Multi-level Motion Artifacts Reduction in Photoplethysmography Signal Using Singular Value Decomposition

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Abstract. Photoplethysmography (PPG) is used for measuring vital cardiopulmonary indices such as heart rate and blood oxygen saturation (SpO_2). But PPG signals get inevitably corrupted by movements of the patient and results in inaccurate calculation of heart rate and SpO_2. In this paper, we report a method that uses a multi-level singular value decomposition (SVD) technique for effective reduction of motion artifacts while preserving the PPG morphology along with baseline. Results show impressive improvement on the signal quality and suppression of motion artifacts of the PPG signal. The PPG signals without motion artifacts obtained using out proposed method shows an average error of 0.69% in heart rate measurement with respect to the reference signal and an average max difference of 1.73% in the SpO_2 estimation (in comparison to the average max difference of 1.69% for the reference signal). The proposed method has potential for accurate estimation of heart rate and SpO_2 from PPG signal.

Keywords: Photoplethysmography · Heart rate · Blood oxygen saturation · Motion artifacts · Singular value decomposition · Singular values

1 Introduction

In recent decades, Photoplethysmoghraphy (PPG) has become a standard, low-cost, and non-invasive technique in clinical and in-house healthcare setups for monitoring cardiopulmonary parameters such as heart rate (HR) and blood-oxygen saturation (SpO_2) [1, 2]. A PPG sensor, shown in Fig. 1, uses a source light on a skin periphery like finger, earlobe. The transmitted/reflected light from/through the skin is detected by a photodetector [2]. It measures the blood volumetric changes due to cardiopulmonary activity. The measurement is known as PPG signal. However, PPG signal is extremely sensitive to motion and gets affected easily even by a slight movement at the point of contact between sensor and skin surface [3]. Such artifacts due to motion lead to erroneous estimation of HR and SpO_2 [1], and difficult to remove from the PPG signal when it appears in the desired signal band. Therefore, an effective method is needed to remove these motion artifacts from the signal while preserving its basic morphology.

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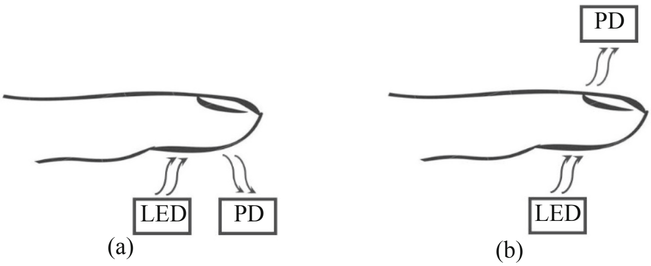

Fig. 1. PPG sensor configurations with light source (LED) and photodetector (PD): (a) reflection mode PPG and (b) transmission mode PPG.

Several techniques have already been proposed to reduce motion artifacts in the PPG signal. One among the easiest method is the use of moving average filter, proposed by Rusch et al. [4]. However, it is only effective for a limited range of motion artifact. Another approach of employing independent component analysis (ICA) for motion artifact removal was proposed by Kim and Yoo [5]. It is based on the assumption that the PPG and motion artifacts components are statistically independent of each other, which doesn't hold true in practical scenario [6].

Adaptive filtering is also considered as another attractive technique for reducing motion artifact from the PPG signal [7–9]. However, this technique always requires a reference motion artifact signal which can be processed directly from the corrupted PPG signal [7] or using accelerometer sensor [8, 9]. The performance of the adaptive filter is dependent on a highly correlated reference motion artifact signal, which is difficult to generate. This limits the reliability of this method.

