Rakenteiden Mekaniikka (Journal of Structural Mechanics)
Vol. 44, No 4, 2011, pp. 345-362

Photoplethysmography and its detailed pulse waveform analysis for arterial stiffness

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Summary. Arterial stiffness index is one of the biomechanical indices of vascular healthiness. These indexes are based on detailed pulse waveform analysis which is presented here. After photoplethysmographyic (PPG) pulse wave measurement, we decompose the pulse waveform for the estimation and determination of arterial elasticity. Firstly, it is electro-optically measured PPG signal and by electromechanical film (EMFi) measured signal that are analyzed and investigated by dividing each wave into five logarithmic normal function components. For both the PPG and EMFi waveform we can find very easily a good fit between the original and overlapped and summed wave components. Each wave component is assumed to resemble certain phenomenon in the arteries and certain indexes can be calculated for example based on the mutual timing of the components. Several studies have demonstrated that these kinds of indexes calculated based on actual biomechanical processed can predict future cardiovascular events. Many dynamic factors, e.g., arterial stiffness, depend on fixed structural features of the arterial wall. For more accurate description, arterial stiffness is estimated based on pulse wave decomposition analysis in the radial measured by EMFi and PPG method and tibial arterial walls measured by PPG method parallelly. Elucidation of the precise relationship between endothelial function and arterial stiffness can be done through biomechanics. However, arterial wall elasticity awaits still further biomechanical studies with clinical relations and the influence of arterial flexibility, resistance and ageing inside of the radial pulse waveform.

Key words: arterial stiffness, photoplethysmography, pulse wave analysis, decomposition

Introduction

The changes of the optical absorption through fingers can be easily monitored by photoplethysmography which measures the opacity changes in arteries, in this case, the distal arteries of the index finger and second toe. The mechanical heart signal of the wrist can be easily monitored by EMFi technique which measures the arterial waveform, in this case, the radial arteries of the hand. The waveforms of the signals measured reflect some average property of a whole arterial system, especially arterial and aortic walls. The technique is simple, noninvasive, and does not cause any damage or discomfort to the subject, because no press is applied [1].

As a motive, we know that when arteries stiffen the pulse wave velocity increases which has been shown by many techniques [2, 3]. Arteries stiffen as a consequence of normal aging process, but also caused by the arteriosclerosis which is a group of diseases characterized by thickening and loss of elasticity of the arterial walls. There are many phenomena behind of the elasticity loss [4]. Age related hardening occurs when the elastic fibers within the arterial wall muscles (elastin) begin to lose their resistance

to rupture due to mechanical stress. Cardiovascular diseases (CVD) are the world's largest killers, claiming 17.1 million lives a year according to WHO (World Health Organization). Most countries face high and increasing rates of CVD. Artery stiffen as a consequence of age, smoking, high cholesterol, lipid concentrations, obesity and sedentary life style. Sedentary life style also increases the risk for developing diabetes and arteriosclerosis [3].

Here we are optically investigating by non-invasive means measuring heart pulse waveforms detected in the periphery, namely on the finger and toe tip. Photoplethysmographic (PPG) device is typically used in analysis of oxygen saturation, but it enables assessing peripheral pulse waveforms, monitoring anesthesia, breathing, and apnoea. In addition PPG waveform based indexes can be used to follow changes in the elastic properties of the arteries causing arterial wall stiffening during ageing and in cases of CVD. However, these indicative indexes can inform about the necessity for life style changes [2, 5].

Analysis of the arterial pulse waveform becomes an important tool to find out and assess the pulse wave components and their relations, e.g., on medical treatment. The wave contains information on arterial physical properties and useful information on left ventricle activity, dynamics of autonomic nervous systems and heart-brain interaction, and arterial stiffness [6]. In addition to the arterial tree structure, the compound arterial pulse wave depends on ventricular ejection pattern which is determined by palpation at the periphery as a percussion wave. Much important information can be received based on the wave shape of the arterial pulse waveform, e.g., arterial stiffness, effects of drugs [7]. The calculated parameters of arterial stiffness index and the photoplethysmographic index are shown to be different for healthy volunteers and patients [8]. The method is still waiting for clinical validation. The time domain analysis presented here could give valuable information on the state of peripheral arteries when we fit by a component separation method as it is done on this case. This time domain component separation method presented here is based on logarithmic normal function which fits accurately giving information on the arterial pulse wave when we analyze each component separated by this method parallel with residual errors giving a very good goodness of fit after iteration process. Normal Gaussian functions do not fit very well to the PPG data according to visual inspection, because they are symmetric but PPG pulse waveform is not [9]. In the analysis on noiseless PPG waveforms, the PPG pulse waveform is processed by Levenberg-Marquart algorithm (LMA). Each iteration works well and we didn't need to guesswork parameters in young healthy persons but on the elderly healthy PPG pulse waveforms.

Materials and methods

Photoplethysmographic (PPG) device was constructed based on phase sensitive detection (PSD) in transmission mode. For the measurement of a high quality PPG record, IR LED lighted through a left index finger and second toe tip and the resulting LED light was measured and amplified with the principle of phase sensitive detector circuit. The PSD circuit cancels the ambient light and also power line noise producing low noise PPG signal from the finger and toe simultaneously. The lower cutoff

frequency of the PPG device is DC which make possible to analyze very low frequency autonomic nervous fluctuation in the PPG measurements. The timing purpose it was also simultaneously measured by electromechanical film (EMFi) from the wrist of six subjects. The higher cutoff frequency is over 30 Hz which make possible to analyze accurately the pulse waveform in all cases. The experiments were carried with 83 volunteers a.m. in supine position for five minutes, and in addition with 6 volanteers by EMFi and simultaneous PPG measurements.

The measured PPG and EMFi signals were analyzed by the Origin 7.5 software (Origin Lab Corporation, 2002). The arterial pulse wave decomposed into the five lognormal functions with parameters that were identified in the pulse separation procedure. This optimization procedure is based on LMA which is an iterative technique that locates the minimum of a function that is expressed as the sum of squares of nonlinear functions, such as logarithmic normal functions fitted in the radial arterial pulse wave. Measured intensity of light in PPG detectors differs between subjects and skin sites because of skin structure and human age. Thus, absolute PPG values cannot be compared quantitatively if we don't find the right parameters. We calculate two arterial pulse wave indexes called ageing index. The first one (AGI1) is based on the second derivative of the EMFi and PPG pulse wave defined as (b–c–d–e)/a, see Figure 2 [10]. The other index (AGI2) is based on the peak values of the decomposed wave components defined as $(t_2+t_3+t_4+t_5)/t_1$, where t_1 is the peak value of the percussion, t_2 the tidal, t_3 the dicrotic, and t_4 and t_5 the pre-systolic wave components, see Figure 3.

Results and discussion

Figure 1 shows a raw data with the DC removed of a healthy male person (70 years) where there is his electrocardiogram (ECG), finger (PPG1) and toe photoplethysmograms (PPG2), respectively. It is possible mathematically to decompose the measured PPG1 waves to analyze their time domain features. Each five components, percussion, tidal, dicrotic, and two pre-systolic components are shown in Figure 3. The whole PPGs are shown in Figure 2 from where the first pulse waves of each record are taken for analysis based on the LMA. The measured PPG and its fit lines very well overlap but not at the start and at the end of the pulse wave. Actually, the tidal component is totally hidden one. These differences between measured and calculated function forms can be seen clearly on the residual error function for both EMFi and PPG signals, see Figure 4.

