Quantifying Cardiorespiratory Thorax Movement with Motion Capture and Deconvolution

Christoph HOOG ANTINK1, David HEJJ1, Bernhard PENZLIN1

1Philips Chair for Medical Information Technology, Helmholtz-Institute for Biomedical Engineering
RWTH Aachen University, Pauwelsstr. 20, 52074 Aachen, Germany
hoog.antink@hia.rwth-aachen.de, david.hejj@rwth-aachen.de, penzlin@hia.rwth-aachen.de

Abstract. Unobtrusive sensing is a growing aspect in the field of biomedical engineering. While many modalities exist, a large fraction of methods ultimately relies on the analysis of thoracic movement. To quantify cardiorespiratory induced thorax movement with spatial resolution, an approach using high-performance motion capture, electrocardiography and deconvolution is presented. In three healthy adults, motion amplitudes are estimated that correspond to values reported in the literature. Moreover, two-dimensional mappings are created that exhibit physiological meaningful relationships. Finally, the analysis of waveform data obtained via deconvolution shows plausible pulse transit behavior.

Keywords
Cardiorespiratory Movement, Motion Capture, Deconvolution, Biosignalprocessing, Unobtrusive Sensing

1. Introduction

Ambient and unobtrusive cardiorespiratory sensing techniques form an increasing sub-field within biomedical engineering [1]. Sensor principles range from camera-based methods [2] over ultrasound [3], radar [4] and laser [5] to force sensors [2] and high-frequency oscillator circuits [6]. For a comprehensive overview, the interested reader is referred to [1]. While the sensors span a wide range of devices and physical principles, many methods that allow unobtrusive monitoring of heart and lung are ultimately based on the analysis of thoracic movement. Most of the time, unobtrusive sensing modalities are evaluated in terms of their ability to detect respiratory rate, respiratory patterns, heart rate or beat-to-beat intervals. Thus, they are commonly compared to a medical gold standard, such as the electrocardiogram (ECG) or a an air flow sensor. However, spatially resolved quantification of the actual thoracic motion is seldom performed. For this, specialized measurement equipment is necessary. Moreover, if cardiac induced motion is to be quantified, sub-millimeter accuracy is required. At the same time, spatially resolved information could help to optimize regions of interest for existing and future sensing modalities.

Thus, the aim of this paper is to develop a method for the spatially resolved analysis and mapping of cardiorespiratory induced thorax movement. For this, volunteers sitting in an armchair are monitored with a high-performance motion capture (MoCap) system and an ECG. To extract and quantify the spatial impulse responses of cardiac and respiratory activity, deconvolution [7] is used.

2. Materials and Methods

The overall setup of the system is demonstrated in Fig. 1. Only three of the seven cameras used for MoCap are visualized, which are placed around the subject in a semicircle.
2.1. Hardware

For motion capture, the “Oqus” system from Qualisys AB, Göteborg, Sweden configured with seven “Opus 500+” infrared (IR) tracking cameras and ten passive reflective markers was used. Each camera has a resolution of 4 megapixels at \( f_{s,\text{max}} = 180 \) Hz and is equipped with a C-mount lens with a focal length of 13 mm. The aperture was set to \( f/4.0 \) and manual focusing was performed. Illumination was provided by rings of IR LEDs integrated into each camera unit. Marker positions were tracked at \( f_{s,M} = 100 \) Hz. For ECG acquisition, the “MP30” patient monitor, manufactured by Philips, Amsterdam, The Netherlands was used as analog front end. Digitalization was performed at \( f_{s,A} = 800 \) Hz with a DAQ system which was synchronized with the cameras.

2.2. Trial Setup

Three healthy volunteers participated in the trial which was conducted as self-experimentation. A schematic of the marker positions is given in Fig. 2 A), which are further described in Tab. 2.2. Fig. 2 B) shows a photograph of the marker positions for one participant and in Fig. 2 C), the coordinate system is given, \( x \) being the right/left axis. Since the subjects are sitting in a chair with approximately 20° recline, \( y \) and \( z \) only approximate the dorsoventral and the craniocaudal axis, respectively.

