Continuous non-invasive blood pressure during continuous repositioning by pulse transit time

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Hieyong Jeong1*, Kayo Yoshimoto2, Tianyi Wang3, Takafumi Ohno1, Kenji Yamada1, Michiko Kido3 and Yuko Ohno1,3

Abstract: The purpose of the present study was to propose a method to measure continuous non-invasive arterial pressure (CNAP) of severely handicapped patient during continuous repositioning. We have been interested in healthcare for severely handicapped children. Although their long stay in hospital could be led to a circulatory disorder or a serious secondary disease, there was little way to give an adequate healthcare service for them due to several kinds of side effects. Thus, we developed the non-invasive sensor system to measure pulse transit time (PTT) through the different output signal between the two different measuring points. The proposed extended model of algorithm enabled us to measure continuous blood pressure (BP) with the measured PTT. The algorithm considered the influence of gravity on BP; there was no need to re-tune the system even if the posture of patient was changed. We performed the continuous repositioning experiment from the supine posture to 45 or 75° postures after the effectiveness of the proposed algorithm was confirmed. Through experimental results, it was found that the proposed method has the strongest correlation with commercial BP device. The experimental results showed that it was possible for the proposed algorithm to measure CNAP during continuous repositioning without the re-tune of system. It

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PUBLIC INTEREST STATEMENT
A child with severe mental and physical handicaps stays in bed all his or her life. A long bed stay causes a lot of side effects: bed sore, sarcopenia, circulatory defect, etc. We let a severely-handicapped child start a light exercise in order to prevent side effects such as bedsores and symptoms of sarcopenia. However, the child is easy to produce an orthostatic hypotension. Thus, it is important that severely handicapped children have a need to measure the continuous blood pressure during the exercise. Although the proposed method of the present study was similar to expensive conventional device in terms of focused point, the conventional device had a week point to re-tune the system whenever the body posture was changed. We would like to emphasize that our model of algorithm showed the originality to measure continuous non-invasive blood pressure (CNAP) during continuous movement without any re-tune of system.
was recommended that some points of developed prototype hardware were necessary to be improved and the integration of other bio signals was more helpful for providing important insight into the overall physical condition.

Subjects: Acute Care; Aging; Assistive Technology; Children and Youth; Disability; Electrocardiology; Nursing Older People; Rehabilitation Medicine

Keywords: continuous non-invasive blood pressure; pulse transit time; pulse wave velocity; severely handicapped children; side effects

1. Introduction

Severe motor and intellectual disabilities (SMID) syndrome is a term used in Japan and was developed from considerations of social welfare. Most children with SMID have a severe generalized form of cerebral palsy, resulting from abnormal brain development or brain damage in early development (pre- or perinatally). Apart from their cognitive and motor impairments, children with SMID are at risk of developing several additional health problems. The number of children with SMID diagnosed each year have been increasing (Ministry of Health, Labour & Welfare in Japan, 2008). It is well known that they are susceptible to bedsores (Roy, Basmajian, & Asada, 2005). They confined to the bed for a long period of time need to be periodically turned and repositioned to avoid painful bedsores and pneumonia (Courtney & Elizabeth, 2008). Their long stay in hospitals due to these secondary ailments amounts to monetary damage of up to USD 55 billion per year (Cost Savings Through Bedsore Avoidance [Online], 1997). Bedsores are formed due to lack of blood perfusion caused by local pressure concentrations on a patient’s body. Viral pneumonia is the result of lower respiratory infection and has been the cause of more than 90% of deaths for individuals over 65. Stagnant mucus in the lower airways is a medium for bacterial growth, should pathogens reach the lower airways. An effective remedial measure is to reposition the patient at regular intervals to ensure frequent pressure redistribution (Roy, Basmajian, & Asada, 2005). Routine turning and repositioning also assist in mobilization of secretions. The current practice in hospitals and nursing homes relies heavily on nursing personnel. Every two to four hours, each patient is rolled onto one side and rolled back to the other side. This is a fairly labor-intensive task requiring at least two caregivers for each patient. There is an acute shortage of nursing personnel and the current workforce frequently suffers back injuries which cost up to USD 24 billion every year (June & Cho, 2011). The more serious difficult thing is that children have also some risk of side effects such as the sickness, pyrexia, palpitation, an irregular pulse, and so on during the repositioning of body through the change of blood pressure. It is necessary for the bio signal to be checked because the direction of gravity gives an influence on a child’s physical condition (Jennifer, Delphine, Jean-Piere, Yves, & Abdul, 2013). The blood supply to the heart is reduced when a person stand up because the arterial pressure amount of 500~800 ml is moved to the abdomen and lower limb, and then the activity of arterial pressure control organ decreases. Generally, it is known that the normal value of blood pressure is maintained by the sympathetic nerve, the increase of pulse, and the cardiac contractile function when a person is health (Jennifer et al., 2013). However, symptoms including sickness, palpitation, and so on are occurred when the lowered value of arterial pressure does not recover to the normal value (Japanese Circulation Society, 2012). Thus, it is important that severely handicapped children have a need to measure the continuous blood pressure during the repositioning of body. A continuous measurement of blood pressure is desirable for consistent patient care and monitoring (Rasmussen & Laumann, 2012).