In all measurements, the finger and toe PPGs was diverse between the young and elderly healthy subjects. The decomposed PPG waveforms fit well into its five logarithmic normal components indicating the coefficient of determination R^2=0.995 or over. The residual errors are also close to zero during the pulse waves. The logarithmic normal function describes the response of the arterial system. The first wave component is the percussion, originating from the contraction of the left ventricle. The second component is the tidal, occurring during the later part of the systole, caused by the elasticity of aortic wall, and probably reflected from the renal artery bifurcation. The third component is the dicrotic occurring during the beginning of diastole, caused by the reflection from the lower body bifurcation to the legs. The fourth and fifth component,

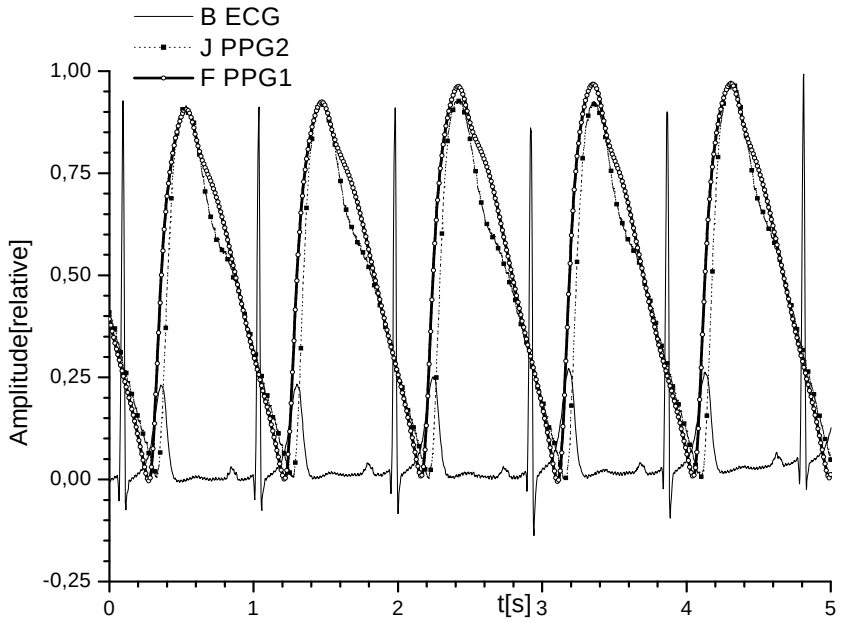

Figure 1. ECG, finger, and toe PPGs (PPG1 & PPG2 in Figure) of age 70 years (male) for five seconds where ECG shown by the continuous line, the finger PPG by (o)-mark, and toe PPG by (black square)-mark, respectively.

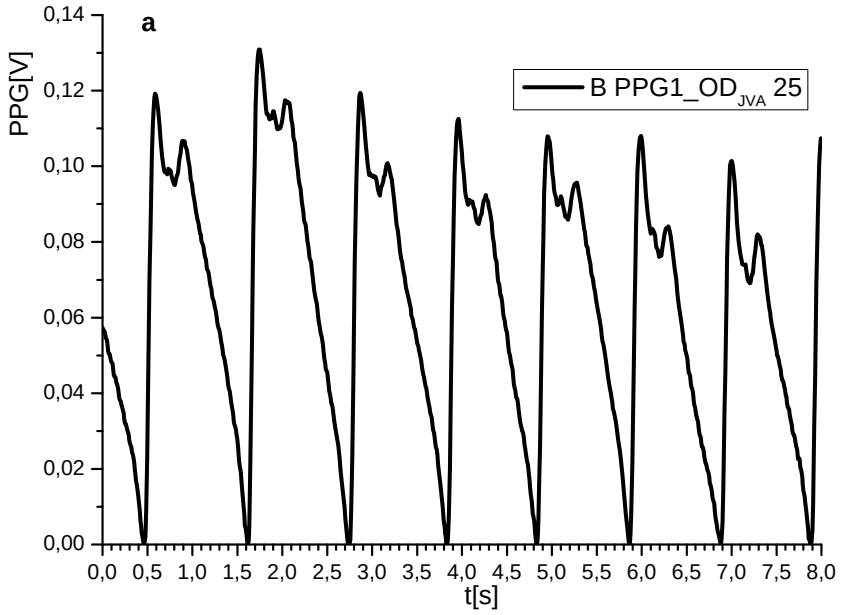

Figure 2a. Radial PPGs (PPG1): age 25 years male for eight seconds.