![Fig. 2. A) schematic of marker positions, B) photography of actual marker positions, C) coordinate system.](image)

<table>
<thead>
<tr>
<th>#</th>
<th>Position x</th>
<th>Position z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Central axis</td>
<td>Center of forehead</td>
</tr>
<tr>
<td>2</td>
<td>Right nipple</td>
<td>1 cm above right nipple</td>
</tr>
<tr>
<td>3</td>
<td>Central axis</td>
<td>Sternum, superior part</td>
</tr>
<tr>
<td>4</td>
<td>Left nipple</td>
<td>1 cm above left nipple</td>
</tr>
<tr>
<td>5</td>
<td>Central axis</td>
<td>Sternum, inferior part</td>
</tr>
<tr>
<td>6</td>
<td>Right nipple</td>
<td>1 cm below costal margin</td>
</tr>
<tr>
<td>7</td>
<td>Central axis</td>
<td>1 cm below costal margin</td>
</tr>
<tr>
<td>8</td>
<td>Left nipple</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Centered between 6 and 7</td>
<td>Navel</td>
</tr>
<tr>
<td>10</td>
<td>Centered between 7 and 8</td>
<td>Navel</td>
</tr>
</tbody>
</table>

Tab. 1. Position of reflective markers for motion capture.

2.3. Data Analysis

The proposed model is shown in Fig. 3. The motion of each marker \( i \) is described as \( y_i \) and is influenced by a cardiac and a respiratory component. For each marker, these components are generated by filtering a virtual train of impulses originating from the heart and the lung with marker-specific transfer functions \( a_{\text{card},i} \) and \( a_{\text{resp},i} \), respectively. If \( y_i, s_{\text{card}} \) and \( s_{\text{resp}} \) are known, the filter coefficients \( a_{\text{card},i} \) and \( a_{\text{resp},i} \) can be estimated via deconvolution [7].

![Fig. 3. Proposed source-filter structure of thoracic movement influenced by a superposition of cardiac and respiratory component.](image)
Let $[\cdot]^T$ be the transpose, $[\cdot]^H$ the Hermitian transpose and $[\cdot]^\ast$ the conjugation operator. If the source signal is known, the optimal filter coefficients in terms of a minimal quadratic error can be determined with

$$a_{i, \text{est}} = \left[y_i^\ast \cdot \text{ES}^T + y_i \cdot \text{ES}^H\right] \cdot \left[\text{ES}^* \cdot \text{ES}^T + \text{ES} \cdot \text{ES}^H\right]^{-1},$$

with the matrix

$$\text{ES} = [e[0], e[1], e[N-1], \ldots, e[N-1], e[N-1]] \cdot [1, 0, 0, \ldots, 0, \ldots, 0, 0, 0]$$

and the vector

$$y_i = [y_i[0], y_i[1], \ldots, y_i[N-1]].$$

For a more detailed derivation and an applications to blind deconvolution, the interested reader is referred to [8].

Note that the calculations are carried out separately for all $i$ markers, for the respiratory component and for the cardiac component. Moreover, a separate filter is estimated for the each dimension $x$, $y$, and $z$. To obtain the cardiac related motion $y_{i, \text{card}}$, the marker position is filtered with a second-order Butterworth band-pass with 0.8 to 30 Hz passband. The respiratory component $y_{i, \text{resp}}$ is obtained via filtering with a passband of 0.01 to 0.3 Hz. The cardiac impulse signal $s_{\text{card}}$ is obtained from R-peaks of the ECG, while $s_{\text{resp}}$ is obtained via peak-detection on the geometric mean of $y$ and $z$ component of the central marker #5. To quantify the cardiac and respiratory induced motion, the range of $a_{i, \text{est}}$, i.e. the maximum minus the minimum of the respective impulse response, is calculated. For visualization, the range is color-coded and interpolated, the mapping is shown in Fig. 4.