Meanwhile, from a public health perspective, regular exercise can play a major in preventing several leading degenerative diseases in industrialized societies. Although most degenerative diseases such as coronary artery disease manifest themselves in adulthood, their genesis may be traced to unhealthy behaviors in earlier years (Williams, 1993). The proper amount of exercise is presumably important for the optimal development and health status of children. Too little exercise may have some adverse effects (Rasmussen & Laumann, 2012). Unfortunately, it seems to be impossible that severely handicapped children have enough amount of exercise. Although caregivers or nurses figure out the necessity to exercise them, it is practically difficult because their physical condition can be worse suddenly during
the repositioning from the supine to the sitting. Besides, there is the case which the blood pressure may be decreased temporarily by the mental or psychological problem. Nevertheless, because it is important to keep small attempts, we would like to emphasize the need of continuous non-invasive bio signal device in order to provide important insight into their overall physical condition.

Therefore, the purpose of the present study was to propose a new method to measure continuous non-invasive arterial pressure (CNAP) of severely handicapped patient during continuous repositioning in order to check the physical condition. We developed the non-invasive sensor system to measure pulse transit time (PTT) through the different output signal between the two different measurements. The proposed algorithm considered the influence of gravity on blood pressure (BP); there was no need to re-tune the system even if the body posture of patient was changed. Through experimental results, it was found that the proposed method has the strongest correlation with commercial BP device. The results showed that it was possible for the proposed algorithm to measure CNAP during continuous repositioning without the re-tune of system.

The sections of the present paper are ordered as follows. In Section 2 we describe unresolved points in conventional research while reviewing conventional research. In Section 3 we derive a new proposed method with the consideration of the influence of gravity on BP and explain the developed prototype sensor system. Section 4 deals with measured results during continuous repositioning. In Section 5 improving points of developed prototype hardware are discussed. Finally, we conclude this paper to show the effectiveness of proposed method.

2. Conventional research

CNAP is the method of measuring arterial blood pressure in real-time without any interruptions (continuously) and without the direct cannulation into the human body (non-invasive). CNAP combines the advantages of the following two clinical standards: it measures BP continuously in real-time like the invasive arterial catheter system and it is non-invasive like the standard upper arm sphygmomanometer. There have been three methods for current CNAP technologies (Continuous noninvasive arterial pressure, 2015): vascular unloading technique, tonometry, and PTT. Vascular unloading technique is to unload the arterial wall in order to linearize this phenomenon with a counter pressure as high as the pressure inside the artery (Fortin et al., 2006; Justin & Peggy, 2015; Pivovarov, 2006; Spiroarteriocardiorhythmograph system, 2004; Tanaka, Nogawa, Yamakoshi, & Yamakoshi, 2007). Tonometry is the resurrection of the old sphygmograph technology as it again describes a mechanism for the automatic noninvasive palpation on the arteria radialis (Hypertension Diagnostics TM, 2013). In order to obtain a stable BP signal, the tonometric sensor must be protected against movement and other mechanical artifacts.

It is commonly accepted that PTT is correlated with BP (Jeong et al., 2014) and a number of commercial BP monitors use PTT to infer BP. When the heart ejects stroke volume to the arteries, it takes a certain transit time until the blood volume reaches the periphery. This circumstance can be used for the non-invasive detection of BP changes (Josep, 2011; Meigar, Kattai, & Lass, 2001; Soller, Zou, Prince, et al., 2016; Teng & Zhang, 2003; ViSi Mobile System, 2015; Watkins, Whisman, & Booker, 2015). The typical device which has developed by ViSi mobile (ViSi Mobile System, 2015) provides direct access to vital parameters, early detection to avoid complications, and rapid response at the bedside. It continuously monitors all core vital signs and provides patient information to the clinician whenever wanted and whenever needed.