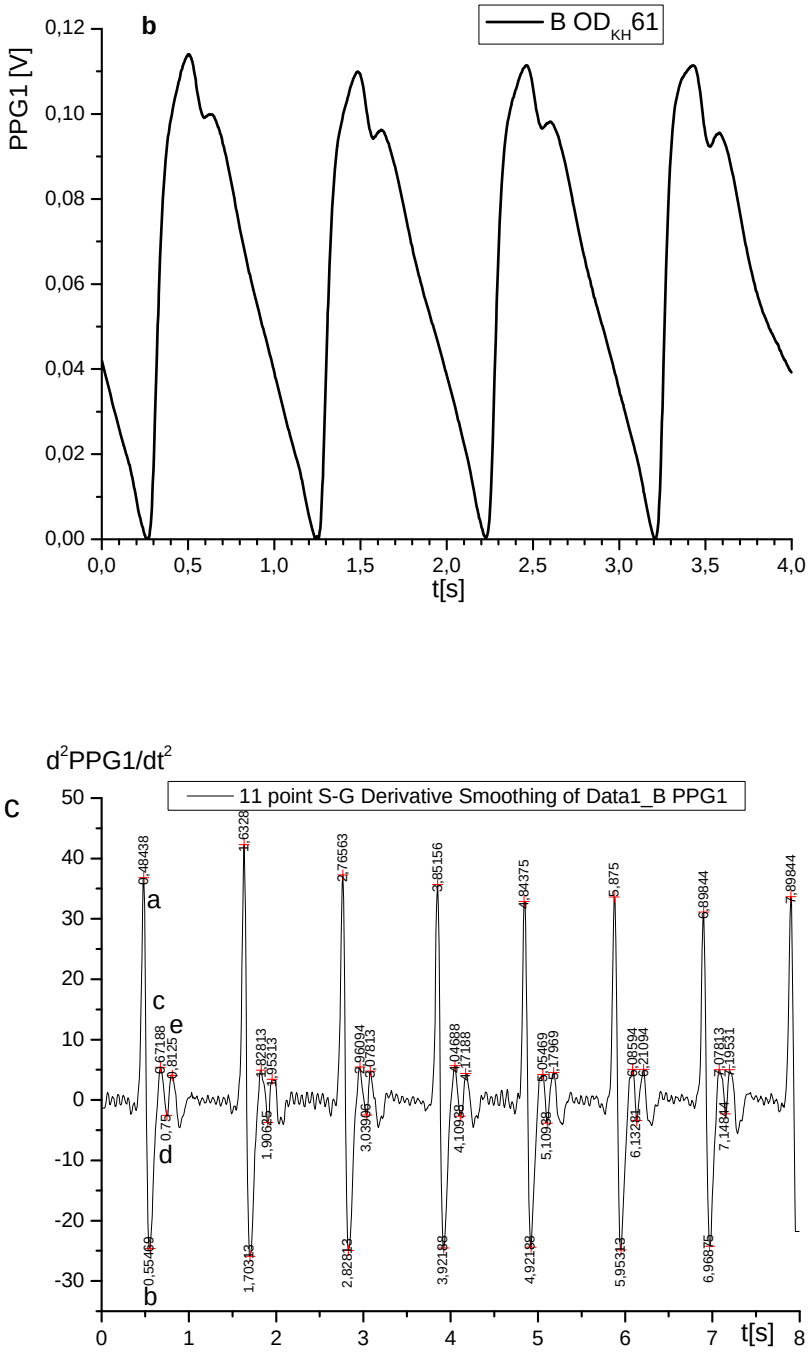

Figure 2. (b) Radial PPGs (PPG1): age 61years male for four seconds. (c) Second derivatives of the radial PPGs (PPG1): age 25 years male for eight seconds, marked with the characteristic values: a, b, c, d and e.

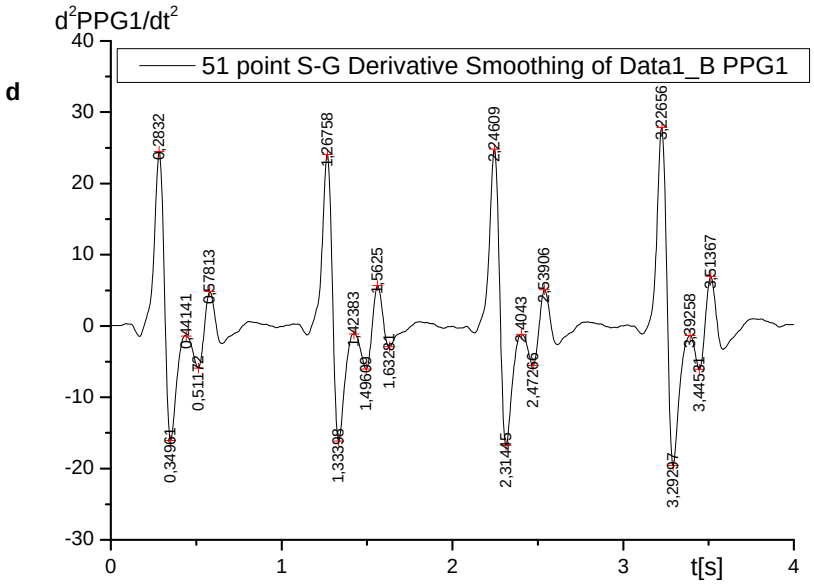

Figure 2. (d). Second derivatives of the radial PPGs (PPG1): age 61years male for four seconds, marked with the characteristic values: a, b, c, d and e.

so called pre-systolic components occur during the end of diastole coming back from the bifurcations and other reflection sites [12].

In Figure 6 it is shown the relative areas to the percussion component area of the PPG pulse wave (Figure 3) as a function of component number. The tidal component clearly deviates from the straight line whereas the percussion, dicrotic, the first pre-systolic and the second pre-systolic component are on the straight line with the correlation coefficient > 0.998.

For further analysis purpose, arterial pulse waveforms from finger (PPG1) and toe (PPG2) were drawn in Figure 7, 8, and 9 (left) with its Lissajous patterns for three male subjects of 5, 37 and 74 years. Parameter values are not fitted to the patterns because there is no theory for this fitting process yet. However, we can see a certain pattern in these figures, namely, an arrow-like part of the Lissajous figure which is similar in the two cases. In the case of 74 years old male the oscillatory part of PPG signals has already disappeared because of age, but otherwise similar. From these pulse wave Lissajous figures, the time lag between the finger and toe wave, or PPG and EMFi wave can be determined at the onset of the rising part of the loop. The results indicate that the finger arteries are much larger than those in the toe arteries in the PPG signals.

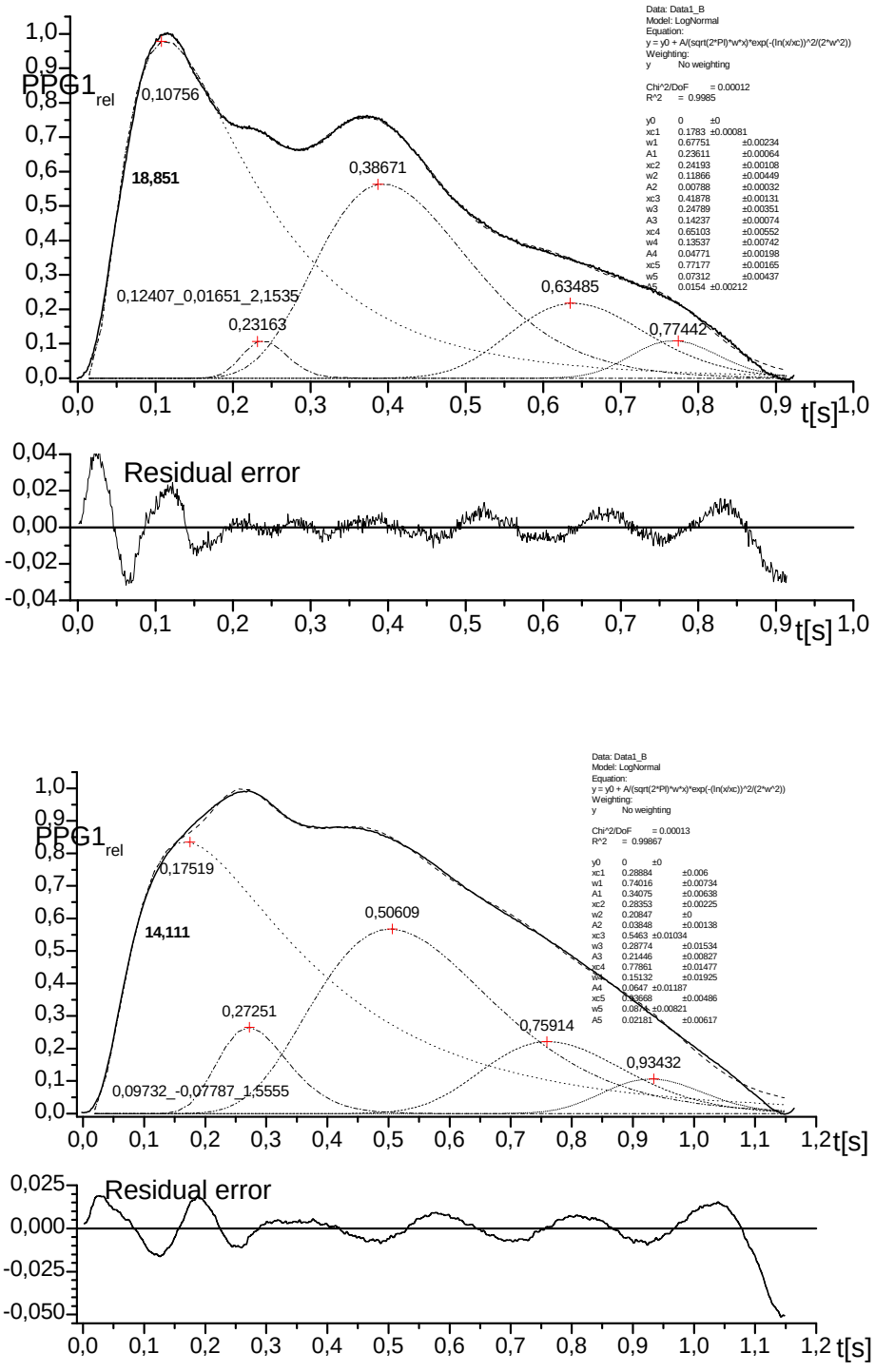

Figure 3. Radial arterial pulse waveforms (above, age 24 male), (below, age 61 male), and (next page, age 70 male) decomposed. The peak value of each component is shown with its ageing index value18.851 for 24 years old, 14.111 for 61 years old, and 12.600 for 70 years old, respectively see Figure 5.

