subjects were allowed to recover for about one minute before repeating the breath-holding procedure. After the second breath-holding test, another one-minute recovery was allowed for the subject. Next, the subject was instructed to exhale deeply and then hold his or her breath for as long as it was comfortable. This exhalation procedure was repeated after a one-minute recovery period.

1-D measurements in the sitting position

The subjects were measured in the sitting position on a normal office chair. Each measurement session lasted about ten minutes. In addition to rest measurements, the subjects performed a phase of exaggerated breathing. The subjects were instructed to sit tall and still. This was done because in during the development of the system, it was noticed that not sitting tall impairs the quality of the signal.

3. Results

3.1 General observations

The acquired 3-D SCG, 1-D SCG, ECG, and PPG signals were consistent and did not exhibit large beat-to-beat variations. From the acquired data, the cardiac cycles were successfully identified. Hence, the amplitude and timing relations were feasible for studying. Figure 9 shows typical tracings of the x-, y-, and z- axis SCG, PPG, ECG and respiration measurements. The acquired 3-D SCG waveforms featured repetitive waveforms that could be visually identified to match certain events in the cardiac cycle (see Figure 10). The effect of breathing was observable from both averaged and beat-to-beat SCG presentations (see Figure 9 and Figure 11).

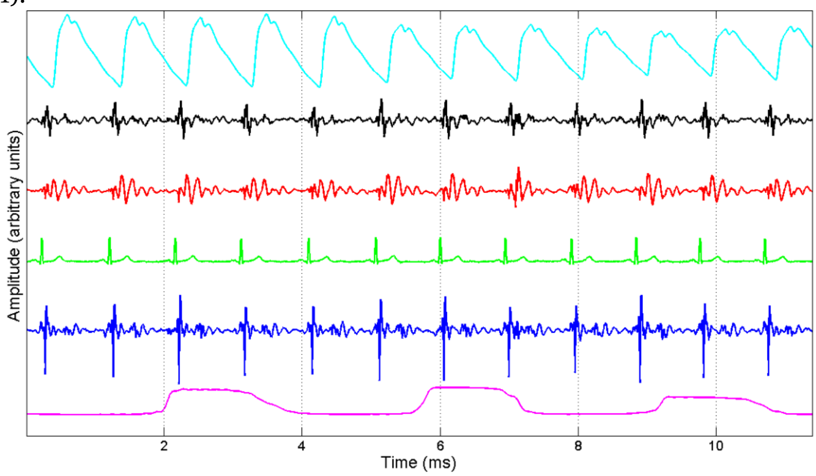

Figure 9. Typical tracings of the signals recorded with the 3-D measurement system . The signals from top to are the following: the PPG, the x-axis SCG, the y-axis SCG, the ECG, the z-axis SCG, and the respiration signal.