Singular value decomposition (SVD) is a powerful statistical method. It can be used to decompose data matrix of a signal into orthonormal data matrices. The singular values of the data matrices contain information of noise levels present in that signal [10]. Reddy and Kumar reported an SVD based technique for strongest component extraction from a PPG signal [11]. This method selects a segment of a PPG signal (say first six cycles) and converts it into a data matrix depending on its strongest periodic component. In the data matrix each row represents a single PPG signal cycle. To remove motion artifacts the PPG data rows are averaged column-wise to output a PPG signal cycle (represented by a single row data, in this case the first cycle). After that, the first cycle is removed from the selected segment and a new cycle is inserted at the end of the segment. The process described above is repeated to compute the second artifact free PPG cycle and so on. However, this technique fails if all the cycles in the data-matrix are corrupted with motion artifact.

In order to overcome the issue with the SVD based technique discussed above, we propose a new SVD based algorithm as shown in Fig. 2. The method employs SVD at the first stage to select the data matrix with strongest component. Then the singular values of that data matrix are exploited to estimate noise in multiple levels and an averaging technique is employed to reconstruct a motion artifacts reduced PPG signal. Next, the signal is passed through a smoothening filter and used for HR and SpO_2

calculation. Our proposed methodology, which does not need a certain reference signal, can reduce the motion artifacts effectively and efficiently and provide accurate HR and SpO_2 calculation.

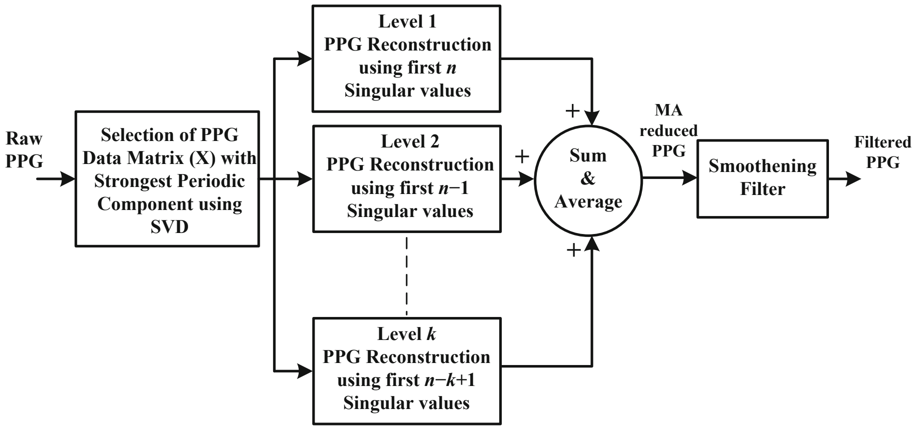

Fig. 2. The proposed algorithm based on singular value decomposition (SVD), multi-level PPG signal reconstruction, averaging, and smoothening filter.

2 Singular Value Decomposition and the Proposed Algorithm for Motion Artifacts Reduction

Singular value decomposition (SVD) method plays a key role in this new algorithm. It not only converts the PPG signal into a data matrix based on the strongest periodic component, but also reduces noise by exploiting the singular values of the data matrix. Therefore, a basic concept of SVD is needed to explain the working principle and effectiveness of the proposed algorithm.

2.1 Singular Value Decomposition (SVD)

SVD is a competent tool in linear algebra. The SVD of a real-valued data matrix X of dimension $p \times q$ is given as follows [10],

$$X = USV^T \tag{1}$$

where U and V are $p \times p$ and $q \times q$ unitary matrices such that $U^T U = I$ and $V^T V = I$, where I is an identity matrix. The column values of U and V are called left and right singular vector of X, respectively. S is a diagonal matrix of dimension $p \times q$ and its elements are called singular values, which are in fact positive square-roots of the Eigen values of $X^T X$. The diagonal values of S can be presented as $S = diag(\sigma_1, \sigma_2, \sigma_3 \ldots)$ and they are always in the descending order i.e. $(\sigma_1 > \sigma_2 > \sigma_3 \ldots)$. The singular values of X can actually be analyzed to determine its true rank, noise level, energy [12], and period detection [10].