![Fig. 4. Mapping of the color-coded ranges, see Fig. 6. Note that the mapping is slightly distorted as the subjects were monitored in a sitting position with a recline of approximately 20°.](image)

### 3. Results and Discussion

In Fig. 6, the color-coded ranges are visualized. Several observations can be made. First, neither cardiac nor respiratory activity create a significant $(i.e. \text{left-right})$ motion in any subject, which is to be expected. Next, the strongest respiratory motion in the $y$ (dorsoventral) direction occurs in the belly area, whereas the strongest $z$ (craniocaudal) component is measured in the upper part of the thorax. This is consistent with normal physiological breathing, where the ribcage is lifted and the downward motion of the diaphragm displaces organs which extend the belly. In terms of amplitude, the maximum respiratory induced motion is in the range of 5 to 7 mm, while the maximum cardiac induced motion ranges from 0.25 to 0.3 mm, which is consistent with values reported in the literature [9, 10]. In conclusion, more than an order of magnitude lies between the cardiac and the respiratory effect. Similar to the observations made with respect to respiration, the strongest $z$ component can be measured in the upper part of the thorax close to the heart, whereas the strongest $y$ movement of the thorax due to cardiac activity occurs in the belly region. At the same time, a relatively strong $y$-motion of approximately 0.25 mm can be observed on the foreheads of all subjects. Compared to the thoracic region, the influence of respiratory induced motion on the forehead is relatively low.

In Fig. 5, the impulse response of the $z$-component of marker 4 and 9 are shown for subject 1. On can see that the largest peak occurs at 110 ms in the timecourse of marker 4, whereas for marker 9, the largest peak is found at 310 ms. Thus, the marker closest to the heart exhibits a delay of 110 ms with respect to the R-peak, i.e. the electrical activity, whereas the pulse transit time between both markers is 200 ms.
Fig. 6. Mapping of respiratory (left) and cardiac (right) induced movement, see also Fig. 4. For each subject, an individual color code was used for respiratory and cardiac movement, which was constant for $x$, $y$, and $z$ component. Values are given in mm.
4. Conclusions and Outlook

In this paper, the use of motion capture and deconvolution to quantify cardiorespiratory thorax movement was demonstrated. Using a high-performance MoCap system and an ECG, movement amplitudes from three healthy subjects were obtained that are consistent with values reported in the literature. From these values, spatially resolved maps were created that exhibit physiological plausible distributions. Moreover, the phenomenon of pulse transit could be observed and quantified. In the future, a larger study with a statistical analysis needs to be performed. It is hoped that our findings can be used in the future for the optimization of regions of interest for unobtrusive sensing, for example by focusing on the head or belly region.

Acknowledgements

Research described in the paper was supervised by Univ.-Prof. Dr.-Ing. Dr. med. Steffen Leonhardt. The authors would like to thank Jakob Orschulik for participating in the measurements.

References


About the Authors...

Christoph HOOG ANTINK was born in Lohne (Oldenburg), Germany in 1985 where he finished his Abitur in 2005 and then began his studies in Aachen. As a visiting student on a Fulbright Travel Grant he obtained a M.S. degree in mechanical engineering from the University at Buffalo, Buffalo, New York, USA in 2011. In 2012 he finished his diploma in electrical engineering at the RWTH Aachen University where he is currently working towards a Ph.D. degree in electrical engineering at the Philips Chair for Medical Information Technology. His research interests include medical sensor fusion and imaging technologies.

David HEJJ was born in Budapest, Hungary in 1991. He finished his A-levels in 2010 and proceeded with his Bachelor studies in Mechatronics at the Technical University of Budapest. He specialized on Biomechatronics and spent a Semester abroad in Karlsruhe, Germany with a DAAD grant. He received his Bachelor of Science degree (with honors) in 2014. He got the scholarship of the Mummert Foundation and began the Biomedical Engineering M.Sc. in Aachen, Germany, at RWTH Aachen University. He is currently working on his thesis at the Philips Chair for Medical Information Technology and will obtain the Masters degree in 2017. His interests include sensor technologies, signal analysis, and complex prostheses.

Bernhard PENZLIN was born in Bad Soden am Taunus, Germany, and received the Dipl.-Ing. degree from OvGU University, Magdeburg, Germany, in 2012. He had been a scientific employee at the chair for mechatronics, Institute for Mobile Systems at OvGU Magdeburg University from end of 2012 to September 2014. Currently he is a scientific employee and PhD student at the Philips Chair for Medical Information Technology, Helmholtz-Institute for Biomedical Engineering at RWTH Aachen University. His research interests include rehabilitation robotics, especially exoskeletons, design of active orthosis and trajectory control.