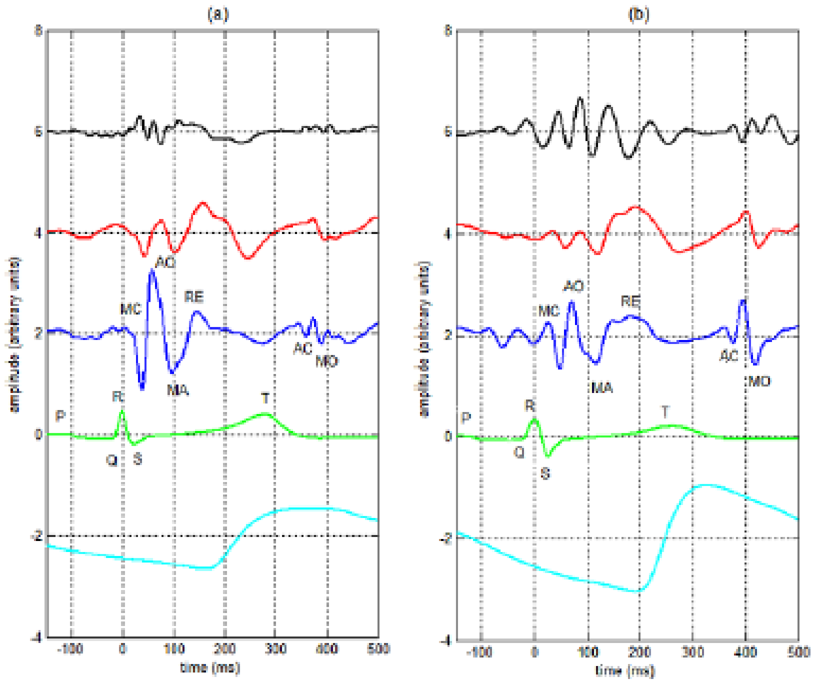

Figure 10. Cardiac cycle events annotated on the z-axis seismocardiogram. The seismocardiograms are ensemble averages of 10 heartbeats of (a) a 52-year-old male subject and (b) a 40-year-old female subject. The mitral valve closing (MC), the aortic valve opening (AO), the maximum acceleration of blood in the aorta (MA), the rapid ejection of blood into the aorta (RE), the aortic valve closing (AC), and the mitral valve opening (MO) are visually detected and marked for both subjects. The black line is the signal on the SCG x axis, the red on the SCG y axis, the blue on the SCG z axis, the green is the ECG signal, and the cyan the PPG signal. [P4]

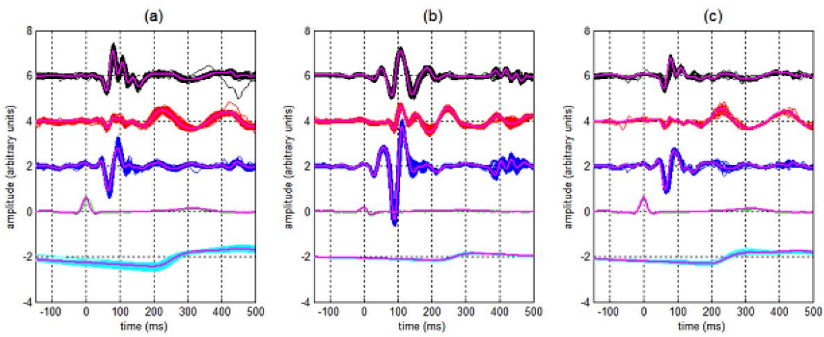

Figure 11. Segmented heartbeats of a 58-year-old male subject and their averages superimposed on the same time window under different respiration conditions: (a) 256 heartbeats at rest, (b) 126 heartbeats during apnea in the inhalation phase, and (c) 42 heartbeats during apnea in the exhalation phase. The black line indicates the SCG x axis, the red the SCG y axis, the blue the SCG z axis signal, the green the ECG signal, and the cyan the PPG signal. [P4]

3.2 Effects of respiration on seismocardiographic waveforms

The measured respiration signals were used to produce the breathing phase-based SCG waveform averages. Figure 12 and Figure 13 show the effect of the phase of breathing on the segmented SCG waveforms on the x, y, and z axes. The waveforms at rest differ from the waveforms during apnea which was also observed by Pandia et al. (2012). When compared to average waveforms obtained at rest, it also seems that the breathing phase-based averages are more consistent. This observation duplicates the results of Tavakolian et al. (2008). The effect of respiration is seen in an extreme way in Figure 12, where it seems that the averages computed at rest feature two distinct paths probably due to breathing.

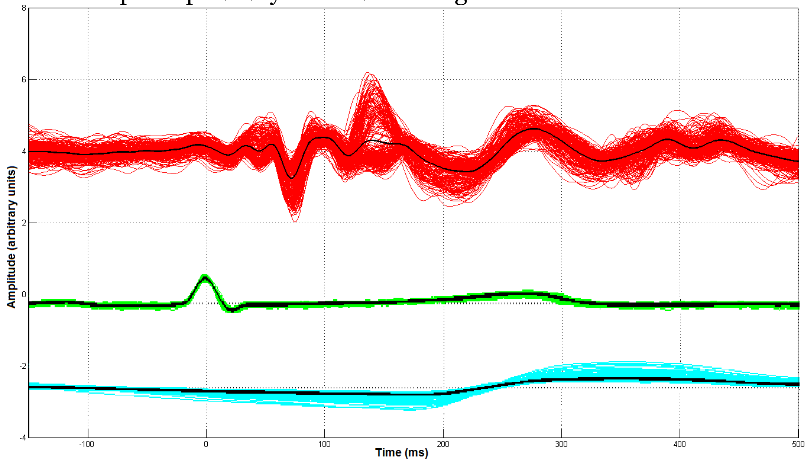

Figure 12. 246 heartbeats of a subject superimposed in the same figure. The black curves that are superimposed on each signal represent the average of the corresponding signal. The red curves depict the superior-inferior SCG, the green the ECG and the cyan the PPG. [P3]

