Validation of a Smart shirt for tracking work postures of the trunk

Validering av en Smart tröja för mätning av bålens arbetsställningar

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This master thesis project was performed in collaboration with Karolinska Institutet
Supervisor at Karolinska Institutet: Mikael Forsman

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Master of Science Thesis in Medical Engineering
Advanced level (second cycle), 30 credits
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Abstract

Background

Ergonomists are interested in measuring the work postures and movements workers perform during their workday. The most common evaluation method to date, is observational studies, where the ergonomist visits the workplace and performs an evaluation. This is time consuming and different ergonomists tend to have low correlation between their evaluations. To make objective evaluations and speed up the process, a system to capture the work postures and movements would be helpful. Optical motion capture (OMC) systems have shown to have high accuracy and precision for capturing work postures and movements, but OMC systems are quite costly and often need a whole laboratory to be set up. This is not feasible in most workplaces. Inertial sensors on the other hand, enable sufficient capturing of the motions but still have the convenience of being mobile and easy to set up. The purpose of this thesis is to contribute to the development of a motion capture system, based on inertial sensors.

Methods

An existing Android application was modified for measuring the working postures of the trunk. To evaluate the construct validity, measurements of the inertial sensors were compared to an OMC system, which was used as a gold standard. Three different sensor-placements of the inertial sensors for the trunk was tested. The positions were above the C7, T4 and L1/S5 vertebrates and at the Sternum. The relative angle between L5/S1 and the Sternum, called SaSt, was calculated. Twelve participants performed a validation experiment, following a protocol for motions in a pace set by a metronome to 20 BPM. Four of the participants repeated the validation experiment wearing a Smart shirt. The participants performed a “Posture test”, where the participants were instructed to perform the uniaxially movements flexion/extension, lateral bending and rotation. Also, the participants performed two “Work-task tests”, called symmetrical- and asymmetrical lifting.

Results

In the Posture test’s result showed that the mean Root Mean Square Difference (RMSD) of all inertial sensors for all types of movements performed, was 4.1˚ and the inter-system correlation was generally high (≥0.782), compared to the OMC system. Symmetrical lifting, showed in the same manner, a mean RMSD of 13˚. The correlation was high (≥0.990) in flexion/extension (over the axis where movement occurred). Asymmetrical lifting, showed a mean RMSD of 26˚. The correlation was high (≥0.732) for all types of movements.

Discussions and Conclusions

For the Posture test, the sensor-placements T4 and C7 had the lowest RMSD for flexion/extension and lateral bending, compared to the OMC system, but SaSt had the least RMSD when the participants were performing rotation. For the symmetrical lifting task, T4 and C7 showed much lower RMSD than SaSt for flexion/extension. The same applies for asymmetrical lifting, but this time both for flexion/extension and lateral bending. To place the inertial sensors in a Smart shirt instead of on the skin, did not affect the accuracy for the movements flexion/extension and rotation. Only lateral bending was affected, probably because the shirt does not fit tight when lateral bending is performed. The tested inertial sensor-based motion capture system is comparable to an OMC system for uniaxially movements. The inertial sensors had high correlation and low RMSD compared to the OMC system, which is impaired when the participants combined movements over two or more planes.
Sammanfattning

Bakgrund

Ergonomer är intresserade av att mäta de rörelser som arbetare utför under sin arbetsdag. Den mest använda metoden idag är observationsstudier där ergonomen besöker arbetsplatsen och utför en utvärdering. Detta kan vara tidskrävande och olika ergonomer tenderar att ha låg interkorrelation mellan sina bedömningar. För att göra dessa utvärderingar mer objektiva och påskynda denna process skulle ett system för automatiskt mäta arbetsställningar vara till stor hjälp. Optiska "Motion Capture" (OMC) har visat hög noggrannhet och precision då de används för att mäta arbetsställningar och rörelser. Men OMC-system är ganska dyra behöver ofta ett helt rum för att uppnå hög noggrannhet. Detta är inte möjligt på de flesta arbetsplatser. Tröghetsensorer å andra sidan, möjliggör en approximation av de arbetsställningar arbetare utför, men har fördelen att de är relativt enkla att använda och ofta trädlösa. Syftet med detta examensarbete är att bidra till utvecklingen av ett system för mätning av arbetsställningar med hjälp av tröghetsensorer.

Metoder


Resultat

"Posture test" var dem genomsnittliga RMSD för alla tröghetsensorer, för samtliga typer av rörelser, 4,1° jämfört mot OMC systemet. I allmänhet var korrelationen hög (≥0.782) mellan OMC-systemet och varje tröghetsensor. Symmetrisk lyftning gav på samma sätt en genomsnittlig RMSD på 13°, korrelationen var dessutom hög (≥0.990) i flexion/extension (där rörelse inträffade). Asymmetrisk lyftning gav på samma sätt en genomsnittlig RMSD på 26°. Korrelationen var också hög (≥0.732) för alla typer av rörelser.

Diskussioner och slutsatser

Acknowledgements

I would like to send my sincere gratitude to the following persons:

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Wim Grooten, for all help and guidance in the Research and Movement Laboratory, I truly hope to collaborate more with you in the future.

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Last but not least, I would like to thank my family, for always being there, shimmering with joy and positive energy.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>DPS</td>
<td>Degrees Per Second</td>
</tr>
<tr>
<td>EKF</td>
<td>Extended Kalman Filter</td>
</tr>
<tr>
<td>IMU</td>
<td>Inertial Measurement Unit</td>
</tr>
<tr>
<td>MC</td>
<td>Motion Capture</td>
</tr>
<tr>
<td>MEMS</td>
<td>Microelectromechanical Systems</td>
</tr>
<tr>
<td>OMC</td>
<td>Optical Motion Capture</td>
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<tr>
<td>RMSD</td>
<td>Root Mean Square Difference</td>
</tr>
<tr>
<td>ROM</td>
<td>Range of Motion</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>WMSDs</td>
<td>Work Related Musculoskeletal Disorders</td>
</tr>
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</table>
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1. Introduction

The movements of the trunk have in a relatively short time, changed from being the flexible movements of hunters and gatherers, to be the monotonous movements working on a factory line or in an office environment. In the attempt to prolong the acquiring from attritional wear due to monotonous movements, ergonomists are looking at several methods to capture and measure these movements, enabling further analysis. The most common method used today, is observational studies, where an ergonomist visits a workplace and performs an ergonomic evaluation. This could be time consuming and the evaluations has been shown in several studies, to vary between different ergonomists. To speed this process up and make the evaluations more objective, a system to capture the work postures and movements would be helpful. In the recent years the art of capturing movements of the human body has come in to the limelight with many applications such as movies where actors could control a computer-generated avatar through a motion capture (MC) system, or sports professionals where e.g. running analysis is popular. There exist several MC modalities today. One modality is the optical motion capturing (OMC) system, whose function relies on markers mounted on the object of interest. A computer connected to several cameras then triangulates the movements of the markers in three-dimensions. Many articles have confirmed OMC to have great accuracy and precision when capturing bodily posture and movements during laboratory conditions. OMC systems are usually quite pricey and requires a laboratory to be setup properly. Therefore, ergonomists are seeking alternative systems to enable measurement of workers movements during the workday. Inertial sensors (IMUs) are mobile and relatively cheap and could in principle be used for capturing the work postures and movements. IMUs are also easy to set up and often wireless, but can only approximate its current alignment, based on the gravitational and magnetic conditions in the sensor’s surrounding. The use of IMUs has in many articles been shown to have good correlation with OMC systems for certain tasks, but, at the time, there is no established placement standard where to put the IMUs on the trunk for best capturing work postures, even though several have been suggested. One article (Schall et al. 2015) suggests the use of two IMUs and to calculate the relative angle between them. One placed above the L5/S1 vertebrae and another at Sternum. Another suggestion, was to use only one IMU above the C7 vertebrae (Dahlqvist et al. 2016). A third suggestion was to also use one IMU but place it above the T4 vertebrae (Korshøj et al. 2014). The purpose of this thesis was to test these three suggested placements and find out which one has the least Root Mean Square Difference (RMSD) and highest correlation compared with an OMC system. And, to find out if it affects the accuracy when wearing the IMUs in a Smart shirt instead of wearing them directly on the skin. The background chapter is attached in the appendix.
2. Aims