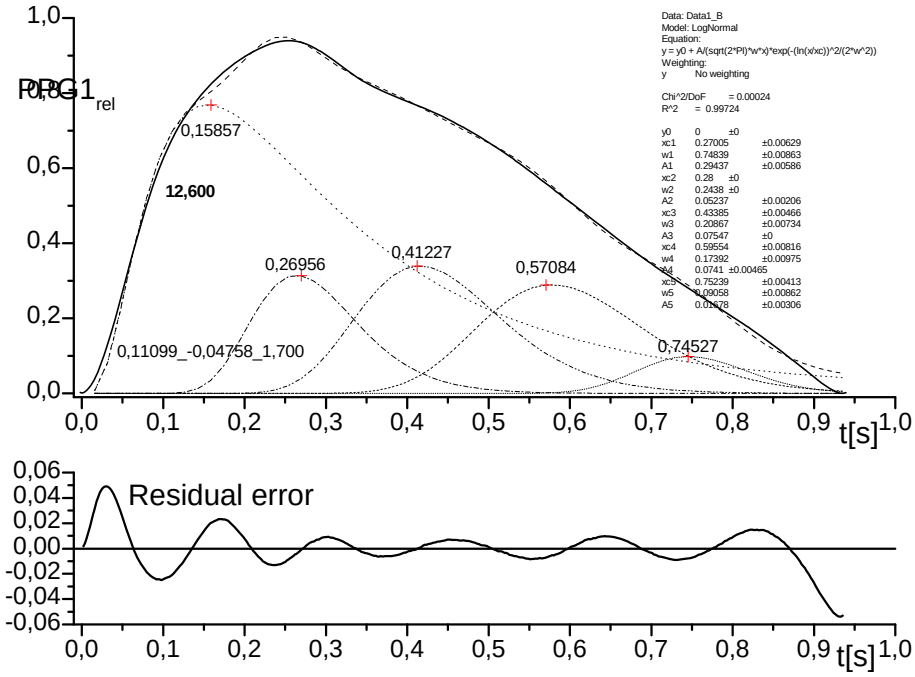

Figure 3 continued. Radial arterial pulse waveforms decomposed, age 70 male. The peak value of each component is shown with its ageing index value18.851 for 24 years old, 14.111 for 61 years old, and 12.600 for 70 years old, respectively see Figure 5.

For analysis purpose a pulse waveform is magnified in Figure 5 so that the peak values of the percussion and tidal components are easier to see for calculation of the ratio of percussion to tidal peak time value. This relation is drawn as a function of their difference for 83 subjects (Figure 10, left). The values fit well to the straight line which shows close relation of these parameters. At the positive end there are the young and at the negative end the elderly subjects. There is a strong concentration of values at the value of 0.5 (=1/2). The line could be used as a measure of arterial stiffness after enough data will be captured. The further investigation would be warranted to see if a predictive index of blood pressure changes might be obtained from pulse wave analysis of PPG waveforms.

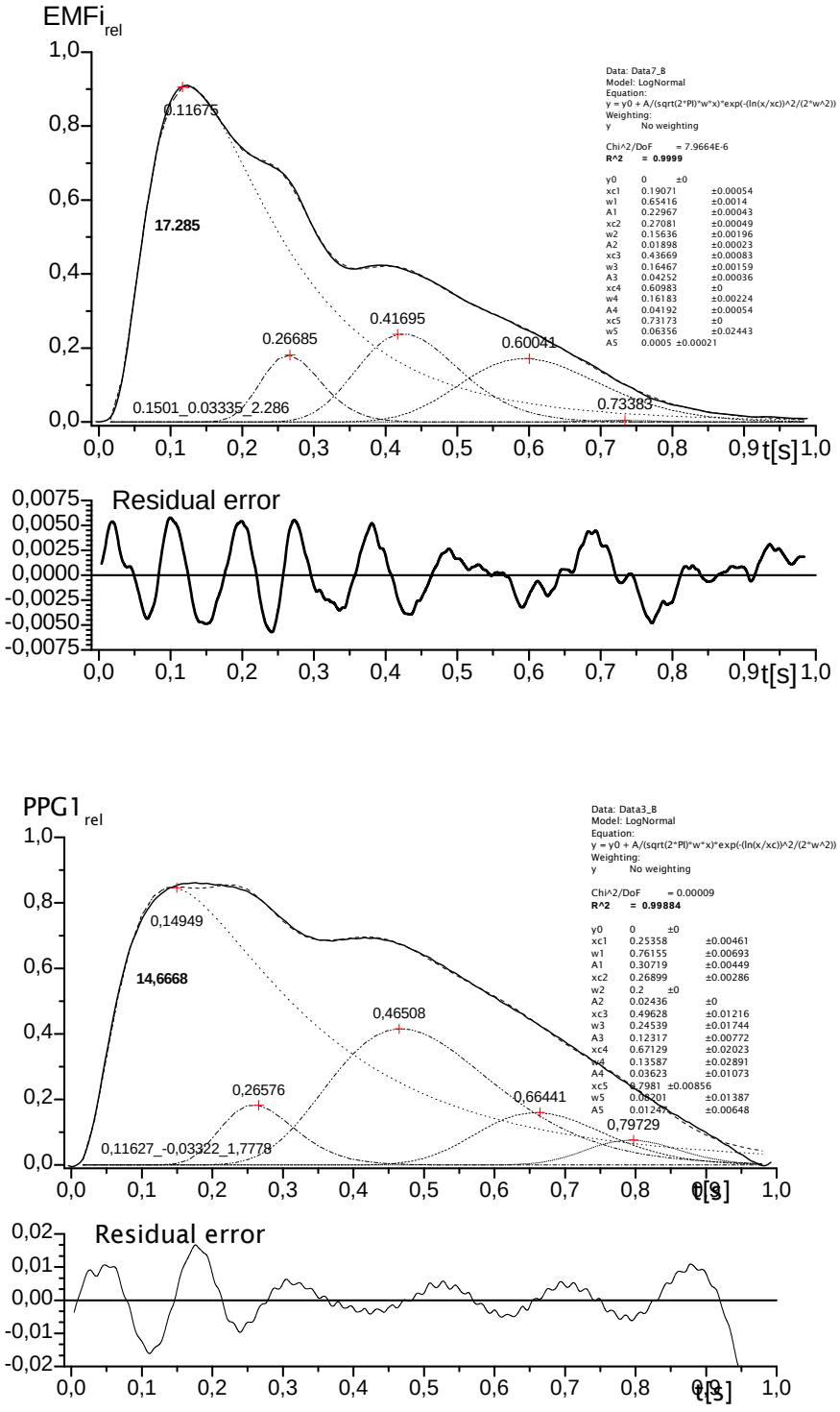

Figure 4. Radial arterial pulse EMFi signal (left) and PPG1 signal (right) of the same pulse wave (age 31 years male) and decomposed. The peak value of each component is shown with its ageing index value 17.286 for EMFi, 14.888 for PPG1, respectively.