Although the proposed method of the present study based on PTT was similar to conventional research, we would like to emphasize that our model of algorithm showed the originality to measure CNAP during continuous repositioning without any re-tune of system even if the body posture of patient was changed. That point was the unsolved point in conventional research. Thus, without any extra re-tune of system, the proposed model could measure CNAP during continuous repositioning. Besides, our device did not have any restrictions for measuring points in order to cope with individual difference, and the only one time calibration was conducted during the supine posture.
3. Human subjects and methods

3.1. Human subjects and experimental procedure

Figure 1 showed an overview of experimental environment. All of participants were twenty females in their early 20s without any disease (age: 22 ± 3 years old, Body mass index (BMI): 21 ± 4.5 kg/m²). The change of body posture was regulated by the motorized adjustable bed (XVA131630 TAIS/00367-000230, PANASONIC). Figure 2 showed the experimental procedure. At first we measured CNAP during the supine posture for 5 min, then after we regulated her body posture to 45 or 75° postures during 30 s, we also measured CNAP for 5 min, and finally after we regulated her posture to the supine, we measured CNAP for 5 min. For comparison with the commercial BP device (HEM7120, OMRON), we measured BP for each interval of 30 s as shown in Figure 2.

In accordance with the regulation set forth by the Human Studies Committee of Osaka University, informed consent was obtained from all participants and from a parent or guardian of all subjects of less than 18 years of age (No. 265, June 20, 2013).

3.2. Prototype sensor system

Figure 3 showed a concept of measurement system for BP. We used that photoplethysmography (PPG) was one such technique, which could be used to predict many vital health concerned parameters. It was reported that non-invasive, cuff-less, and continuous measurement of BP could be done using this technique (Reisner, Shaltis, McCombie, & Asada, 2008; Shamir, Eidelman, Floman, Kaplan, & Pizov, 1999). It used an Infrared Light Emitting Diode (IR LED) and a corresponding photodiode to measure small blood volume changes in the arteries.
Figure 4(a)–(c) showed a circuit diagram of PPG measuring system of the present study. The circuit consisted in three equipment: (a) light emitting section (PT23G, KODENSHI CORP.), (b) light receiving section (EL23G, KODENSHI CORP.), (c) power section with a DC-DC converter (SUCW60512C, COSEL).
Figure 5. A developed prototype sensor system to measure PTT.

Figure 6. Photos of attaching sensors on the earlobe and the sternoclavicular joint.
The earlobe and sternoclavicular joint as shown in Figure 3 were illuminated with the IR LED and the transmitted light was detected using the photodiode. The photodiode generated a current which was proportional to the intensity of light falling on it. This photo generated current was converted to voltage using a transimpedance amplifier. The signal obtained needed conditioning as it had very small amplitude and was also infested with a huge amount of noise. So, this signal was amplified using an inverting amplifier. To filter out the noise, active low pass filter of cutoff frequency 20 Hz was used.

Figure 5 showed the developed prototype sensor system to measure PTT, and Figure 6 showed photos of attaching sensors. The size of sensor attaching on the earlobe and the sternoclavicular joint was 10 mm × 200 mm, and the size of prototype board was 100 mm × 800 mm, respectively. All of measured data were analyzed by the computer with the sampling time of 1 kHz.

3.3. Definition of PTT in the present study

Figure 7 represented an explanation for definition of PTT in the present study. Top plotted graphs (Figure 7(a)) showed measured raw data before band pass filtering of 0.5~2.0 Hz, and bottom plotted graphs (Figure 7(b)) showed filtered data, respectively. The band pass filter removed the noise of the breathing or fetal movements. The green plot indicated data of sternoclavicular joint, and the blue plot indicated data of earlobe, respectively. Because two data represented values of capillary blood vessel, there was the difference of definition between the present study and the conventional research. Thus, PTT of the present study was calculated by the difference of peak-to-peak time between the two different plotted lines in the dotted red box. We defined PTT as averaged value during 30 s. For example, average value of bottom graph in Figure 7(b) was 0.116 ± 0.081 s. We could calculate the systolic blood pressure (SBP) through measured data of PTT.
3.4. Algorithm without the consideration of influence of gravity on BP

In this section we derived the relationship between BP and PTT without the consideration of influence of gravity on BP. The algorithm had to re-tune the system whenever the body posture of patient was changed.