The aim of this thesis was to contribute in the development of a practical measurement method, based on Smart textiles, to measure work postures and movements of the trunk. The specific aims were to develop a trunk angular module of an existing inertial sensor-based system, and to answer the following research questions:

- How valid is a present inertial sensor-based system for measuring work postures of the trunk?
- Which of the three-established sensor-placements (C7, T4 and relative angle between Sternum and L5/S1) show the lowest RMSD and the highest correlation with an OMC system?
- Is the validity of the inertial sensors affected negatively by placing the inertial sensors in a Smart shirt instead of directly on the skin?
3. Materials and methods

3.1 Participants

Twelve participants took part in the validation experiment (8 males and 4 females). Average age 26 years (from 20 to 34 SD 4.0), average length 177 cm (from 160 to 192 SD 9.4), average weight 74 kg (from 54 to 110 SD 15.9). The participants had full mobility of their upper body. Before the study, all participants were informed of the aims and procedure of the validation experiment and signed an informed consent. The study was approved by the Regional Ethics Committee in Stockholm (Dnr 2016/724-31/5).

3.2 Measurement systems

To construct validity, measurements were taken with an optical motion capture (OMC) systems, since OMC systems have shown in other studies to have great accuracy and precision. All measurements gathered with the IMUs were then compared to the OMC system.

3.2.3 Inertial measurement units (IMU) motion capture (MC) system

In the validation experiment four LP-Research Motion Sensor Bluetooth version 2 (LPMS-B2, LP Research, Tokyo, Japan) IMUs were used, with the sample rate set to 25 Hz. The specifications of LPMS-B2 are attached in the appendix (figures 23-24). The IMUs were placed above the C7, T4, L5/S1 vertebras and the Sternum. The IMUs were attached with allergy tested double-sided tape. An Android application was already developed at STH KTH, for gathering data from the IMUs. The Android application was modified for measuring the movements of the trunk.

The Smart shirt was manufactured by the Hultafors Group. The IMUs were inserted into sewn pockets below the collar called P1 (above the spinal column), at L5/S1 and at Sternum called P2. Since the T4 vertebrae is between the shoulder blades, in a correct stance body posture, the shoulder blades make the textile loose at that position, which would greatly affect the IMU’s output. Therefore, the Smart shirt was manufactured without a pocket at that position.

3.2.1 Optical MC system

The validation experiment was performed in Karolinska Institute’s Research and Movement Laboratory with their Elite MC system using eight cameras (Elite 2002, version 2.8.4380; BTS, Milano, Italy). Elite MC system’s sample rate was set to 100 Hz, with an accuracy of 1 mm in an area of 2x2 meters (Grooten et al., 2017). Each participant had eight spherical retroreflective markers, placed on each Acromion (left and right), each side of Femur Greater Trochanter (FGT), one marker at C7, one at T4, one at L1 and one at L5 (shown in Figure 1). The markers were attached with double-sided tape.

3.3 Protocol for validation experiment

The participants followed a “Protocol for validation experiment”, that is attached in the appendix. A metronome was set to 20 BMP during all recordings and the participants was instructed to follow the pace of the metronome during the whole session. First the participants performed a set of standard postures, called the Posture test, such as flexion/extension, lateral bending and transversal rotation. Then, two simulated work-tasks were performed by the participants, called Work-task tests. The first simulated work-task was that the participants should lift a box, up on a table and down again with three repetitions, called symmetrical lifting. The second work-task, called asymmetrical lifting, was that the box was placed 45˚ of the participants, and perform the liftings in similar manner as symmetrical lifting. This case is the most probable for practical scenarios (Faber et al., 2009). The participants did not receive any restrictions or recommendations of how to lift the box, except that they should not bend their legs. This for enabling the participants to lift in “their” own way. Before each task, the participants could practice the movements. The participants performed the whole validation experiment standing with both feet on the floor.
3.4 Data processing

Procedures in Matlab R2017b were written for e.g. calculating the angles between vectors. The procedures included filtering the raw data by a Butterworth filter (of the 6th order with cutoff frequency at 5 Hz) to smooth the data. The raw data were missing some samples, why a linear interpolation was required for filling out the gaps and down sampling to 25 Hz. Also, synchronizing each IMU with the calculated angles from the OMC system. For the OMC, to calculate trunk flexion, a vector was created by subtracting the 3d-position of the marker placed above the L5/S1 vertebrae from the marker above the C7 vertebrae, when the participant was standing in an upright position. As the participant bends forward in the sagittal plane, the vector would change direction. The angle between origin vector and the movable vector was calculated by equation (1). To calculate lateral bending and rotation of the trunk, two vectors were created. One vector between the markers placed on each Acromion and another between the two markers placed on each Femur Greater Trochanter. The angle between the two vectors was also calculated by using equation (1). \( \theta_x, \theta_z \) and \( \theta_y \) gives trunk flexion, lateral bending and rotation as the axes are defined in this study.

\[
\begin{align*}
(\theta_x, \theta_y, \theta_z) &= \sin^{-1}\left(\frac{(u \times v)}{|u||v|}\right) \quad u, v \in \text{vectors} \\
|\theta_x, \theta_y, \theta_z| &= \theta
\end{align*}
\]

The output from the IMUs was already converted into linearized Quaternions from the Sensor fusion performed with an Extended Kalman Filter (EKF). So, the output from the IMUs above the C7 and T4 vertebrae where just converted to Euler angles. For the IMUs above the L5/S1 vertebrae and at Sternum, the inverted linearized quaternions from the IMU placed above the L5/S1 vertebrae was multiplied with the Sternum quaternions, this for receiving the relative angle between the IMU above L5/S1 vertebrae and Sternum. Some singularities were formed when converting the IMU’s output into Euler angles due to some of the movements were >180°. An algorithm was written for this to be remediated.