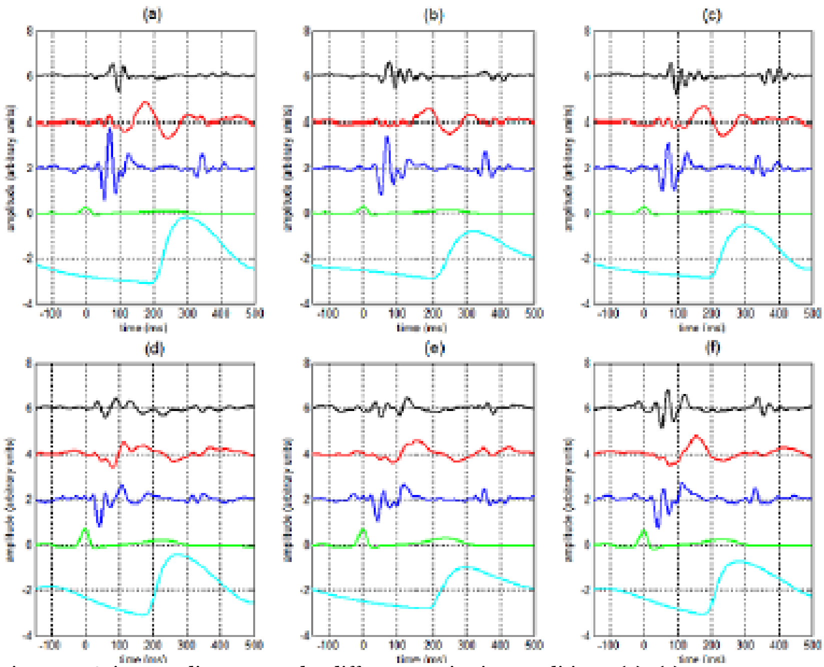

Figure 13. Seismocardiograms under different respiration conditions. (a)–(c) represents three measurements for a 25-year-old male subject holding his breath in the inhalation phase and (d)–(f) three measurements of the same subject holding his breath in the exhalation phase. The black line is the SCG x axis, the red the SCG y axis, the blue the SCG z axis signal, the green the ECG signal, and the cyan the PPG signal. [P4]

3.3 Comparison of seismocardiographic waveforms on the y axis in the supine and sitting positions

The supine and the sitting position yielded similar results when measured using the y-axis SCG. The corresponding waveforms however seem to be slightly delayed when the subject is measured in the sitting position. Also, the waveform amplitudes were generally greater in the sitting position than in the supine. These observations are similar as the ones obtained using ballistocardiography by Alametsä et al. (2008).

Both the z- and the y-axis SCG signals featured similar waveforms in terms of shape and timing of the waveforms. However, the waveforms appearing on the y axis seemed to emerge approximately 45 milliseconds after the corresponding z-axis waveforms. The breathing phase-based analysis showed that the MA-RE waveform on the y axis was 80% higher during the inspiration and 10% higher in the expiration phase than the corresponding waveform on the z axis.