The Moens–Korteweg equation was often employed in BP calibrations, describing the relationship between BP and pulse wave velocity (PWV). It assumed that PWV in a short elastic vessel was obtained from its geometric and elastic properties and given by:

\[
PWV = \sqrt{\frac{Eh}{\rho2r}} \tag{1}
\]

where \(E\) related to the elasticity modulus of the vessel wall, \(h\) was its thickness of blood vessel, \(\rho\) was the density of blood, and \(r\) was the radius of the vessel (Chen, Kobayashi, Ichikawa, Takeuchi, & Togawa, 2000; Hirata, Kawakami, & O’rourke, 2006; McCarthy, O’Flynn, & Mathewson, 2011; Proenca, Muehlsteff, Aubert, & Carvalho, 2010; Saarakkala et al., 2004). It has been noted that the elastic modulus of the vessel increases exponentially with increasing BP. BP and PWV were interconnected by the relationship between the elasticity and BP (Badeer, 2001):

\[
E = E_0 e^{\alpha BP} \tag{2}
\]

where \(E_0\) was the elastic modulus at zero pressure, BP was the systolic blood pressure mm Hg and \(\alpha\) was a coefficient ranging from 0.016 to 0.018 mm Hg\(^{-1}\). Pressure in this case was the mean arterial pressure (MAP). PTT was related to PWV by:

\[
PWV = \frac{d}{PTT} \tag{3}
\]

where \(d\) was a proportional coefficient, indicating the distance that the pulse had to travel between the two measuring points.

The parameters involved in the equations were subject-dependent and not easily measurable. Based on these equations calibration functions could be derived to translate PTT to BP assuming constant vessel thickness and radius. By combing both equations that substitute Equations (3) and (2) into (1), we achieved a logarithmic dependency:

\[
BP = C_1 \ln \frac{r}{PTT^2} + C_2 \tag{4}
\]

where \(C_1\) and \(C_2\) represented constants which were dependent on vessel stiffness, elastic modulus of individual difference. Because both constants of \(C_1\) and \(C_2\) were changed by the different posture of body, two constants could be decided by the initial calibration from measured values. The value of \(r\) in the present study was 7 mm which was standard level of blood vessel near the sternoclavicular joint. The value of \(d\) was the distance of 0.3 m between the two measuring points. It was emphasized that blood pressure was actually regulated by additional factors such as cardiac output, contractility, peripheral resistance and cardiac preload (Proenca et al., 2010).

The model of Equation (4) did not consider the influence of gravity on BP. Thus, according to each body posture, the model of Equation (4) was necessary to re-tune the system during minimum 10 min for measurement of 20 times PPT (Because it took 30 s for one PPT in the present study,) in order to decide two constants of \(C_1\) and \(C_2\). Our main target was severely handicapped children. It was necessary to measure CNAP for different posture with the only one-time re-tuning of the supine posture. Thus, we needed to adapt Equation (4) for the purpose of present study.
3.5. Algorithm with the consideration of influence of gravity on BP

In this section we derived the relationship between BP and PTT with the consideration of influence of gravity on BP. The algorithm did not have to re-tune the system whenever the body posture of patient was changed. Namely the only one-time re-tuning of system during the supine posture could cover all of body posture in order to apply to severely handicapped children.

We considered the radius of blood vessel and gravity as possible factors to affect BP in the present study. Although the radius of blood vessel could be calculated by the relationship between BP of vertical direction to blood vessel and force exerted on blood vessel, the problem was how to decide BP of vertical direction to be changed by the gravity. Here, focusing on the actual measuring point of capillary vessel, we showed the way to decide the relationship between BP of vertical direction to the blood vessel and the gravity by using Bernoulli’s equation.

The conventional work done by the pulse wave (Proenca et al., 2010) could be expressed in terms of the kinetic energy of the wave and the gravitational potential energy:

\[ F_v \cdot d = \frac{1}{2} mv^2 + mgz \]  
(5)

where \( F_v \) was the force exerted on blood wall, \( d \) was the distance between the two measuring points, \( m \) was the mass of blood, \( v \) was PWV, \( g \) was the value of acceleration due to gravity, and \( z \) was the elevation of the point above a reference plane, with the positive \( z \) direction pointing upward.

Assuming that there was little potential energy (\( mgz \approx 0 \)) by blood mass, Equation (5) could be written:

\[ F_v = \frac{1}{2d} mv^2 = \frac{md}{2} \cdot \frac{1}{PTT^2} \]  
(6)

BP\(_v\), of vertical direction to the blood vessel was defined by:

\[ BP_v = \frac{F_v}{2\pi r^2} = \frac{md}{4\pi r^2} \cdot \frac{1}{PTT^2} \]  
(7)

where \( r \) was the radius of blood vessel. When we could regard \( BP_v \), as the constant, the relationship between \( r \) and PTT was from Equation (7):

\[ r = \sqrt{\frac{md}{4\pi BP_v}} \cdot \frac{1}{PTT} = \frac{C}{PTT} \quad (C = \text{constant}) \]  
(8)