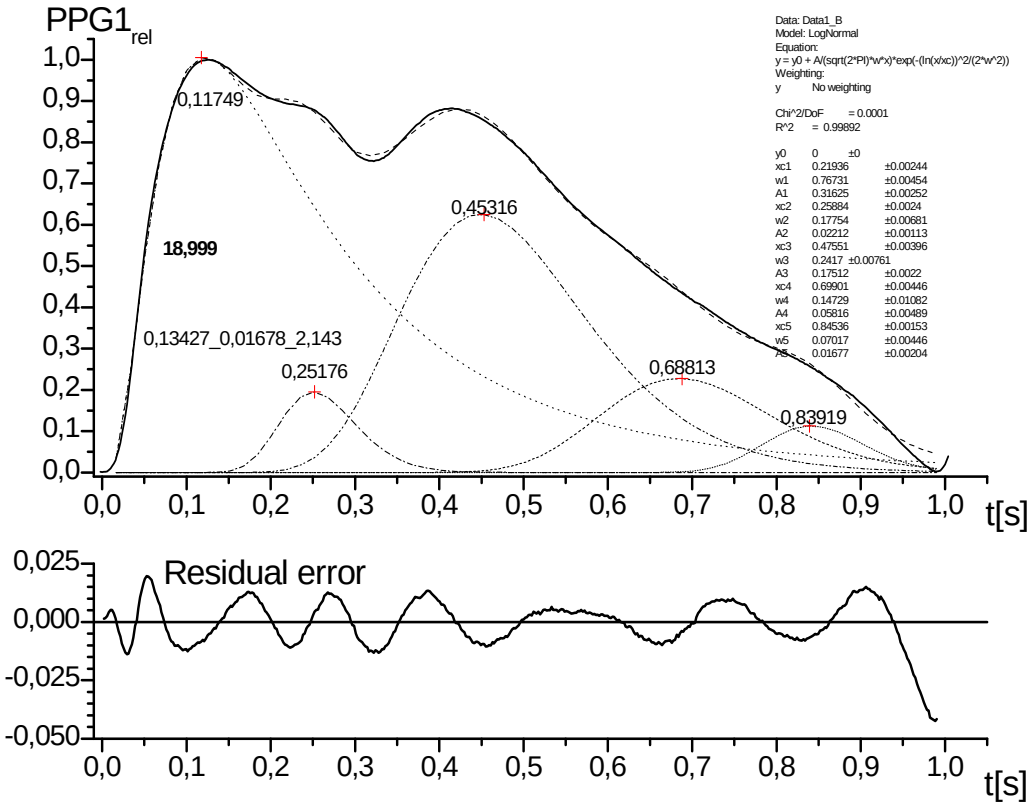

Figure 5. Radial arterial PPG (male, 24 years) with the percussion and tidal time peaks defined and marked. The calculated ageing index AGI2=18.999. The other values are the time interval between the tidal peak time subtracted by the percussion peak time (=0.13427 s), the time difference between percussion and tidal (=0.01678 s), and the ratio of the tidal wave from the start (0) divided by the percussion peak time.

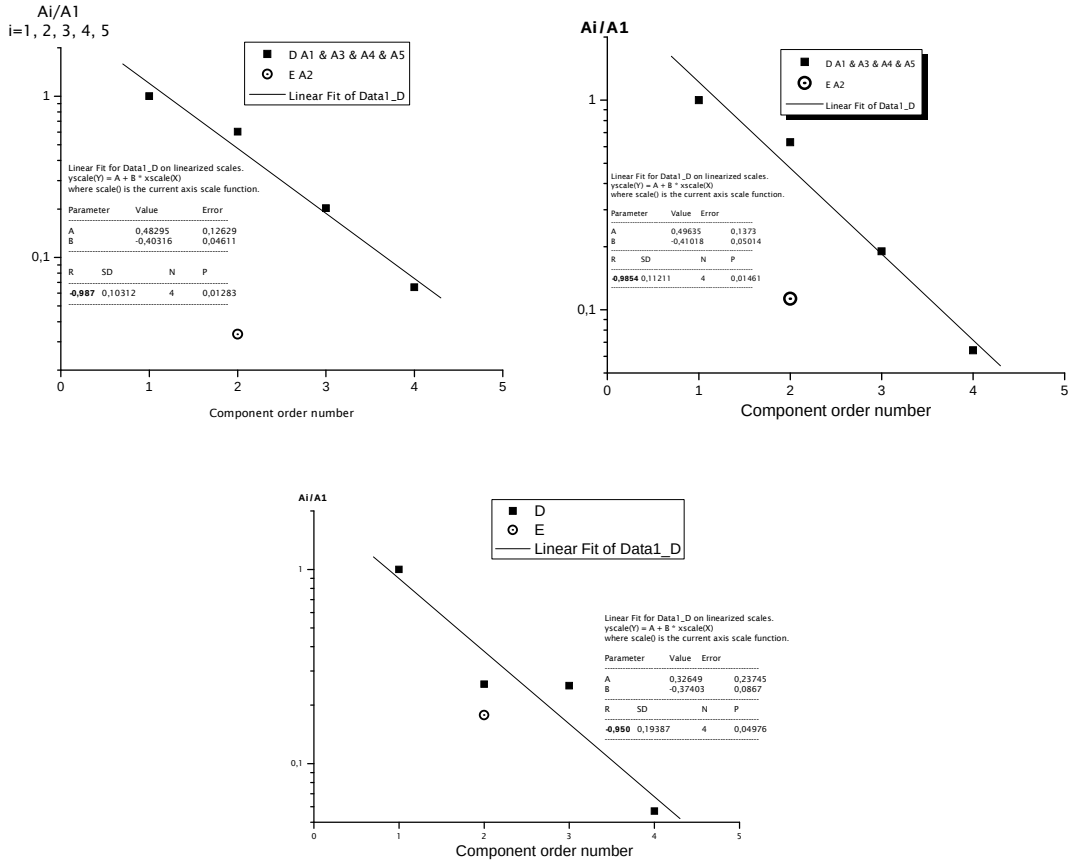

Figure 6. The areas of each component divided by the corresponding percussion component area as a function of component order number for the pulse waves in Figure 3. The tidal component area (o-mark) clearly deviates from the straight line in each case whereas the percussion, dicrotic, the first pre-systolic and the second pre-systolic component areas (black squares) are on the line with the correlation coefficient > 0.988.