The 10th, 50th and 90th percentiles of RMSD (3) between the OMC and each IMU was calculated for each type of the movement: flexion/extension, lateral bending and rotation. The mean and SD and the correlation for each IMU together with the OMC. Also, the median RMSD angular velocity between each IMU and the OMC was calculated. For the Posture test, the correlation between the IMUs at P1, P2 was calculated with the IMUs at C7 and SaSt.

\[
\text{RMSD} = \sqrt{\frac{\sum_{t=1}^{n}(\text{IMU}_t - \text{OMC}_t)^2}{n}} \quad (3)
\]
4. Results

4.1 Postural test: IMUs attached to the skin

In the Posture test, participants performed uniaxial movements in the following order: flexion, extension, left lateral bending, left rotation and right rotation. Each IMU position (above the C7, T4 and the relative angle between the L5/S1 vertebrae and the Sternum, called SaSt), the RMSDs at the 10th, 50th and 90th percentile compared to the OMC system, is shown in table 1 and figures 5-7. The IMU positioned above the C7 vertebrae had the largest RMSD of 10.7° when the participants performed rotation, closely followed by T4 and SaSt at 8.8° and 6.0°. The largest median RMSD for angular velocity was in for rotation were C7 was 2.1°/s. The Pearson correlation between the IMU and the OMC systems, was the lowest for SaSt for rotation. But in general, the IMUs could capture the trunk's uniaxial movements with high accuracy (≥0.834) and low RMSDs. Figure 10 shows a plot for the three sensor-placements together with the OMC system.

Table 1. Posture test: IMUs attached to the skin. RMSD for 12 participants at the 10th, 50th and 90th percentiles (˚) for angular distribution, median RMSD angular velocity and Pearson correlation for three placement protocols for the IMUs and type of movements compared to the OMC system.

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Flexion/extension</th>
<th>Lat. Bending</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C7  T4  SaSt</td>
<td>C7  T4  SaSt</td>
<td>C7  T4  SaSt</td>
</tr>
<tr>
<td>10th</td>
<td>0.35  0.6  3.3</td>
<td>0.3  0.2  0.7</td>
<td>1.9  0.7  1.5</td>
</tr>
<tr>
<td>50th</td>
<td>2.2   2.0  6.5</td>
<td>0.7  1.1  0.9</td>
<td>4.8  7.4  5.9</td>
</tr>
<tr>
<td>90th</td>
<td>9.0   7.7  13.4</td>
<td>4.3  4.1  7.2</td>
<td>21.2 17.7 13.7</td>
</tr>
<tr>
<td>Mean(SD)</td>
<td>3.6 (3.7) 2.9 (2.6) 7.5 (3.8)</td>
<td>1.5 (1.6) 1.8 (1.6) 2.2 (2.6)</td>
<td>10.1 (8.3) 8.8 (6.4) 6.0 (5.5)</td>
</tr>
</tbody>
</table>

| 50th       | 0.6   0.3  1.6    | 0.2  0.2  0.4 | 2.1  2.2  2.2 |

<table>
<thead>
<tr>
<th>Pearson Correlation</th>
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<tr>
<td>OMC</td>
</tr>
<tr>
<td>0.966</td>
</tr>
<tr>
<td>0.976</td>
</tr>
<tr>
<td>0.958</td>
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<tr>
<td>0.988</td>
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<tr>
<td>0.986</td>
</tr>
<tr>
<td>0.958</td>
</tr>
<tr>
<td>0.896</td>
</tr>
<tr>
<td>0.855</td>
</tr>
<tr>
<td>0.834</td>
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</table>
4.2 Postural test: Smart shirt.

In the Postural test, the participants performed uniaxial movements in the same order as previously. The Smart shirt had a pocket sewn directly under the collar (over the spinal column) called P1, seen in figure 8. The relative angle between the IMUs placed above the L5/S1 vertebrae and Sternum is called P2, seen in figures 8-9. The RMSDs at the 10th, 50th and 90th percentile compared to the OMC system, is shown in table 2. Largest RMSD is found at P1, namely 6.3˚ for lateral bending. The median RMSD angular velocities for the Smart shirt were small, with max at P1 in flexion/extension. The Pearson correlation for uniaxial movements, comparing each IMU and the OMC system, was the lowest for P1 for rotation, but still high (≥0.782). Table 2 also shows the Pearson correlation between the IMUs placed in the Smart shirt compared to when they were attached to the skin, which was high for flexion/extension and rotation (≥0.909), but lateral bending showed low correlation. Figure 11 shows a plot for the two sensor-placements together with the OMC system.

Table 2. Posture test: Smart shirt. RMSD for 4 participants at the 10th, 50th and 90th percentiles (˚) for angular distribution, median RMSD angular velocity and Pearson correlation for three placement protocols for the IMUs and type of movements compared to the OMC system. Also, the Pearson Correlation between P1 and P2, respectively C7 and SaSt.

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Flexion/extension</th>
<th>Lateral Bending</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1</td>
<td>P2</td>
<td>P1</td>
</tr>
<tr>
<td>10th</td>
<td>0.1</td>
<td>0.7</td>
<td>4.8</td>
</tr>
<tr>
<td>50th</td>
<td>1.6</td>
<td>1.7</td>
<td>5.8</td>
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<td>90th</td>
<td>5.5</td>
<td>4.2</td>
<td>8.6</td>
</tr>
<tr>
<td>Mean(SD)</td>
<td>2.2(2.5)</td>
<td>2.1(1.7)</td>
<td>6.3(1.7)</td>
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</table>

Absolute angular velocity difference between systems (˚/s)

<table>
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<th>Percentile</th>
<th>Flexion/extension</th>
<th>Lateral Bending</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.4</td>
<td>0.2</td>
<td>0.1</td>
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</table>

Pearson correlation

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<tr>
<th></th>
<th>OMS</th>
<th>C7</th>
<th>SaSt</th>
</tr>
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<tbody>
<tr>
<td>Flexion/extension</td>
<td>0.968</td>
<td>0.974</td>
<td>x</td>
</tr>
<tr>
<td>Lateral Bending</td>
<td>0.941</td>
<td>1.010</td>
<td>x</td>
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<tr>
<td>Rotation</td>
<td>0.924</td>
<td>0.996</td>
<td>-0.012</td>
</tr>
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</table>
4.3 Work-task tests: IMUs attached to the skin

The Work-task tests was divided into two simulated work-tasks: symmetrical- and asymmetrical lifting. In symmetrical lifting, the participants performed lifts of a box onto a table and down to the floor, with three repetitions. In asymmetrical lifting, the box was instead placed at 45° angle instead of in front of the participants. For each IMU position (above the C7, T4 and the relative angle between the L5/S1 vertebras and the sternum, called SaSt), the RMSD at the 10th, 50th and 90th percentile compared to the OMC system, is shown in tables 3–4. Symmetrical lifting, shown in table 3 and figure 12, had the largest mean RMSD of 64.6° for SaSt in flexion/extension. Thereafter comes T4, C7 and SaSt for rotation with RMSDs of 27.1°, 14.9° and 14.9°. The largest median RMSD for angular velocity had SaSt for flexion/extension that was 4.6°/s. The Pearson correlation between each IMU and the OMC system, for symmetrical lifting, was high (≥0.990) for the included movements (flexion/extension). Asymmetric lifting, shown in table 4 and figure 13, had a RMSD for SaSt of 79.7° for flexion/extension. Thereafter comes T4 and SaSt for rotation with RMSDs of 47.1° and 41.6°. The largest median RMSD for angular velocity was for C7 in flexion/extension that was 7.8°/s. For asymmetrical lifting, there is generally a high correlation (≥0.743), but low for lateral bending for T4 and SaSt. Figure 13 shows a plot for the three sensor-placements together with the OMC system for the task asymmetrical lifting.
Table 3. Work-task test: symmetrical lifting. RMSD for 4 participants at the 10th, 50th and 90th percentiles (˚) for angular distribution, median RMSD angular velocity and Pearson correlation for three placement protocols for the IMUs and type of movements compared to the OMC system.