Then, we needed to decide the particular condition which we could consider \( BP_v \), as the constant in some cases. Assuming that the blood flow was the inviscid and incompressible flow, a common form of Bernoulli’s equation, valid at any arbitrary point along a streamline, was (Badeer, 2001):

\[ \frac{1}{2} v_1^2 + gz_1 + \frac{BP_{v1}}{\rho} = \frac{1}{2} v_2^2 + gz_2 + \frac{BP_{v2}}{\rho} \]  
(9)

where \( \rho \) was the density of the blood at all points in the fluid. Here, the subscript number of 1 and 2 indicated two different measuring points. In the present study we measured the value of capillary vessel near the skin surface as shown in Figure 6. Focusing on actual measured values of capillary vessel between the two measurements as shown in Figure 7(b), we could decide that there was little difference between \( v_1 \) and \( v_2 \) \((v_1 = v_2)\). Thus Equation (9) could be re-written:

\[ BP_{v1} = BP_{v2} + \rho g z_2 \quad (z_1 = 0) \]  
(10)
Equation (10) represented \( BP_{v_1} - BP_{v_2} = \rho g z_2 = \text{Constant} \). Thus when there was little difference of measured value between the two measuring points, we could use Equation (8) as the relationship between \( r \), the gravity, and PTT (namely \( v_1 = \frac{d}{\text{PTT}_1} \) was similar to \( v_2 = \frac{d}{\text{PTT}_2} \)).

By combining both Equations of (4) and (8), we achieved a logarithmic dependency:

\[
BP = C_3 \ln \frac{1}{\text{PTT}_3} + C_4
\]

(11)

where the value of \( C_3 \) and \( C_4 \) indicated the slope of calculated plot line, and the \( y \)-intercept of graph, respectively.

At first we could calibrate two constants of \( C_3 \) and \( C_4 \) one time during the supine posture. After that, because \( C_3 \) was not changed while the body posture was changed, we could decide \( C_4 \) by calculating the average value of measured PTT as the definition of PTT in the present study. Of course the parameters involved in Equation (11) were subject-dependent. Based on these equations, calibration function could be derived to translate PTT to BP assuming constant vessel thickness, inviscid/incompressible flow, and measuring points of capillary vessel.

The model of Equation (11) considered the influence of gravity on BP. Thus, even if the body posture was changed, the model of Equation (11) was not necessary to re-tune the system.

4. Results

4.1. Correlation between PTT and SBP

4.1.1. Algorithm without the consideration of influence of gravity on SBP

Figure 8 showed experimental results of measurement under the condition of supine, 45 and 75° through the model without the consideration of influence of gravity on SBP in Equation (4). The horizontal axis represented \( \ln \frac{0.007}{\text{PTT}} \), and the vertical axis represented values of SBP, respectively. All of measured data were interpolated by the least squares method. The blue line indicated results of supine, the red line indicated results of 45°, and the green line indicated results of 75°, respectively:

Supine:

\[
\text{SBP} = 6.98 \times \ln \frac{0.007}{\text{PTT}} + 119 (p < 0.01)
\]

45°:

\[
\text{SBP} = 10.8 \times \ln \frac{0.007}{\text{PTT}} + 123 (p < 0.01)
\]

75°:

\[
\text{SBP} = 21.9 \times \ln \frac{0.007}{\text{PTT}} + 137 (p < 0.01)
\]

The averaged error was 2.20 ± 1.90 mm Hg (supine), 2.36 ± 2.75 mm Hg (45°), and 1.69 ± 1.48 mm Hg (75°). However, although measured results showed the high correlation between SBP and PTT, this algorithm had a limitation to re-tune the system whenever the body posture was changed (Soller et al., 2016; Teng & Zhang, 2003). That was the reason why we had to consider the influence of gravity on BP in order to apply to the repositioning severely handicapped children.
The algorithm of Equation (4) is useful for the bedridden patient with cardiac heart failure which is necessary to regulate the physical condition every day for optimized medicine treatment.