The determination of age-related changes in the arterial pulse wave by the high fidelity PPG and EMFMi devices provide important supplementary information to that obtained by use of the blood pressure measurements. The use of these devices enhances new investigations of the effects of ageing and also early CVD states on cardiovascular function. In the future studies, more experiments will be conducted to examine the variation in parameters of logarithmic normal function which were extracted from PPG pulse waveform and radial pulse signals based on percussion, tidal, but also dichrotic wave detection using the technique presented in this paper. The time domain features revealed by the LMA with the logarithmic normal function gives conspicuous information on the arterial pulse waveform with other analysis techniques like first, second, or third derivatives, principal component analysis, or wavelet based analysis [8].

For further analysis, it is drawn the ageing index 1 (second derivative based index, AGI1) as a function of the ageing index 2 (decomposition based index, AGI2) and

human age as a parameter in Figure 11. The straight line has the correlation coefficient 0.96337 which demonstrate very good correlation between different indexes, of which the AGI1 is based on amplitudes of the second derivative and AGI2 is based on peak times of the decomposed arterial pulse wave, respectively.

Though biomechanical studies and controlled methods are needed to further improvement for waveform decomposition presented here, the proposed method can provide for a simple and reliable decomposition method both for the EMFi and PPG pulse waves. Future work is currently under way to investigate on different patients the techniques to improve further the classification of arterial elasticity. The statistical significance of this study grows as we continue to gather new data on subjects from different pathological backgrounds. Here we demonstrated the correlation between vascular ageing so that the both calculated ageing indexes depend on human age very strongly. The second derivative wave can be a useful method to evaluate the vascular ageing. When there is a missing on the characteristic waves of second derivative wave, so it would be possible to use the other ageing index based on the decomposed arterial pulse wave. As a conclusion the heart pulse waveform can be divided into five pulse wave components, but there can exist more in some cases depending on the person's vascular system.

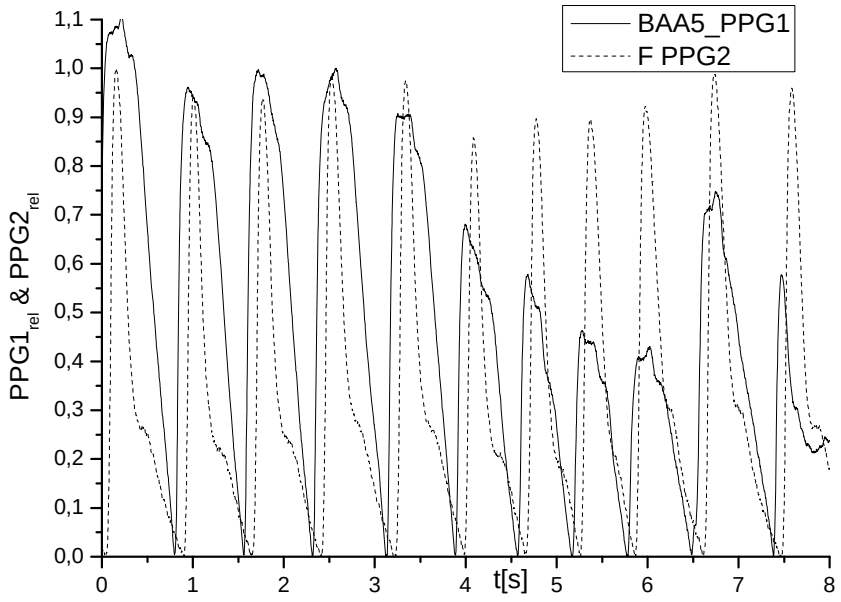

Figure 7. Arterial pulse waveforms from finger (PPG1) and toe (PPG2) with the second derivative of the finger PPG (next page, top) with their Lissajous patterns (next page, bottom) for a male subject of 5 years.

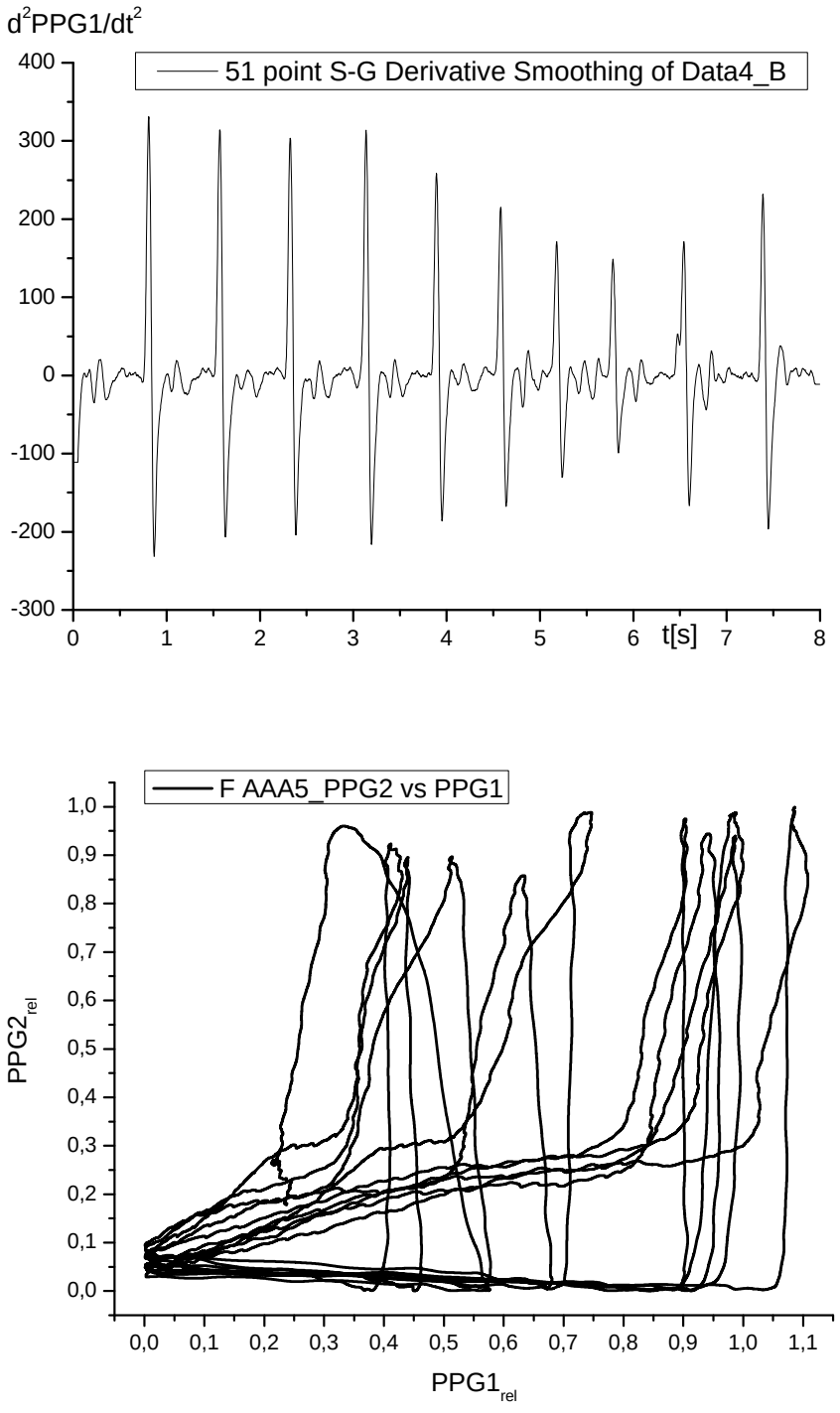

Figure 7 continued. Arterial pulse waveforms from finger (PPG1) and toe (PPG2) (previous page) with the second derivative of the finger PPG (top) with their Lissajous patterns (bottom) for a male subject of 5 years.