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Flexion/extension</th>
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<tbody>
<tr>
<td></td>
<td>C7</td>
<td>T4</td>
<td>SaSt</td>
</tr>
<tr>
<td>10th</td>
<td>3.4</td>
<td>5.8</td>
<td>17.8</td>
</tr>
<tr>
<td>50th</td>
<td>10.3</td>
<td>11.4</td>
<td>76.3</td>
</tr>
<tr>
<td>90th</td>
<td>32.7</td>
<td>15.0</td>
<td>88.1</td>
</tr>
<tr>
<td>Mean(SD)</td>
<td>14.2(13.4)</td>
<td>10.9(3.9)</td>
<td>64.6(31.8)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Absolute angular difference between systems (˚)</th>
<th>Flexion/extension</th>
<th>Lat. Bending</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentile</td>
<td>C7</td>
<td>T4</td>
<td>SaSt</td>
</tr>
<tr>
<td>50th</td>
<td>1.8</td>
<td>3.4</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Table 4. Work-task test: asymmetrical lifting. RMSD for 4 participants at the 10th, 50th and 90th percentiles (˚) for angular distribution, median RMSD angular velocity and Pearson correlation for three placement protocols for the IMUs and type of movements compared to the OMC system.

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Flexion/extension</th>
<th>Lat. Bending</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C7</td>
<td>T4</td>
<td>SaSt</td>
</tr>
<tr>
<td>10th</td>
<td>4.4</td>
<td>5.1</td>
<td>7.1</td>
</tr>
<tr>
<td>50th</td>
<td>19.1</td>
<td>19.2</td>
<td>96.8</td>
</tr>
<tr>
<td>90th</td>
<td>40.6</td>
<td>57.0</td>
<td>118.2</td>
</tr>
<tr>
<td>Mean(SD)</td>
<td>20.8(15.1)</td>
<td>25.1(24)</td>
<td>79.7(50.3)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Absolute angular velocity difference between systems (˚/s)</th>
<th>Flexion/extension</th>
<th>Lat. Bending</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>50th</td>
<td>7.8</td>
<td>1.0</td>
<td>7.1</td>
</tr>
</tbody>
</table>

Pearson Correlation

| OMC | 0.966 | 0.990 | 0.992 | 0.170 | 0.433 | -0.103 | 0.363 | 0.552 | 0.172 |

<table>
<thead>
<tr>
<th>Absolute angular velocity difference between systems (˚/s)</th>
<th>Flexion/extension</th>
<th>Lat. Bending</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>50th</td>
<td>0.979</td>
<td>0.984</td>
<td>0.980</td>
</tr>
</tbody>
</table>
Figure 12. A representative plot from the Asymmetrical lifting task when the participant had the IMUs attached to the skin.

4.4 Work-task tests: Smart shirt

Work-task tests: Smart shirt was by the same manner divided into two work-tasks: symmetrical- and asymmetrical lifting. For the Smart shirt the RMSD at the 10th, 50th and 90th percentile compared to the OMC system, is shown in tables 5-6. Symmetrical lifting, shown in table 5, had the largest RMSD of 33.7˚ and 16.8˚ at P2, for flexion/extension and rotation. The largest median RMSD for angular velocity was 5.2 °/s for P2 in flexion/extension. The Pearson correlation between each IMU and the OMC system for the included movements (flexion/extension) was high (≥0.997) for the symmetrical lifting. Asymmetrical lifting, shown in table 6, showed largest RMSD of 66.0˚ and 46.6˚ compared to the OMC system, at P2 and P1 for flexion/extension. The largest median RMSD for angular velocity had P1 was rotation was 4.2 °/s. For asymmetric lifting the correlation was high (≥0.926) in the flexion/extension and lateral bending, but lower for rotation. Figure 11 shows a plot for the two sensor-placements together with the OMC system for the task asymmetrical lifting.

Table 5. Work-task test: symmetrical lifting Smart shirt. RMSD for 3 participants at the 10th, 50th and 90th percentiles (˚) for angular distribution, median RMSD angular velocity and Person correlation for three placement protocols for the IMUs and type of movement

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Flexion/extension</th>
<th>Lateral Bending</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1</td>
<td>P2</td>
<td>P1</td>
</tr>
<tr>
<td>10th</td>
<td>3.3</td>
<td>28.6</td>
<td>2.6</td>
</tr>
<tr>
<td>50th</td>
<td>4.6</td>
<td>35.4</td>
<td>6.5</td>
</tr>
<tr>
<td>90th</td>
<td>24.3</td>
<td>37.2</td>
<td>7.5</td>
</tr>
<tr>
<td>Mean(SD)</td>
<td>10.7(11.7)</td>
<td>33.7(4.5)</td>
<td>5.5(2.6)</td>
</tr>
</tbody>
</table>

Table 6. Work-task test: asymmetrical lifting Smart shirt. RMSD for 3 participants at the 10th, 50th and 90th percentiles (˚) for angular distribution, median RMSD angular velocity and Person correlation for three placement protocols for the IMUs and type of movement

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Flexion/extension</th>
<th>Lateral Bending</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1</td>
<td>P2</td>
<td>P1</td>
</tr>
<tr>
<td>50th</td>
<td>3.8</td>
<td>5.2</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Pearson correlation

<table>
<thead>
<tr>
<th></th>
<th>OMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>50th</td>
<td>0.997 0.998 0.934 0.944 0.047 0.731</td>
</tr>
</tbody>
</table>
Table 6. Work-task test: asymmetrical lifting Smart shirt. RMDS for 3 participants at the 10th, 50th and 90th percentiles (˚) for angular distribution, median RMDS angular velocity and Person correlation for three placement protocols for the IMUs and type of movement

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Flexion/extension</th>
<th>Lateral Bending</th>
<th>Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1</td>
<td>P2</td>
<td>P1</td>
</tr>
<tr>
<td>10th</td>
<td>9.0</td>
<td>46.4</td>
<td>5.7</td>
</tr>
<tr>
<td>50th</td>
<td>49.7</td>
<td>70.1</td>
<td>8.2</td>
</tr>
<tr>
<td>90th</td>
<td>81.0</td>
<td>81.5</td>
<td>14.9</td>
</tr>
<tr>
<td>Mean(SD)</td>
<td>46.6(36.1)</td>
<td>66.0(17.9)</td>
<td>9.6(4.8)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Absolute angular velocity difference between systems (˚/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50th</td>
</tr>
<tr>
<td>P1</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>1.4</td>
</tr>
<tr>
<td>4.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pearson correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMS</td>
</tr>
<tr>
<td>0.982</td>
</tr>
</tbody>
</table>

Figure 13. A representative plot from the Asymmetrical lifting task when the participant wore the Smart shirt
5. Discussion
For the Postural test, both with and without the Smart shirt, the RMSDs were generally small and the correlations were high. The yaw axis, which was defined in this study to be the axis where rotation occurred, was the most sensitive to magnetic disturbances. That could be the reason for the largest RMSDs are found for rotation. Some of the measurements of the IMUs had an over time, increasing error, which made the RMSD error compared to the OMC system larger. This could perhaps also explain the larger RMSD for rotation, since that was the last movement the participants performed in the Posture test. The mean RMSD for all IMUs and all types of movements is 4.1˚, which are comparable to findings in other articles (Duc et al. 2014).