2.2 The Proposed Algorithm

Let's say X is a data matrix of a periodic signal with each row containing one period, as shown in (2). When SVD is applied on the X, its S matrix contains only one non-zero singular value i.e. $\sigma_1 \neq 0$ representing its one and only dominant component, while other singular values are zero.

$$X = \begin{bmatrix} x(1) & x(2) & \cdots x(j) \\ x(j+1) & x(j+2) & \cdots x(2j) \\ \vdots & \vdots & \vdots \quad \vdots \\ x((i-1)j+1) & x((i-1)j+2) & \ldots \quad x(ij) \end{bmatrix} \tag{2}$$

However, for a quasi-periodic signal like PPG, once X is decomposed, S matrix will have several non-zero singular values with $\sigma_1 > \sigma_2 > \sigma_3 \ldots$, interpreting its several components in descending order. This information can be used to determine the dominant frequency in a PPG signal and convert it into a data matrix X, with each row containing one PPG signal cycle [11]. The singular values of data matrix X get affected by the presence of noise or artifacts in the PPG signal. Generally, the lower singular values (σ_1 – σ_6, or less) in the S matrix represent almost all the signal components, whereas the higher singular values represent the noise or artifacts [13]. Therefore, by reducing the rank of the S matrix, in other words by making the higher singular values zero, a noise free signal can be reconstructed.

Our method incorporates both applications of SVD discussed above. In the first block (see Fig. 2), the raw PPG data is converted into data matrix X using the same technique proposed in [11]. A segment of PPG data, sampled in 100 Hz, is converted into multiple matrices with different periodicities represented by the row length. The row lengths of the matrices are varied from 125 to 33 elements, representing periodicities from 0.8 Hz to 3.03 Hz (48 to 182 heart beats per minute). Then SVD is employed to all of the matrices and the ratio of their first two singular values i.e. σ_1/σ_2 are computed. The data matrix with highest value of σ_1/σ_2 is chosen as X.

Once X is determined, the corresponding S matrix is analyzed for noise reduction. The data matrix is reconstructed by reducing the rank of S to n, (where $n <$ total number of singular values), in other words by selecting first n singular values, using formula (1). The reconstructed data matrix then converted into a 1-dimensional PPG signal, marked as level 1 in Fig. 2. The value of n is selected carefully to retain the PPG morphology, which still may contain some noise, referred as in-band noise [13]. The PPG signal can be reconstructed using lesser singular values to remove in-band noise but the signal pattern is compromised, which is a trade-off [13]. To overcome this trade-off, the PPG signal is reconstructed in multiple levels. In level 1 the signal morphology is retained with in-band noise components. In the subsequent levels, n is reduced by 1 up to $n - k + 1$ until k levels (where $k < n$ and $k > 0$), making sure the in-band noise components (along with some signal components) are eliminated from the PPG signal. Next, the reconstructed PPG signals from k levels are averaged to remove the in-band noise while recovering the most of lost signal components. At last, a smoothening filter is applied on the averaged signal to remove any glitches present at the reconstructed signal. Then, the entire algorithm is repeated for the next segment of the data.