4.1.2. Algorithm with the consideration of influence of gravity on SBP

Figure 9 showed experimental results of measurement under the condition of supine, 45, and 75° through the model with the consideration of influence of gravity on SBP in Equation (11). The horizontal axis represented $\ln \frac{1}{\text{PTT}^3}$, and the vertical axis represented values of SBP, respectively. All of measured data were interpolated by the least squares method. The blue line indicated results of supine, the red line indicated results of 45°, and the green line indicated results of 75°, respectively:

Supine:

$$\text{SBP} = 4.70 \times \ln \frac{1}{\text{PTT}^3} + 84.5 (p < 0.01)$$

45°:

$$\text{SBP} = 4.70 \times \ln \frac{1}{\text{PTT}^3} + 82.3 (p < 0.01)$$

75°:

$$\text{SBP} = 4.70 \times \ln \frac{1}{\text{PTT}^3} + 81.5 (p < 0.01)$$

The averaged error was $2.19 \pm 1.90$ mm Hg (supine), $2.61 \pm 2.92$ mm Hg (45°), and $3.02 \pm 1.63$ mm Hg (75°). Our results showed that the result of supine was much larger than that of 45°, and that of 45° was larger than that of 75°, because of blood movement of approximately 500~800 ml to abdomen and lower limb during the standing (Jennifer et al., 2013).

The algorithm of Equation (11) is useful for the bedridden patient with the necessity of repositioning. Accordingly we anticipate contributing to exercise severely handicapped children regularly by monitoring the physical condition.

Figure 8. Results of measurement under the condition of supine, 45 and 75° through the algorithm without the consideration of influence of gravity on SBP.
4.2. Continuous measurement during continuous repositioning

Figure 10 showed the experimental results of estimated SBP data and measured PPT data. Figure 10(a-1) and (b-1) showed experimental results of non-invasive periodical SBP estimation during the continuous change from supine to sitting position (45 and 75°) by using the proposed method, and Figure 10 (c-1) showed results during the change from 75° sitting position to supine. Figure 9(a-2), (b-2), and (c-2) showed measured PPT data for estimating SBP. The horizontal axis of each graph...
represented the one period per 30 s, and the vertical axis represented the estimated SBP averaged value and standard deviation, respectively. During the final period of 270~300 s, we measured SBP by using the commercial SBP device for the comparison with estimated SBP data.

Although there was a little difference of estimated SBP at the moment that the body position was changed by the robotic bed within three periods of 90 s, we could see that estimated SBP returned to the normal steady state. During the continuous change from supine to sitting position (45 and 75°), estimated SBP showed the tendency to increase the value of 5~10 mm Hg (Figure 10(a-1) and (b-1)). During the continuous change from 75° sitting position to supine, data of estimated SBP showed the opposite tendency to decrease the value of 7~15 mm Hg. This came from the orthostatic hypotension. Namely the blood supply to the heart was reduced when a person stood up because the arterial pressure amount of 500~800 ml was moved to the abdomen and lower limb, and then the activity of arterial pressure control organ decreases.

Table 1 showed comparison results between the estimated SBP by the developed device and the measured SBP by commercial non-invasive device. The small standard deviation of 3 mm Hg was shown during supine, and the larger standard deviation of 6~8 mm Hg was shown according to each body posture of 45 and 75°. However it was known that this error was not significant (Jennifer et al., 2013). For the daily life, the difference of 10 mm Hg was usually occurred. Furthermore, there was no big difference of averaged value of 2~3 mm Hg between estimated and measured values.

As a results, experimental results show that non-invasive periodical SBP estimation is enough possible to check the physical body condition. However we have a lot of problems to improve the developed device before applying for the clinical trial. In the next section, we would like to discuss hardware points in detail.

### 5. Discussion

Although the extended algorithm of Equation (11) showed the usability with the consideration of influence of gravity on SBP, the developed prototype sensor system had still something to be improved. Let us discuss those improving points of sensor system.

- **Noise**
- **Measuring point:** As shown in Figure 7(a), we could see that the noise of raw data was dependent on the measuring point. For comparison with the noise of earlobe, there was existed larger noise of sternoclavicular joint. We considered that this came from the breathing or fetal movement. Thus, it is necessary to consider the measuring point which there is little influence of breathing or fetal movement.
- **Integral amplifier sensors:** The prototype system transmitted measured signals to amplifier through the twisted cable in the present study. Because the measured bio signal was very weak, the device was vulnerable to some noise. Thus, it is necessary to combine the sensor with the amplifier.
- **Other bio signal including breathing.**

| Table 1. Comparison results between continuous measured SBP and BP by commercial BP device |
|--------------------------------------|------------------|------------------|
| Average [mm Hg] | Standard deviation [mm Hg] | Measuring by electronic manometer [mm Hg] |
| Supine | 108 | 1.0 | 107 |
| 45° | 105 | 2.9 | 100 |
| 75° | 107 | 3.0 | 105 |
It is well known that there is the 1–4 relationship between breathing and heart rate (Ding, Zhang, Liu, Dai, & Tsang, 2016; Forouzanfar et al., 2013; Jang, Park, & Hahn, 2016; Liu, Yan, Yu, Zhang, & Poon, 2014; McDonald, Nichols, O’Rourke, & Hartley, 1998; Nichols, 2005; Wilkinson, Cockcroft, & Webb, 1998; Wilkinson, Fuchs, Jansen, et al., 1998). When either of them gets to be worse, the other one also becomes to get to be worse. Thus, it is necessary to measure not only SBP but also others including breathing signal at the same time.