The correlations between the OMC and the IMUs were in general high for the Posture test. When calculating the correlations of the IMUs placed at P1, P2 of the Smart shirt, together with C7, SaSt when attached to the skin, an interesting unexpected result appeared. For both flexion/extension and rotation the correlations between the positions where high. But for lateral bending there was no correlation. This may be due to movement artefacts of the textile as lateral bending occurs, probably because that the shirt does not fit tightly when lateral bending is performed.

In symmetrical lifting the main movement performed was flexion/extension. For lateral bending and rotation there were very small movements. Therefore, symmetrical lifting had high correlation for flexion/extension, compared to the OMC system, but low or no correlation for lateral bending and rotation. For flexion/extension the RMSDs, SaSt and P2 were 64.6˚ and 33.3˚. This was unexpected, since SaSt and P2 were expected to have much lower RMSDs than the two other sensors placed above the C7 and T4 vertebrae. This may be due to the method of calculating the relative angle between the IMUs. The method used in this thesis, calculates the relative quaternion between the IMUs, after sensor fusion had been carried out. In an article by Schall et al. 2015, they use another method. They calculated the relative angle directly from the outputs of the accelerometers, gyroscopes and magnetometers, before the sensor fusion. The salespoints behind the choice of IMU sensors used in this thesis, was the fact that the IMUs themselves performed sensors fusion and the output were in quaternions. With the method used in the article by Schall et al. 2015, one could use considerably cheaper sensors. The RMSDs for all IMUs for symmetrical lifting (both with and without Smart shirt) were considerable lower. If SaSt and P2 are excluded for flexion/extension, the mean RMSD for all IMUs is 13˚.

For asymmetrical lifting (both with and without Smart shirt), the correlation between IMUs and OMC was high for all movements. The IMUs at SaSt and P2 in flexion/extension follows the same reasoning as for symmetrical lifting. If SaSt and P2 are excluded for flexion/extension, the mean RMSDs for all IMUs is 26˚, which may be too large to be usable for an ergonomist. The results of symmetrical and asymmetrical lifting are comparable to an article by Faber et al., 2009, but they used other sensor-positions (T9, Sacrum and a movable inertial sensor) along the vertebral column.

5.1 Social aspects
To enable cheap, mobile and validated MC systems based on inertial sensors, may result in more reliable and autonomous and thereby faster ergonomic evaluations of work-tasks. This may increase the wellbeing for many working groups, especially blue-collar jobs, where WMSDs are prevalent.

5.2 Future studies
More participants may be required for making general estimates since only 4 participants wore the Smart shirt. Also, the participants were young, healthy students in the age span 20-34 recruited from the university, which may not be representable of the working force.

The method of calculating the relative angle between the IMUs at the Sternum and L5/S1 requires more investigation. In this thesis, the method was to calculate the relative quaternion between the IMUs, which showed in the two simulated Work-task tests to not be that accurate in flexion/extension.
6. Conclusions

The tested IMU-based MC system is comparable to an OMC system for measuring uniaxially movements e.g. in the sagittal-, coronal- or transverse planes. The IMUs have high correlation and low RMSD compared to the OMC system. This is impaired when the participants combine movements over two or more planes. In the Posture test, T4 and C7 has the lowest RMSD for flexion/extension and lateral bending, compared to the OMC system. But SaSt has the lowest RMSD when the participants performed rotation. For symmetrical lifting, T4 and C7 shows vast lower RMSD than SaSt in flexion/extension. The same applies for asymmetrical lifting in flexion/extension. It does not affect the validity of the measured work postures and movements flexion/extension and rotation when the IMUs are placed in a Smart shirt compared to when they are attached directly to the skin, only lateral bending is affected, probably because the shirt does not fit tightly when lateral bending is performed.
Appendix

A. Background

A.1 The human trunk

The human trunk can be bent or rotated along several axes due to its complex structure with hundreds of muscles pair and ligaments. But are usually modeled as having three gross movements around the planes: Sagittal, Coronal and Transverse plane. Figure 15 shows the movement ranges of each plane (Cafolla et al. 2015). The risks of attaining work-related injuries increase when combining the rotations around two or more axes of the trunk, but more substantiated quantitative measurements are required before any conclusions can be drawn (Eklund 2017). The human vertebral column, seen in figure 14, consists of 7 Cervical, 12 Thoracic, 5 Lumbar, 5 Sacrum vertebrae and 4 Coccyx or tailbones. For enabling trunk rotation, the vertebrae are capable of axial rotation between vertebrae pairs. Between the vertebrae pairs lies an intervertebral disc. The intervertebral discs function is to reduce friction and function as shock absorber. The magnitude of the axial rotation is determined of the shape and condition of the intervertebral disc and spinal ligaments. The most mobile part is the cervical vertebrae, enabling the large range of movement the head (Duc et al. 2014). The six upper Thoracic vertebrae pairs are capable of axial rotation of approximately 10 degrees at both sides. At T8 and below the axial rotations progressively decrease until the Lumbar region is reached, where the axial rotations only reach up to 2 degrees at both sides. The intervertebral discs are damaged by natural ageing, disease or incorrect body posture. The damages reduce the intervertebral discs capabilities in shock absorbing and increases the risk of rupture. Also, allowing the vertebrae to be closer to each other, growing the risk of compressing the nerves (Carvalho et al. 2017; Kumar 2002).

Figure 14. The human vertebral column reprinted with permission from the publisher (Krapohl 2015).

Figure 15. The three anatomical planes of the trunk reprinted with permission from the publisher (Cafolla et al. 2015).
A.2 Work-related Musculoskeletal disorders (WMSDs)

In the Nordic countries and the Netherlands, it is estimated that WMSDs are costing society between 0.5 - 2% of the GDP (Buckle and Devereux, 1999). Upright bipedalism of the human species began to evolve for 225 million years ago, and the industrialization of countries began only some centuries ago. The movements of the trunk have in a relatively short time evolutionary speaking, changed from being the flexible movements of hunters and gatherers, to be the monotonous movements working on a factory line or in an office environment (Kumar 2002). The risk assessments of today are mainly performed manually by consultant services or occupational health care (Eklund 2017). A method often used is self-reporting the issues the workers may have. But it has been shown that self-reporting does not correlate well with actual measurements (Hansson et al. 2001; Hardt Jilk et al. 2008). In an article by Carvalho et al. 2017, the authors developed a biofeedback system for reeducation of body posture. The system was based on five IMU sensors along the vertebral column that warned the user if he or she had an incorrect body posture by vibrating and making sounds. The experiment was performed during only two days, and it both achieved a reduction of the total time per day spent in an incorrect body posture and the total number of them. One can only speculate what would happen if the experiment lasted during a longer time. Would the participants after one week or maybe a month, relapsed to their original time and amount of being in an incorrect body posture as before the experiment began? Or maybe, the participants would have strengthened their posture muscles, so that they would have spent even less time in an incorrect body posture.