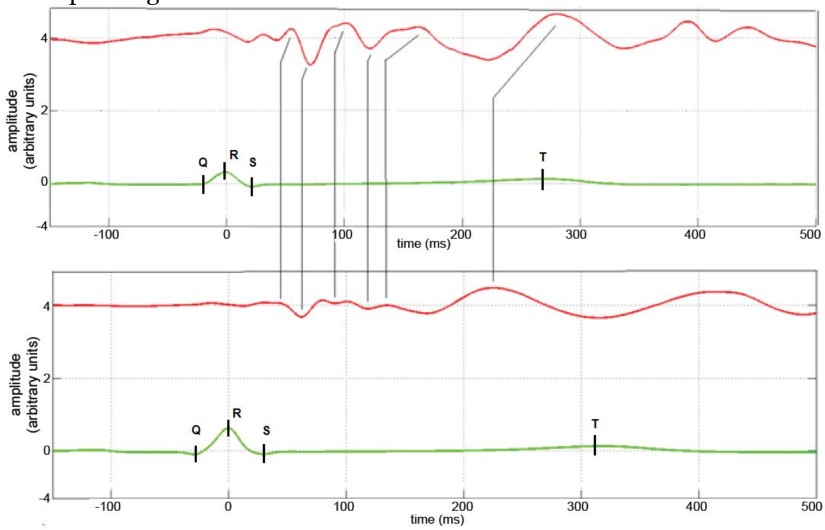

Figure 14. The y-axis SCG in the sitting position (above) and in the supine position (below) captured from the same subject. The red lines depict the SCG signal and the green lines the ECG signal. The black lines mark the corresponding waveforms. [P3] The ECG T wave is slightly delayed in the supine position. This is probably due to multiple reasons including posture, heart rate, and that the measurements were performed on separate days.

4. Discussion

4.1 Is there a need for new measurement modalities for the cardiovascular system?

Evidence has been presented that a healthy lifestyle, health promotion, and pharmacological care may reduce the risk of disease and cut healthcare costs (Aldana, 2001; Chiuve et al., 2008; Weintraub et al., 2011). However, when primary prevention fails, it is important to detect the disease as soon as possible to yield a better prognosis of treatment. To achieve this, regular monitoring for latent diseases is required. However, regular monitoring of healthy subjects in clinical conditions is expensive and resource-intensive. One approach that might help solve this challenge is shifting the preventing and monitoring of diseases from hospitals to out-of-hospital conditions. Another strategy would be to increase the diagnosis capabilities of the contemporary clinical environment to achieve a more comprehensive view of the health of an individual.

Monitoring of health in out-of-hospital conditions has been a subject of interest of research for a long time (Korhonen, Parkka, & Van Gils, 2003). Home monitoring and remote disease follow-up management have been proposed to decrease patient mortality (Martínez et al., 2006) and spare healthcare resources (Martínez et al., 2006; Tamura, Mizukura, & Kimura, 2011), improve the speed of diagnosis, increase compliance in taking prescribed medication (Krishna, Boren, & Balas, 2009), and improve blood pressure control (Parati et al., 2009). Despite the promising results, it seems that in order to fully exploit the possibilities of ubiquitous systems in general and in cardiovascular applications, several ethical, legislative, and technical issues need to be addressed [P1]. The ethical and legislative challenges include concern over privacy of medical data, liability distribution, and standardization [P1]. The technical issues include challenges in distributing large amounts of data, robust transducer design, and dealing with the degraded signal quality that is typical for ubiquitous health measurements [P1].

Today, a rather comprehensive view of an individual's general and cardiovascular health can be achieved in the clinical environment. However, the contemporary picture can be made more comprehensive by introducing new measurement modalities. The new measurement modalities might provide complementary information of the cardiovascular function. This seems to be the case for SCG also [P2]. For example, ECG is a widely used method, but all cardiac conditions are not manifested in the ECG signal since ECG measures the electrical activity of the heart. However, other conditions could be detected with another method. An example of this phenomenon is reported by Kaminska et al (2007) where two cases of abnormal seismocardiograms did not coincide with abnormal electrocardiograms. Therefore, developing new measurement modalities for the cardiovascular system is important. The new modalities might provide quicker diagnosis of latent conditions.

4.2 Contemporary implementations of seismocardiographic measurement systems

SCG produces noise-prone complex waveforms (J. M. Zanetti & Tavakolian, 2013). Thus, it is usually coupled with ECG which is used as an auxiliary timing reference to identify cardiac events [P2]. Nguyen et al. (2012) demonstrated a stand-alone approach based on the generalized likelihood ratio for segmenting SCG signals. Blind-segmentation has been used for BCG (Akhbardeh, Kaminska, & Tavakolian, 2007) and could be potentially used for SCG segmentation too. However, due to the simplicity and reliability of the ECG-based timing, stand-alone SCG analysis is not prevalent. Since the measurement systems in [P3] and [P4] are designed to be used in laboratory or clinical conditions, the reliability of ECG as a timing reference was favored over the simplicity of stand-alone SCG instrumentation. In the test measurements in both [P3] and [P4], the use of ECG as a timing reference was successful.