6. Conclusion

It is necessary for severely handicapped children to have the periodical repositioning, but we should minimize side effects while providing important insight into their overall physical condition at the same time. We developed the non-invasive sensor system to measure PTT through the different output signal between the two different measurements. The proposed extended model of algorithm enabled us to measure CNAP with measured PTT. The algorithm considered the influence of gravity on BP; there was no need to re-tune the system even if the posture of patient was changed. It was found that the proposed method had the strongest correlation with commercial BP device. The experimental results showed that it was possible for the proposed algorithm to measure CNAP during continuous repositioning without the re-tune of system. The results obtained show that despite just one time calibration of prototype sensor system, these methods give relatively accurate results and are sufficient for checking out the overall physical condition during continuous repositioning.
Hypertension Diagnostics TM. (2013). Retrieved from http://www.hypertensiondiagnostics.com/about-us.htm
Jang, D. G., Park, S. H., & Hahn, M. S. (2016). A Gaussian Hypertension Diagnostics TM. (2013). Retrieved from http://www.hypertensiondiagnostics.com/about-us.htm
Liu, D., Yan, B. P., Yu, C. M., Zhang, Y. T., & Poon, C. C. (2014). Ministry of Health, Labour and Welfare in Japan. (2008). Retrieved from http://www.mhlw.go.jp/bunya/shouhokohen/other/jiritsu05.html
June, K. J., & Cho, S. H. (2011). Low back pain and work-related time estimation. IEEE Journal of Biomedical and Health Engineering, 3, 346–352.
McDonald, D. A., Nichols, W. W., O’Rourke, M. J., & Hartley, C. (1998). McDonald's blood flow in arteries, theoretical, experimental and clinical principles (4th ed., ISBN 0-340-66414-6). London: Arnold.
Meigar, K., Kattai, R., & Lass, J. (2001). Continuous blood pressure monitoring during body postural change based on pulse transit time (pp. 153–156). In Proceedings of NIH-IEEE 2001 Strategic Conference on Healthcare Innovations and Point-of-Care Technologies for Precision Medicine, Seattle, WA. doi:10.1109/HIC.2001.7038987
Josep, M. S. C. (2011). Continuous non-invasive blood pressure estimation (A dissertation for the Degree of Doctor of Sciences, Diss. ETH. No. 20093). Universitat Politècnica de Catalunya, Barcelona.
June, K. J., & Cho, S. H. (2011). Low back pain and work-related factors among nurses in intensive care units. Journal of Clinical Nursing, 20, 479–487. http://dx.doi.org/10.1111/j.1365-2702.2010.03347.x
Justin, W. W., & Peggy, M. Z. (2015). “Having the heart to be evaluated”: The differential effects of fears of positive and negative evaluation on emotional and cardiovascular responses to social threat. Journal of Anxiety Disorders, 36, 115–126.
Liu, D., Yon, B. P., Yu, C. M., Zhang, Y. T., & Poon, C. C. (2014). Attenuation of systolic blood pressure and pulse transit time hysteresis during exercise and recovery in cardiovascular patients. IEEE Transactions on Biomedical Engineering, 61, 346–352.
McCarthy, B. M., O’Byrne, B., & Mathewson, A. (2011). An investigation of pulse transit time as a non-invasive blood pressure measurement method. Journal of Physicssensors & their applications, 307, 1–5. doi:10.1088/1742-6596/307/1/012060
McDonald, D. A., Nichols, W. W., O’Rourke, M. J., & Hartley, C. (1998). McDonald’s blood flow in arteries, theoretical, experimental and clinical principles (4th ed., ISBN 0-340-66414-6). London: Arnold.
Meigar, K., Kattai, R., & Lass, J. (2001). Continuous blood pressure monitoring using pulse wave delay (pp. 3171–3174). In Proceedings of the 23rd Annual International Conference of the IEEE EMBS, Buenos Aires.
Ministry of Health, Labour and Welfare in Japan. (2008). Retrieved (in Japanese) from http://www.mhlw.go.jp/bunya/shouhokohen/other/jiritsu05.html