A.3 Motion Capture (MC)

There are many types of motion capturing systems, whose common denominator is that they capture movements and rotations of rigid bodies. An OMC system consists of several markers mounted on the object of interest. The markers could be active or passive, meaning they send out light in active ones or reflect light in passive ones. An OMC system also includes several cameras connected to a computer, which then triangulates where the markers are in three dimensions. In an article by Eichelberger et al. 2016, the authors studied the accuracy, precision and uncertainty of systems using six, eight or ten cameras. The authors concluded that an OMC system consisting of eight cameras instead of six showed significant improvements. But the use of ten instead of eight cameras, did not show any significant improvements. Another method of MC is to use Inertial Measurement Unit (IMU) sensors. IMUs are small, have low weight, have the potential to be wireless, could be waterproof and used during damp conditions and are considerably cheap compared to an OMC solution (Goodvin et al. 2006). IMUs also have the benefit that they can be wearable hence they could be sewn into the clothes or taped to the skin by double sided tape etc. But an IMU based MC system does not have the great accuracy of an optical based MC system. An OMC system could have as high accuracy as 0.1 mm (Ancillao et al. 2017), but they are quite costly and are preferable to place in a laboratory to attain that high accuracy. In contrast, an article by Taylor et al. 2017 shows that IMUs available today, has an average accuracy of $0.6° \pm 0.1°$ and average precision of $0.1° \pm 0.1°$ for static postures, compared to the OMC system the authors used. The dynamic average accuracy was $4.4° \pm 0.2°$ degrees per second (dps) and average precision $0.2 \pm 0.3$ dps. But in the article, the authors performed their experiments during excellent environmental conditions, which perhaps does not make their findings to be considered as being in general, though IMU based MC systems perhaps best advantage is their mobility.

A.4 Microelectromechanical systems (MEMS)

MEMS technology are components with the size between 1 - 100 µm, and built with similar materials, methods and tools as the Semiconductor industry use. Common applications of MEMS are accelerometers, gyroscopes, magnetometers, Inkjet printers, microphones, pressure sensors, Bio-MEMS such as Lab-On-Chip and many others. The benefits with MEMS are many, such as with making sensors, actuators etc. so small that even very costly materials can be used, since each MEMS device requires so little of that material. For example, gold wires are commonly used. Similarly, MEMS technology only requires a very small sample size for analysis. MEMS technology is also robust and consumes little energy. The cons with MEMS technology is that the machines for building MEMS devices are expensive. Also, MEMS technology requires a cleanroom laboratory, since most dust particles are in the size of 0.1-1000 µm and can potentially disturb the actuators or sensors function if present during fabrication (Gaura et al. 2006; Sadiku 2002).
A.5 Inertial Measurement Units (IMU) sensors

Modern IMU sensors are built with MEMS technology, today IMUs are in every smart phone, new car etc. Research have in other studies confirmed that the IMUs accuracy are comparable with the more precise 3d MC systems, for measuring body movements (Saber-Sheikh et al. 2010). IMUs could easily be attached to the body segment of interest using double sided tape or an elastic strap (Morrow et al. 2017). IMUs usually consist of both a tri-axial accelerometers, tri-axial gyroscopes and tri-axial magnetometers. The maybe simplest way to explain an accelerometer is to imagine a system that consists of a spring or beams with known spring constant attached to a weight called proof mass with known weight. The movement of the proof mass is caused by an acceleration of the system. In MEMS accelerometers, seen in figure 16, the movements of the proof mass are measured capacitively, piezo resistively or similar. Since the force of gravity is static everywhere on the earth’s surface at sea level, one can calculate the tilt-angles using a tri-axial accelerometer (Guner et al. 2015; Wong et al. 2008).

MEMS Gyroscopes can measure the rotations through the Coriolis force. The Coriolis force could be explained by imaging a rotating system which both the object and observer is currently in the same inertial frame of reference. If a ball gets dropped from a height of 5 m and an observer stands on the earth’s surface. The observer sees the ball dropping from its initial point to the ground in a straight line. But if an observer is not in the same frame of reference, and sees the same ball but through a telescope. The ball seems to be moving in curved line from the dropping point to the ground, which is due to the Coriolis force. The so-called Coriolis force, which like centripetal force, is not really a force, rather it is the sum of all force. The MEMS gyroscope, seen in figure 17, has a proof mass which is oscillating with a certain frequency. The angular rotation is detected by a shift in frequency of the oscillating proof mass, caused by the Coriolis force, when rotation along that axis occurs (Cetin et al. 2017). The oscillating actuators are vacuum sealed, avoiding Brownian motion for the molecules in the air, since they are in the size of micrometers (Armenise et al. 2010). Magnetometers can measure the magnetic field and its direction. Many MEMS magnetometers rely on the Lorentz force, which could be explained by the right-hand rule. If you place your right hand on a wire where DC current is flowing through with your thumb pointing in the same direction as the current goes. A magnetic field goes in the same direction as your curled fingers are pointing. If a charged particle is travelling in the direction of the current, the particle is pushed by the Lorentz force, which is the cross product of the particles speed and the strength of the magnetic field. For MEMS magnetometers, the charged particle is the electron flowing in the wires in the structure of the magnetometer. So, when the Lorentz force deforms this structure, we have measurement of the magnetic field, seen in figure 18. The deformation is detected by optical, voltage or frequency shift sensing (Grosz et al. 2017).
Individually the accelerometer, gyroscope and magnetometer signals are not so accurate since they suffer from drift, scaling, non-zero biases and sensor axis misalignment. Therefore, they need to be corrected by each other. The problem with the accelerometer is that its output includes both the force of gravity and the accelerations it is exposed to. When aligned as in figure 19, with the y-axis pointing in the gravity’s direction, one can only apply roll and pitch to a three-axis accelerometer. The accelerometer only can give the angle of the plane that lies orthogonal to earth’s surface due to earth’s gravity, but not the planes direction to e.g. north. For the gyroscope the integrations of the angular velocity will over time increase the uncertainty, due to drift and offset. The Sensor fusion or Data fusion between tri-axis accelerometers and tri-axis gyroscopes could therefore correct for pitch and roll, but not yaw, since the yaw signals become corrupted by drift and biases over time. To correct for yaw, a tri-axis magnetometer is required since it gives the direction to the magnetic north pole. But since magnetometers are sensitive to magnetic disturbances, they are not applicable in all environments, such as in the presence of ferromagnetic metals (Abyarjoo et al. 2015).