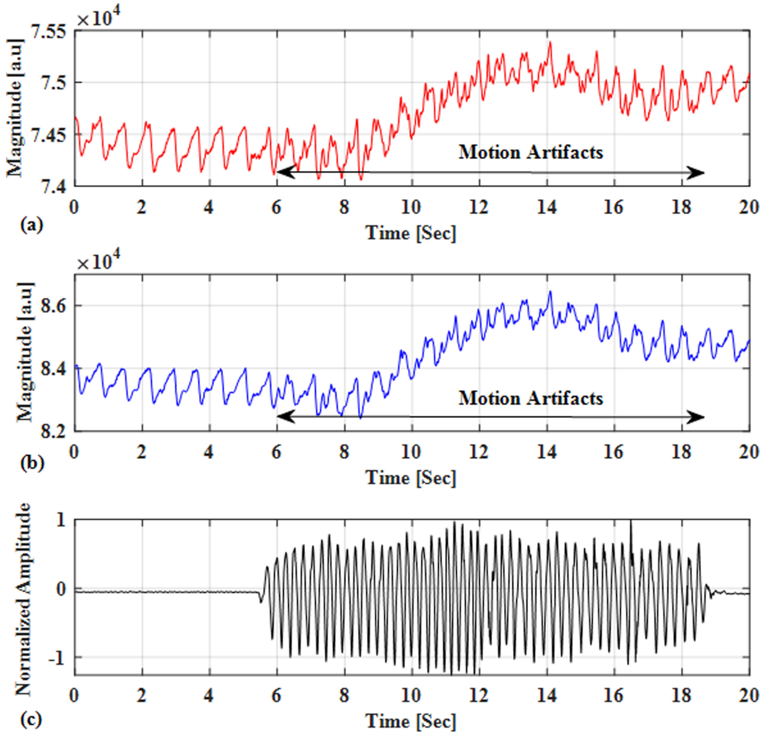

Fig. 3. Recorded PPG signal with motion artifacts: (a) red signal, (b) infra-red signal, and (c) accelerometer data.

3 Experimental Results

The experimental procedure in this study is in accordance with the Deceleration of Helsinki and was approved by Institutional Review Board of McGill University (study number: A04-M21-19B, approval date: 04/17/2019). This study was carried out using a commercial PPG sensor kit (MAX30101ACCEVKIT, by Maxim Integrated). This PPG sensor kit also contains an accelerometer. This PPG sensor has two LEDs (Red and Infra-red) which is necessary for SpO_2 calculation. The sensor was placed on the left index fingertip of a healthy subject and motion artifacts are introduced during the measurement. The recorded signals were sampled at 100 Hz. A portion of the signals (duration 20 s) is shown in Fig. 3. As we can see, the motion artifacts introduced during the measurement corrupts the recorded PPG signal. The corrupted part of the signal perfectly aligns with the accelerometer events. Another PPG sensor was placed on the right index fingertip for motion artifact free reference measurement, which is discussed in the next section. The signal from the left and right index fingertip are considered as measured and reference PPG signal, respectively.

The proposed algorithm, in Fig. 2, was applied to a measured PPG signals at infra-red wavelength shown in Fig. 4(a). The algorithm identified the PPG data matrix with strong component and decomposed its singular matrix S. At first stage, the rank of the rank of