SCG has been coupled with multiple auxiliary physiological measurement modalities, such as photoplethysmography (Tavakolian, Dumont, & Blaber, 2012), ICG (Baevsky et al., 2009), respiration measurement (Baevsky et al., 2009; Tavakolian et al., 2008), and ECHO (Crow et al., 1994; Gurev et al., 2012). Most often, the auxiliary measurements are used as reference signals. However, the auxiliary measurements, such as respiration measurement, can be also used to enhance signal processing (Tavakolian et al., 2008). Respiration is an especially important auxiliary parameter for SCG since respiration significantly modulates heart rate and stroke volume, for example. In [P3], 1-D SCG was simultaneously coupled with ECG, respiration, and PPG measurements to yield additional data to compare the detected SCG events to. To the best of the author's knowledge, this kind of combination for SCG measurements has not been realized elsewhere. In [P4], a step forward was taken by integrating 3-D SCG with ECG, respiration, and PPG measurements.

In contrast to the pioneering works on modern SCG (D. Salerno & Zanetti, 1990) which used bulky sensors, the state-of-the-art implementations use lightweight sensors with similar performance characteristics (Dinh et al., 2011; Pandia et al., 2012). Despite the slightly larger size, the accelerometers used in [P3] and [P4] have a better sensitivity (2 V/g) compared to the accelerometers used by Pandia (0.7 V/g) and Dinh (0.8 V/g) (Dinh et al., 2011; Pandia et al., 2012). The trade-off between size and performance does not seem significant, since the systems implemented in [P3] and [P4] are intended for research. However, implementing wearable systems might tip the scales in favor of size. For example, accelerometers similar to those used by Pandia et al (2012) have been used to implement wearable SCG systems (Castiglioni, Faini, Parati, & Di Rienzo, 2007; Di Rienzo et al., 2011).

4.3 Performance of the implemented systems

Both the 1-D and 3-D SCG systems described in [P3] and [P4] recorded all signals consistently. Figure 9 depicts typical tracings of signals acquired with the 3-D SCG system [P4]. The z-axis SCG waveforms were similar to the ones presented in the literature (Tavakolian et al., 2011; J. Zanetti et al., 1991). As seen in the waveforms of Figure 10, the indicative points of the cardiac cycle were visually detectable from the 3-D SCG z axis signals. The y-axis SCG waveforms in both [P3] and [P4] were visually similar as in McKay et al. (1999). Due to the scarcity of x-axis SCG descriptions in the literature, the x axis was compared to existing works. While the x-axis SCG waveforms were not annotated, it was seen in [P4] that they exhibit a consistent form that is most probably due to the same cardiac events as the z- and y-axis SCG waveforms.

Figure 11 and Figure 12 illustrate the consistency of the 3D-SCG, ECG, and PPG measurements during a single session and between separate measurements. The important ECG waveforms were detectable (see Figure 10). Figure 10 also depicts the PPG measurement's ability to detect the rush of blood to the periphery. The measured respiration signals were successfully used to produce the breathing phase-based SCG waveform averages in both [P3] and [P4]. Some morphological variation in the SCG signals is seen between phases of respiration, as expected (see Figure 11). Some of the detected noise in [P3] was traced back to the mounting method where the SCG sensor was placed under the respiration belt. It seems that mounting the SCG sensor with double-sided adhesive tape as in [P4] facilitates more robust SCG measurements.

In some cases in [P4], quiet breathing was hard to detect, owing this is partly to the mechanical design of the sensor. No such challenges were observed in [P3]. The placement of the respiration sensor also affects the signal. Romei et al. (2010) showed that posture affects respiration kinematics so that in the supine position the movement of the rib cage is decreased compared to the sitting position. Thus, in future, the placement of the respiration sensor may have to be changed depending on the posture of the subject.

As SCG is a valuable tool in the analysis of cardiac time intervals, it is to be noted that the system in [P4] is designed to promote inter-channel synchronization. Firstly, it uses simultaneous sampling ADC with a high sampling rate that decreases errors from conversion time and hence enhances the temporal resolution. Secondly, the anti-aliasing filters are Bessel filters that reduce group-delay errors by featuring a constant group delay. If needed, the group delays from the gain stages can be easily measured and taken into account. Thus a high order of inter-channel synchronization can be achieved with this system. Synchronization is especially important when different research groups compare their measurements that are recorded with different hardware.