The sample rate is of interest, the higher sample rate, like 400 Hz, the more representative the motion capturing will be. But a high sample rate also means that increased processing power are required due to a large amount of gathered data. Often today 25 Hz sampling rate is used, which gives an appropriate representation of the movements, but not too much data to handle and battery drain. Also, 25 Hz is sufficient for averaging away most of the random noise present in the signal. The Sensor fusion, often performed by a Kalman filter, gives the IMUs output a more robust and accurate output than each individual sensor can achieve by itself (Bhatia et al. 2016). Modern IMUs also have other properties that are desirable, they are small in size, weight, and they could communicate wirelessly e.g. via Bluetooth. IMUs could have data logging capabilities either in itself or by the device that it is connected to, and together with a suitable fusion algorithm and sufficiently low disturbances or uncertainty, IMUs provide an attractive measurement system of human motions (Schall et al. 2015). One factor that can decrease the credibility of IMUs is how well the IMU itself is attached to the point of interest. Since IMUs could be quite large, even though the actual sensors, especially those made with MEMS technology, are very small. IMUs usually comes with a printed circuit board, casing and battery etc. seen in figure 20. If the IMUs are placed within the bearer’s cloths or attached by an elastic strap to the body segment of interest, it may slide over the point one wants to measure. Or if the IMUs are attached to the skin with double sided tape, one must consider that the skin itself also is quite flexible and can give rise to soft tissue artifacts (Cutti et al. 2008).
A.6 Disturbances

All electrical signal includes noise. The output of Inertial sensors is depending on the environmental conditions. According to an article by Sabatini (2006), especially gyroscopes are depending on the ambient temperature which variations can determine the bias drift. Since gyroscopes must perform work e.g. oscillations, so they are self-heating. And given some time, they get thermally stabilized and their output biases will become more stable. In an article by Robert-Lachaine et al. (2017), the authors tested to disturb an IMU magnetically, and waited to see how long time it took after the distribution had occurred, for the IMUs to recover. They conclude that the fusion algorithm takes at least 30 seconds to recover the error deflection, after the magnetic disturbance have taken place. In an article by Palermo et al. (2014), the authors tested if the indoors magnetic disturbances are greater than outdoors magnetic disturbances. The authors placed IMU sensors on the ankle, the knee and the hip on a test person and measured several times as the participant walked from outdoors into their lab. The authors concluded that the disturbances were greater indoors but the deflections where limited to the transverse plane. Total mean deflection was for outdoors resp. indoors: the hip 3 degrees, the knee 5 degrees and the ankle 15 degrees. So, in that experimental setup, the magnetic disturbances rise the closer to the floor you are. Since the earth’s magnetic field is parallel to the earth’s surface, this conclusion could potentially be problematic since that plane aligns with the transverse plane when a person is standing up. Since only one participant was tested, it is difficult to generalize this result.

A.7 Sensor calibration

All types of measuring devices need to be calibrated from time to time to ensure that it is measuring what is wanted. Accelerometers are usually calibrated with help of the gravity by measuring an appropriate number of data points and then average them together. The accelerometer calibration procedure includes the gain and offset. Magnetometers are calibrated similarly to an accelerometer, but instead of gravity, the magnetic field of earth are used. The magnetic field of earth is about 50 to 60 microTeslas, and takes average of the collected data points. The magnetic field of earth is parallel to the earth’s surface and points in the direction of the magnetic north pole, unless you are at a pole where it is pointing up if south or down if north from the surface. The magnetometers calibration procedure includes gain and interference bias. Gyroscopes could be calibrated by rotating them with a known angle velocity. The gyroscope calibration procedure includes the movement threshold of the gyroscope, the gain and bias (Safaeifar and Nahvi, 2015; Sarkka et al. 2017).

A.8 Positions of IMU sensors

In an article by Schall et al. (2015), the authors validated the placement of IMUs at the posterior pelvis at the L5/S1 vertebrae and the sternal notch. The authors did a comparison to the values collected with the Lumbar Motion Monitor (LMM) and the IMUs, both for only using the sternum notch IMU and using the sternum IMU and the posterior pelvis IMU. LMM is described in an article by Marras et al. (1992), as very accurate and extremely reliable. The Root-Mean-Square Difference (RMSD) estimates for the combination of the posterior pelvis together with the sternum, had the least difference to the RMSD from the LMM. Using only the IMU placed on the sternum, the RMSD difference was larger, but only slightly. Thus, the authors recommended to use several IMUs for computing thoracolumbar trunk movement. Also, the authors claimed that it is the sensor fusion algorithm that potentially could improve the accuracy of IMUs. Figure 21 shows the three axes of an IMU that is placed on the upper back.
A.9 Rigid Body Kinematics

There are several formalisms that is used to mathematically represent rotations of a rigid body in $\mathbb{R}^3$. Most common are Euler angles, which describes the orientation by using three sequential rotation angles (e.g. yaw, pitch and roll) between two frames. Euler angles work great when the rotation angles are small, but suffer from geometrical singularities when the rotation angles attain certain large values. The transformation matrix $R$ is a product of the three rotation matrices (1-3). The order when multiplying the three rotation matrices are of importance (Perumal 2014). For example, in (4) the sequence of the rotations is $R_{XYZ} = X(\alpha)Y(\beta)Z(\gamma)$. The sequence is confined by singularities at $\beta = \pm \frac{\pi}{2}, \pm \frac{3\pi}{2}$, ... due to (5-7). The resulting transformation matrix (8) has the first and the third axes combined as one instead of two separate. This phenomenon is also known as Gimbal lock. Notice that it is the second matrix in the transformation matrix $R_{XYZ} = X(\alpha)Y(\beta)Z(\gamma)$ that has the narrowest interval between singularities. So, around the plane where the least rotation occurs are usually defined as the second matrix in the sequence, such as roll or pitch for cars. There are several sequences of Euler angles (X-Y-Z, Y-Z-X and X-Z-X etc.) each with different applications. But, to avoid singularities entirely, more than three coordinates must be used such as quaternions.

$$X(\alpha) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) \\ 0 & \sin(\alpha) & \cos(\alpha) \end{pmatrix}$$  \hspace{1cm} (1)  

$$Y(\beta) = \begin{pmatrix} \cos(\beta) & 0 & -\sin(\beta) \\ 0 & 1 & 0 \\ \sin(\beta) & 0 & \cos(\beta) \end{pmatrix}$$  \hspace{1cm} (2)  

$$Z(\gamma) = \begin{pmatrix} \cos(\gamma) & \sin(\gamma) & 0 \\ -\sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$  \hspace{1cm} (3)  

$$R_{XYZ} = X(\alpha)Y(\beta)Z(\gamma) = \begin{pmatrix} \cos(\beta)\cos(\gamma) - \sin(\alpha)\sin(\beta)\sin(\gamma) & \cos(\beta)\sin(\gamma) + \sin(\alpha)\cos(\beta)\sin(\gamma) & \cos(\alpha)\cos(\beta)\sin(\gamma) - \cos(\gamma)\sin(\alpha) \\ \sin(\alpha)\sin(\beta) - \cos(\alpha)\cos(\beta)\cos(\gamma) & \cos(\alpha)\cos(\beta)\cos(\gamma) + \sin(\alpha)\sin(\beta)\cos(\gamma) & \cos(\alpha)\sin(\beta) - \sin(\alpha)\cos(\beta)\sin(\gamma) \\ \sin(\beta)\sin(\gamma) + \cos(\alpha)\cos(\beta)\cos(\gamma) & \cos(\alpha)\cos(\beta)\cos(\gamma) - \sin(\alpha)\sin(\beta)\cos(\gamma) & \cos(\alpha)\sin(\beta) - \sin(\alpha)\cos(\beta)\sin(\gamma) \end{pmatrix}$$  \hspace{1cm} (4)  