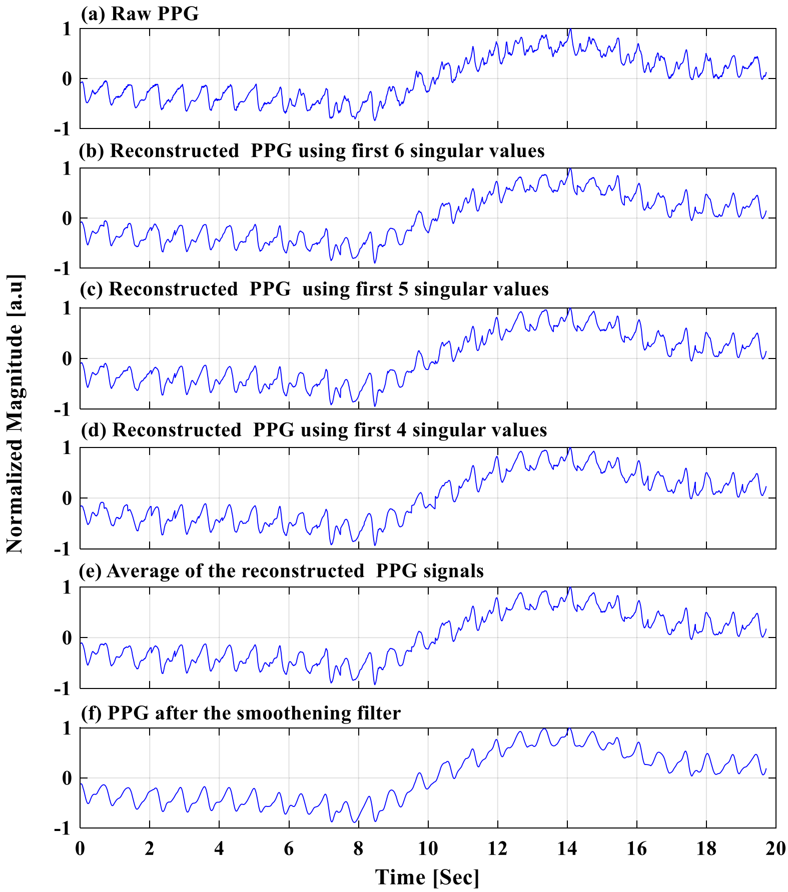

Fig. 4. Proposed method: (a) raw PPG signal; (b), (c), (d) PPG signal reconstructed with 6, 5, 4 singular values, respectively; (e) average of the reconstructed PPGs; and (f) smoothened PPG output at the final stage.

the singular matrix S was reduced up to its first six ($n = 6$) singular values (σ_1 to σ_6) to reconstruct the PPG signal shown in Fig. 4(b). The signal in Fig. 4(b) retained the PPG signal features and removed the high frequency noise. In the subsequent stages ($k = 3$), the singular values were eliminated one at a time and the PPG signal was reconstructed using first five ($n = 5$) and then four ($n = 4$) singular values, respectively, as shown in 4(c) and Fig. 4(d). The average of these three level signals is shown in Fig. 4(e). The average signal was then smoothen out as shown 4(f). It is worth pointing out that the number of levels k aren't limited to 3 and can be more or less depending on the sampling frequency and quality of the signal. However, singular values being chosen from σ_4 to σ_6 (i.e. $n = 4$ to 6) for 3 levels (i.e. $k = 3$) was found optimal for motion artifacts estimation for a signal sampled at 100 Hz. It can be the seen from the final signal (shown in Fig. 4(f)) our proposed method can remove the motion artifacts effectively while this motion reduction has minimal impact on nature of the PPG signals, i.e., amplitude and baseline, in addition to the ability of preserving the unaffected region as the original one.

4 Estimation of Cardiopulmonary Parameters

As mentioned earlier, a PPG data contain significant information about a subject's HR and SpO_2 levels. Whereas, the HR can be calculated from time domain PPG signal, SpO_2 can be calculating by analyzing the DC and AC levels of red and infra-red signals. To see the effectiveness of the proposed algorithm, both HR and SpO_2 are calculated from measured PPG signals of 5 subjects while they were sitting and introduced motion in the left index finger in random times. A motion free reference PPG signal taken from their right index finger was used to calculate the reference HR and SpO_2.

4.1 Heart Rate (HR)

We estimated beat-to-beat HR first in the time domain by calculating the distance between two consecutive PPG peaks and then the average HR was calculated using this formula:

$$HR = \frac{1}{n-1} \sum_{i=1}^{n} \frac{60}{t_{i+1} - t_i}; n \geq 2 \tag{3}$$

where n is the total number of detected peaks in a given segment of PPG data and t_i is the i^{th} detected peak in that segment. The idea behind this is to show how the motion artifacts affects the PPG signal and thereby leads to a false peak selection, which eventually leads to erroneous HR value. Figure 5 shows PPG signal from subject 1. Figure 5(a) shows the PPG signal with motion artifacts along with its selected peaks. In this signal, some of the peaks are false peaks detected due to motion artifacts. The average HR for that duration is found out to be 88 beats per minute (bpm) from the signal with motion artifact. Figure 5(b) shows the motion artifact free signal obtained after applying our proposed method. It can be seen that the PPG peaks are selected accurately in this signal leading to an average HR of 87 bpm which perfectly matches with the average HR of the reference signal shown in Fig. 5(c). To validate this information, PPG data with motion artifacts from 5 subjects were analyzed using the proposed method. Their average HR were calculated from the PPG signal with motion artifact, reconstructed PPG signal after motion artifact removal using our method, and reference PPG signal. The results are tabulated in Table 1. It can be seen that the average HR from motion artifact free signals are closer to the values obtained from reference signal than the average HR obtained from the signal with motion artifacts. For the motion artifact free signal, it shows an average error of 0.69% with respect to the reference signal, affirming the usefulness of the proposed method.