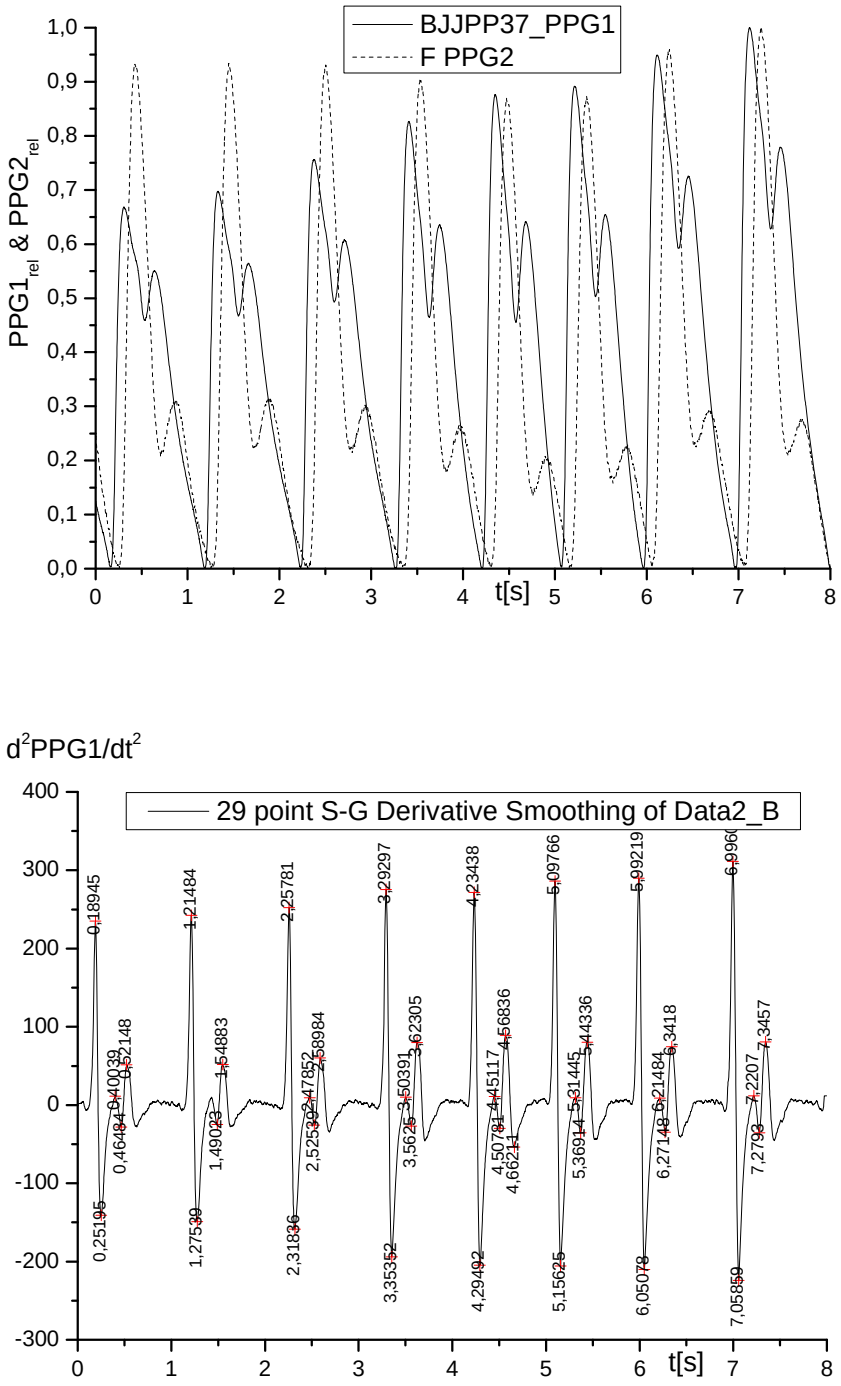

Figure 8. Arterial pulse waveforms from finger and toe (top) with the second derivative of the finger PPG (bottom) with the Lissajous patterns (next pages) for a male subject of 37 years.

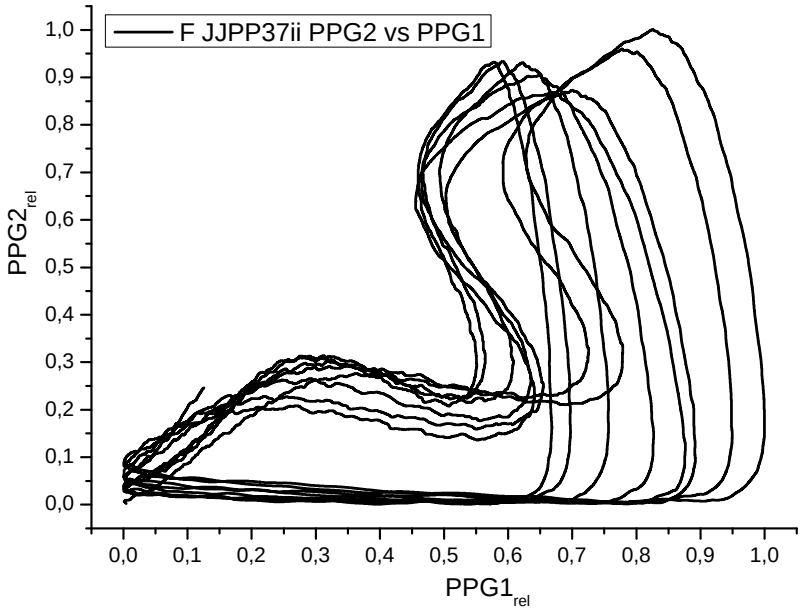

Figure 8 continued. Arterial pulse waveforms from finger and toe (previous page, top) with the second derivative of the finger PPG (previous page, bottom) with the Lissajous patterns for a male subject of 37 years.

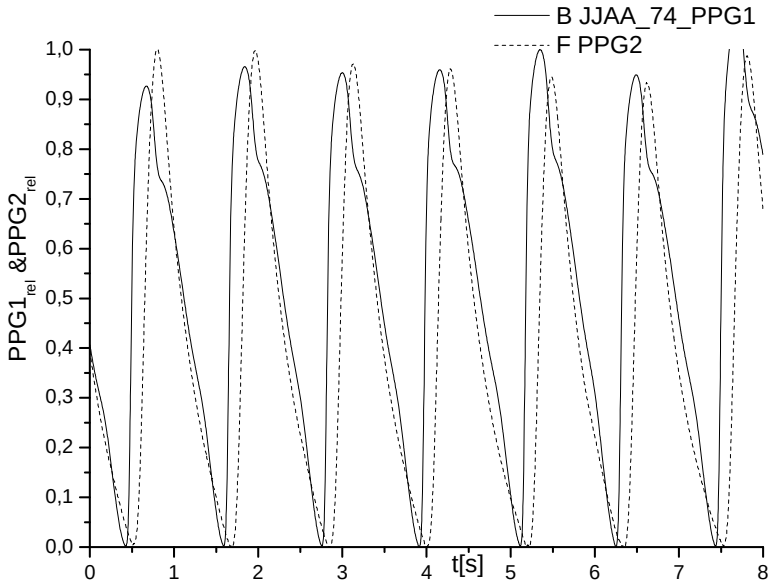

Figure 9. Arterial pulse waveforms from finger and toe with the second derivative of the finger PPG (next page, top) with the Lissajous patterns (next page, bottom) for a male subject of 74 years.