Nichols, W. W. (2005). Clinical measurement of arterial stiffness obtained from noninvasive pressure waveforms. American Journal of Hypertension, 18, PMID 15683725. 3–10. doi:10.1016/j.amjhyt.2004.10.009
Pivovarov, V. V. (2006). A spiroarteriocardiorhythmograph. Biomedical Engineering, 40, 45–47. http://dx.doi.org/10.1109/TBME.2006.870438
Proença, J., Muelsteff, J., Aubert, X., & Carvalho, P. (2010). Is pulse transit time a good indicator of blood pressure changes during short physical exercise in a young population? (pp. 598–601). In 32nd Annual International Conference of the IEEE EMBS, Buenos Aires.
Rasmussen, M., & Laumann, K. (2012). The academic and psychological benefits of exercise in healthy children and adolescents. European Journal of Psychology of Education, 28, 945–962.
Reiner, A. T., Shalits, P. A., McCombie, D., & Asada, H. H. (2008). Utility of the photoplethysmogram in circulatory monitoring. Anesthesiology, 109, 550–558. http://dx.doi.org/10.1095/ALN.09013e31816c8961
Roy, B., Basmajian, A., & Asada, H. H. (2005). Repositioning of a rigid body with a flexible sheet and its application to an automated rehabilitation bed. IEEE Transactions on Automation Science and Engineering, 2, 300–307. http://dx.doi.org/10.1109/TASE.2005.849993
Saarikkalo, S., Korhonen, R. K., Laasonen, M. S., Toyräs, J., Rieppo, J., & Junvelin, J. S. (2004). Mechano-acoustic determination of Young’s modulus of articular cartilage. Biomechanics, 41, 167–179.
Shamir, M., Eidelman, L. A., Floman, Y., Kaplan, L., & Piloz, R. (1999). Pulse oximetry photoplethysmographic waveform during changes in blood volume. British Journal of Anaesthesia, 82, 178–181. http://dx.doi.org/10.1093/bja/82.2.178
Soller, B., Zou, F., Prince, M., Prince, M. D., Dubick, M. A., & Sondeen, J. L. (2016). Comparison of noninvasive ph and blood lactate as predictors of mortality in a swine hemorrhagic shock with restricted volume resuscitation model. Shock, 44, 90–95.
Spirioarteriocardiorhythmograph system. (2004). Retrieved from http://cakp.ru/
Tanaka, S., Nagawa, M., Yamakoshi, T., & Yamakoshi, K. (2007). Accuracy assessment of a noninvasive device for monitoring beat-by-beat blood pressure in the radial artery using the volume-compensation method. IEEE Transactions on Biomedical Engineering, 54, 1892–1895. http://dx.doi.org/10.1109/TBME.2007.894833
Teng, X. F., & Zhang, Y. T. (2003, September 17–21). Continuous blood pressure measurement method. IEEE Transactions on Biomedical Engineering, 54, 1892–1895. http://dx.doi.org/10.1109/TBME.2007.894833
Trevisanuto, S., Mei, P., Marzocchi, L., & Santini, P. (2013). The determinants of the cardiovascular and autonomic response to short periods of physical activity. Journal of Human Kinetics, 38, 1–13. http://dx.doi.org/10.2478/v10071-013-0019-9
Trevisanuto, S., Mei, P., Marzocchi, L., & Santini, P. (2013). The determinants of the cardiovascular and autonomic response to short periods of physical activity. Journal of Human Kinetics, 38, 1–13. http://dx.doi.org/10.2478/v10071-013-0019-9
Watkins, T., Whisman, L., & Booker, P. (2015). Nursing assessment of continuous vital sign surveillance to improve patient safety on the medical/surgical unit. Journal of Clinical Nursing, 25, 278–281.
Wilkinson, I. B., Cockcroft, J. R., & Webb, D. J. (1998). Pulse wave analysis and arterial stiffness. Journal of Cardiovascular Pharmacology, 32, PMID 9883745. 33–37.
Wilkinson, I. B.,uchs, S. A., Jansen, I. M., Spratt, J. C., Murray, G. D., Cockcroft, J. R., & Webb, D. J. (1998). Reproducibility of pulse wave velocity and augmentation index measured by pulse wave analysis. Journal of Hypertension, 16, PMID 9886900. 2079–2084. doi:10.1097/00004452-199816121-00033
Williams, M. H. (1993). Exercise effects on children’s health. Sports Science Exchange, Specific Topics, Special Health Consideration, SSE #43, 4. Retrieved from http://www.gssiweb.org/Article/sse-43-exercise-effects-on-childrens-health