Using a compact design to integrate auxiliary measurements, the implementations in [P3] and [P4] might increase reliability and also convenience by diminishing the amount of equipment that can be potentially set up incorrectly. However, the amount and type of auxiliary measurements should be decided based on the application. Other auxialiary measurements than the ones implemented in this study are obviously needed in some applications but a merit of the present sensor combinations is that they facilitate a wide range of different SCG measurement scenarios in a compact form. The multimodal nature of the measurement systems and the promising test performance suggest that these systems may be used to yield more accurate knowledge of the cardiac function than the present approaches.

4.4 Improvement of seismocardiographic measurements

Even though the technology presented in the literature seems feasible to implement 3-D SCG measurements (Castiglioni et al., 2007; Di Rienzo et al., 2011; Dinh, 2011; Pandia, Ravindran, Kovacs, Giovangrandi, & Cole, 2010) [P2, P4], the z axis is the most prevalent axis in SCG measurements. Consequently, the majority of applications are for the z axis as well. The comparison of the z- and y-axis SCG waveforms in [P3] suggested that certain cardiac cycle events, such as rapid ejection of blood into the aorta, might produce greater impacts on the y-axis waveforms than on the z-axis waveforms. Also, the sitting and supine positions yielded different seismocardiograms (see Figure 14). This might be partly due to the change of the inclination of the heart which results in a different projection of cardiac vibrations on the y axis. Thus, all the changes might not be due to the cardiovascular system adapting to different postures. These observations seem to reassert the proposed superiority of 3-D measurements (De Ridder, Migeotte, Neyt, Pattyn, & Prisk, 2011; Migeotte et al., 2012) when physiological interpretations are sought after in cardiac vibration studies.

McKay et al. (1999), on the other hand, reported promising results in determining the stroke volume using only the y axis SCG. However, the heart and the sternum both vibrate in three dimensions, so information loss is inevitable if only one direction is measured, as seen in [P3] and in (Figure 14. Recently, Migeotte et al. (2012) proposed that the vibration waveforms observed on the y axis are correlated poorly to the magnitude of the maximum systolic force vector computed using all three axes of acceleration. It seems that, to advance SCG, it is important to further explore the possibilities of using 3-D acceleration signals.

One possible application of 3-D SCG is the reduction of inter-subject variation of seismocardiogram between subjects. Even though this variation is a common finding in SCG studies (Pandia et al., 2010) [P4], the physiological origin of the variation is not known. It could be that the origin of the inter-subject variation is the different orientation of the heart, which causes the projections on each axis to be different between subjects. If this is the case, the inter-subject variation could be decreased by approximating the mechanical axis of the heart as Soames and Atha (2001) did using BCG and then rotating the 3-D signals accordingly. Another application is the enhancing of current diagnostic applications of SCG. For example, Korzeniowska-Kubacka et al. (2005) approached the diagnosis of ischemia by computing the difference between pre- and post-exercise amplitude of the AO waveform. However, according to the observations of Migeotte et al. (2012), it could be that the uniaxial approach of Korzeniowska-Kubacka et al. (2005) is unreliable and could be made more reliable by use of 3-D measurements. According to the observations presented in the literature and in this study, it seems that SCG should be measured with a 3-D accelerometer when aiming for the best interpretability.

5. Conclusion

Two SCG measurement systems were implemented in this study. The first system was portable and integrated 1-D SCG, ECG, PPG, and respiration measurements. It also featured wireless communication. In contrast to the first system, the second system featured enhanced analog-to-digital conversion, 3-D SCG, and wired communication. Both systems were technically feasible for use in SCG research. The acquired waveforms were similar to the ones presented in the literature. The present implementations demonstrated the feasibility of SCG by using modern sensors and a multimodal approach.

The multiple simultaneous physiological measurements enhanced SCG analysis. The measuring of respiration facilitated the separation of heartbeats during inspiration and expiration which is important when respiratory modulation of SCG is studied. The ECG measurement facilitated reliable timing of the SCG waveforms. It seems that SCG should be coupled with simultaneous physiological measurements to gain a deeper understanding of the SCG waveforms. The acceleration sensors were more sensitive than in other SCG measurement systems reported in the literature. Additionally, the 3-D approach to the measurement of SCG was more extensively utilized than in previous reports in the literature. The enhancement of the acceleration measurement together with the simultaneous measurement of multiple physiological parameters facilitated improved SCG measurements and will increase the potential of SCG to be taken into clinical practice. The evidence presented in the literature and the observations in this study indicate that SCG is a feasible method for detecting vibrations due to cardiac function.

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