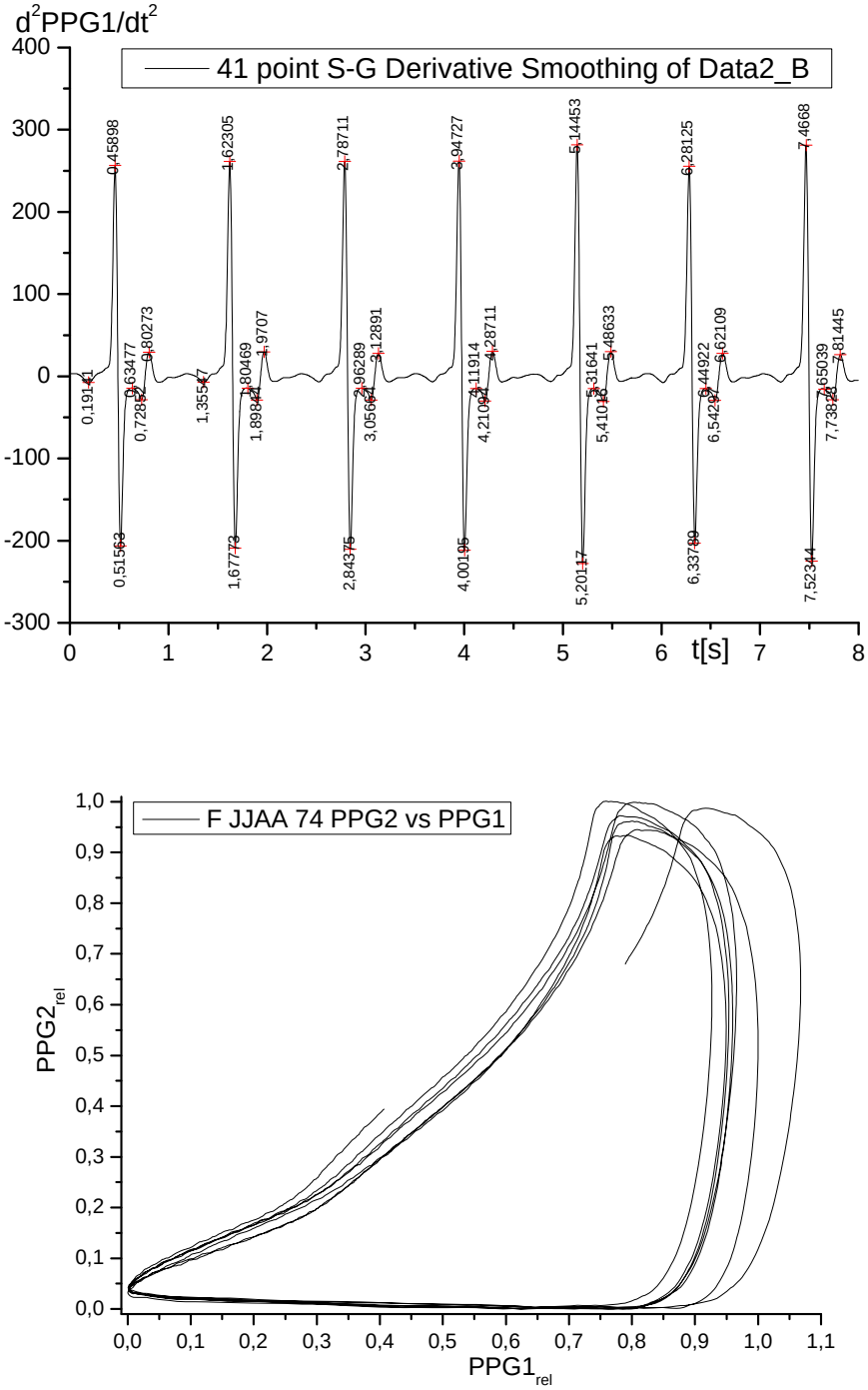

Figure 9. Arterial pulse waveforms from finger and toe (left) with the second derivative of the finger PPG (middle) with the Lissajous patterns (right) for a male subject of 74 years.

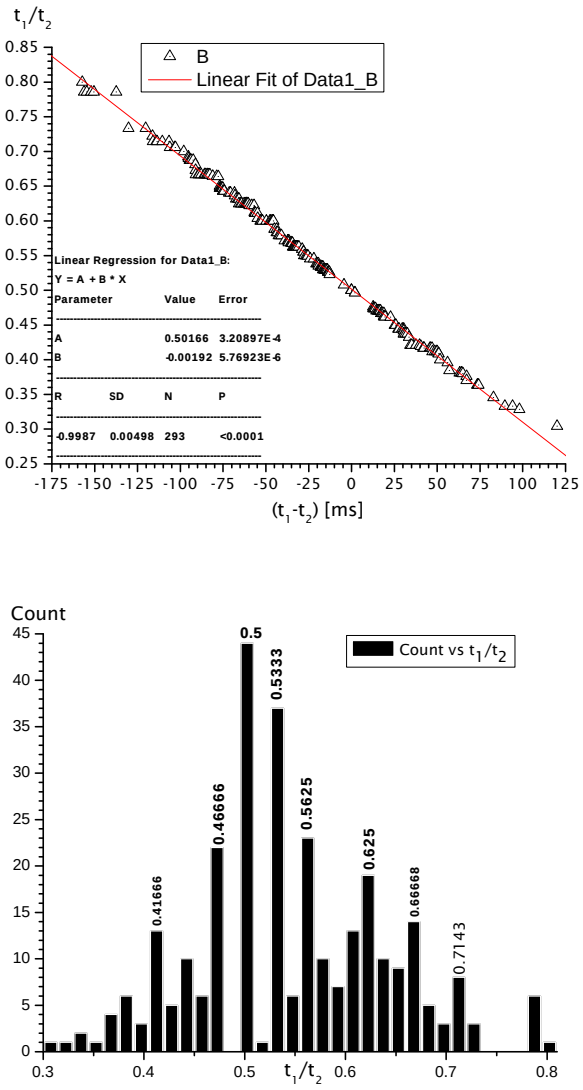

Figure 10. Percussion peak time is divided by tidal component time from the start of each pulse wave as a function of the difference between the tidal wave peak time (from the start of each pulse wave) and percussion wave peak time (left) and the histogram of the count of t_1/t_2. Note that the maximum is at the point 0.5=1/2 and the nearest to it the values =0 and t_2 the time from the start of pulse wave to the peak of the tidal component. Other peaks are also found in this dataset.

Acknowledgment

This study was supported by the Finnish Cultural Foundation to MH and we thank the all volunteers.

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