4.2 Blood Oxygen Saturation (SpO_2)

The blood oxygen saturation (SpO_2) is another important metric, representing percentage amount of oxygenated blood in a healthy subject and should always remain close to

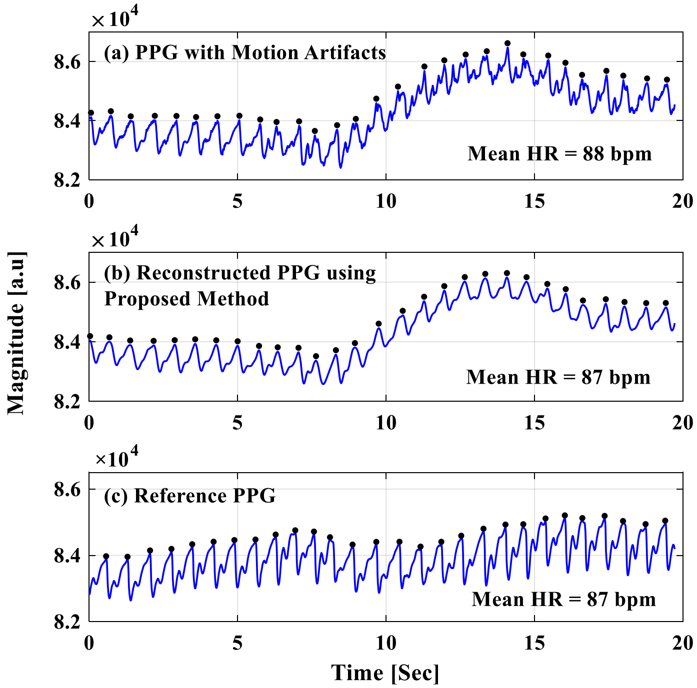

Fig. 5. Average Heart Rate (HR) calculation using: (a) PPG signal with motion artifacts, (b) reconstructed PPG signal using our proposed method, and (c) reference PPG signal.

Table 1. Average HR calculation from raw PPG signal, PPG signal using proposed method, and the reference signal.

Subjects	Average HR from PPG signal with motion artifact	Average HR from PPG signal after motion artifact removal	Average HR from Reference PPG signal	Abs. Error for motion artifact free signal
1	88 bpm	87 bpm	87 bpm	0%
2	81 bpm	81 bpm	80 bpm	1.25%
3	84 bpm	86 bpm	86 bpm	0%
4	90 bpm	89 bpm	88 bpm	1.14%
5	90 bpm	92 bpm	93 bpm	1.08%

100%. The $\%SpO_2$ was calculated by utilizing the ratio AC and DC part of both red and infra-red signals, using the following formula;

$$Ratio = \frac{AC_{Red}/DC_{Red}}{AC_{IR}/DC_{IR}} \tag{4}$$

And the overall $\%SpO_2$ was calculated by;

$$\%SpO_2 = \alpha.(Ratio)^2 + \beta.(Ratio) + \gamma \tag{5}$$

where α, β, and γ are calibration coefficients and are generally determined empirically by studying groups of people.

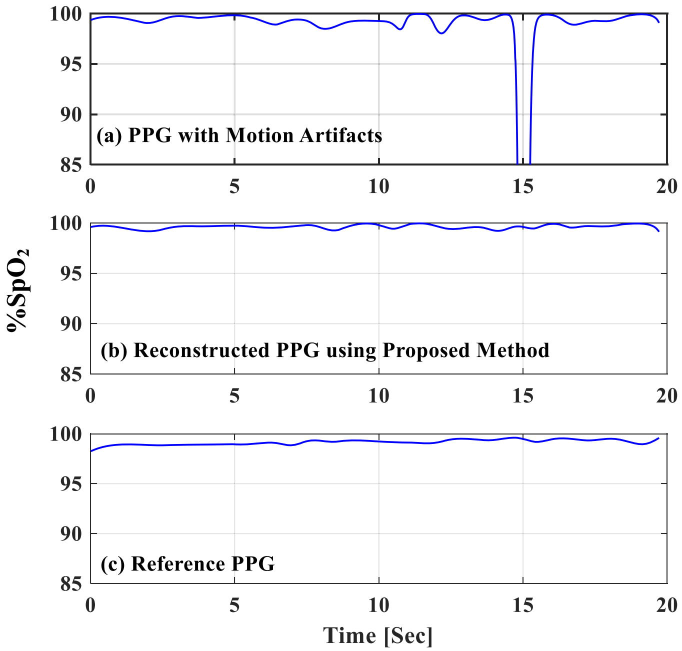

Fig. 6. Blood oxygen saturation ($\%SpO_2$) estimation from: (a) PPG signal with motion artifacts, (b) reconstructed PPG signal using our proposed method, and (c) reference PPG signal.

Due to the presence of motion artifacts in the signal, calculated $\%SpO_2$ may vary significantly and show a false value below 90%, which is considered to be fatal in terms of clinical standards. Therefore, it becomes essential to have motion free PPG signal for better estimation of $\%SpO_2$. For our study, the values of α, β, and γ were chosen to be -45.060, 30.354, and 94.84, respectively [14]. Figure 6 shows the SpO_2 estimation for subject 1 using the PPG signals shown in Fig. 5. The estimation of $\%SpO_2$ for a PPG signal with motion artifacts, reconstructed PPG signal after removing the motion artifacts using proposed method and reference signal are shown in Fig. 6(a), Fig. 6(b), Fig. 6(c), respectively. We can clearly see a few downward fluctuations of $\%SpO_2$ in Fig. 6(a). Even one of them is reaching below 85%. These fluctuation are restored closer to 100% in Fig. 6(b) after the PPG signal is processed with the proposed method. The estimated SpO_2 from the motion artifact free PPG signal is close to the estimated SpO_2 from the reference signal. To further support this information, SpO_2 was estimated from acquired PPG signals from the 5 subjects. For each subject SpO_2 was estimated from PPG signal after removing the motion artifacts using the proposed method and the reference signal.

The results are shown in Table 2. It shows an average max difference of 1.73% and 1.69% in the SpO_2 estimation from the PPG signal without motion artifact and the reference signal, respectively.

Table 2. $\%SpO_2$ calculation from PPG signal using proposed method and the reference signal.

Subjects	$\%SpO_2$ range from PPG signal after motion artifact removal	$\%SpO_2$ range from reference PPG signal
1	99.12—99.95%	98.25—99.61%
2	98.89—99.92%	97.23—99.95%
3	96.88—99.95%	96.8—99.76%
4	97.99—99.95%	98—98.84%
5	98.21—99.95%	98.26—98.84%

5 Conclusion

In this paper, a novel SVD based multi-level motion artifact reduction method is presented to remove the motion artifacts present in PPG signals. The multi-level averaging technique efficiently removed the in-band noise and out of band noise introduced by motion artifacts while retaining the signal features. Estimated HR and $\%SpO_2$ from the motion artifact free PPG signal obtained from our proposed method shows an average error of 0.69% in HR measurement with respect to the reference signal and an average max difference of 1.73% in the SpO_2 estimation (in comparison to the average max difference of 1.69% for the reference signal). The close agreement of the estimated value from the motion artifact free signal and the reference signal validates the effectiveness of the proposed method.

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