$$R_{XYZ} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix}$$  \hspace{1cm} (5)  

$$\sin \alpha = -\frac{r_{32}}{\cos(\beta)}$$  \hspace{1cm} (6)  

$$\sin \gamma = \frac{r_{12}}{\cos(\beta)}$$  \hspace{1cm} (7)  

$$\beta = \pm \frac{\pi}{2}, \pm \frac{3\pi}{2}, \ldots \rightarrow R_{XYZ} = \begin{pmatrix} 0 & -\cos(\alpha)\cos(\gamma) & \cos(\alpha)\sin(\gamma) \\ \cos(\alpha)\cos(\beta) & \cos(\alpha)\sin(\beta) & \sin(\alpha) \\ \sin(\alpha)\cos(\beta) & -\sin(\alpha)\sin(\beta) & \cos(\alpha) \end{pmatrix}$$  \hspace{1cm} (8)  

Quaternions describe any rotation with angle $\theta$ about a 3-dimensional unit vector (Yean et al. 2016). $Q = \cos \frac{\theta}{2} + (u_x i + u_y j + u_z k) \sin \frac{\theta}{2}$ which usually are written as: $Q = q_0 + q_1 i + q_2 j + q_3 k = \sum_{i=0}^{3} q_i$. Matrix (9) is an orthogonal matrix that is corresponding to a rotation. The inverse mapping back to quaternions from (9) is calculated from (10) where we could break out each (11-14). To find the correct sign ($\pm$) for each (11-14) we can use the fact that at least one of $\sum_{i=0}^{3} q_i$ is non-zero, since $q_0^2 + q_1^2 + q_2^2 + q_3^2 = 1$. For example, if $q_0$ is non-zero we can use (15-17) for calculation of (18-20) and find each correct sign for (18-21). If $q_0 = 0$, we simply find another $\sum_{i=0}^{3} q_i$ which are non-zero. Quaternions are a little more strenuous to calculate than Euler angles, but if the application requires unlimited rotations, it is worth it. Also, Euler’s rotation theorem applies to all coordinate systems describing a rigid object in $\mathbb{R}^3$, so quaternions could be converted any formalisms mathematically describing rotations of rigid objects (Schiefer et al. 2014).

$$Q = \begin{pmatrix} q_{11} & q_{12} & q_{13} \\ q_{21} & q_{22} & q_{23} \\ q_{31} & q_{32} & q_{33} \end{pmatrix} = 2 \begin{pmatrix} q_0^2 + q_1^2 - \frac{1}{2} & q_1 q_2 - q_0 q_3 & q_1 q_3 + q_0 q_2 \\ q_2 q_3 + q_0 q_1 & q_0^2 + q_2^2 - \frac{1}{2} & q_2 q_3 - q_0 q_1 \\ q_1 q_3 - q_0 q_2 & q_2 q_3 + q_0 q_1 & q_0^2 + q_3^2 - \frac{1}{2} \end{pmatrix}$$  \hspace{1cm} (9)  

$$\text{tr} \ Q = q_{11} + q_{22} + q_{33} = 2((q_0^2 + q_1^2 - \frac{1}{2}) + (q_2^2 + q_3^2 - \frac{1}{2}) + (q_0^2 + q_3^2 - \frac{1}{2}))$$  \hspace{1cm} (10)
\[ q_0 = \pm \sqrt{\frac{\text{tr}Q+1}{4}} \] (11)
\[ q_1 = \pm \sqrt{\frac{1+2q_{11}-\text{tr}Q}{4}} \] (12)
\[ q_2 = \pm \sqrt{\frac{1+2q_{22}-\text{tr}Q}{4}} \] (13)
\[ q_3 = \pm \sqrt{\frac{1+2q_{33}-\text{tr}Q}{4}} \] (14)
\[ q_{32} - q_{23} = 4q_0q_1 \] (15)
\[ q_{13} - q_{31} = 4q_0q_2 \] (16)
\[ q_{21} - q_{12} = 4q_0q_3 \] (17)
\[ q_1 = \frac{q_{32} - q_{23}}{4q_0} \] (18)
\[ q_2 = \frac{q_{13} - q_{31}}{4q_0} \] (19)
\[ q_3 = \frac{q_{21} - q_{12}}{4q_0} \] (20)

A.10 Sensor Fusion

Signals are of statistical nature, so we need a method of predicting and detecting signals from random signals and noise (Kalman 1960). Tri-axis accelerometers can alone calculate Roll and Pitch, but not as accurate as if a Sensor fusion is performed with signals from tri-axis gyroscopes. The tilt compensating algorithm (21-23) can calculate both the direction of gravity pointing orthogonally upward from and the plane pointing parallel to the earth’s surface (IMU aligned as figure 21). But to be able to calculate the orientation of e.g. north, signals from tri-axis magnetometers are required (24-26). Integration of angular velocity from the gyroscopes are prone to error because of drift and offset. In an article by Zhang et al. (2016), the authors claim that of all published literature there is no way to eliminate the cumulative errors without the use of other sensor types which has no cumulative errors and no drift, such as accelerometers or magnetometers. The signals from gyroscopes and accelerometers are affected by mechanical vibrations and therefore needs a vibration filter to minimize the vibrations from their output (Del Rosario et al. 2016; Guner et al. 2015; McGinnis et al. 2014; Sabatini 2006; Saber-Sheikh et al. 2010; Safaeifar and Nahvi, 2015; Zhang et al. 2016).

The Kalman filter is an algorithm for producing estimates from many inputs containing statistical noise. The inputs could be from multiple sensors, and therefore it is called sensor fusion. A Kalman filter works recursively and base their estimations on the last estimated value seen in (27-28), which in their turn was based on the previously estimated value and so on (Yean et al. 2016). Extended Kalman filter (EKF) can estimate nonlinear signals, which are the most occurring signals in nature. EKF uses Taylor Series to linearize a model to a working point. Figure 22 shows an example of Sensor fusion, where signals from tri-axis accelerometers is fused with tri-axis gyroscopes by a Kalman filter. The estimation is often presented in the form of Euler angles or quaternions.
Calculation of Pitch, Roll and Yaw:

\[
X(\alpha)Z(\gamma)a = G = \left( \begin{array}{ccc}
a_x\cos(\gamma) & a_y\cos(\alpha) & 0 \\
-a_x\sin(\gamma)\cos(\alpha) & a_y\cos(\gamma) & a_2\sin(\alpha) \\
a_x\sin(\alpha)\sin(\gamma) & -a_x\sin(\alpha)\cos(\gamma) & a_x\cos(\alpha)
\end{array} \right) = \left( \begin{array}{c}
0 \\
1 \\
0
\end{array} \right)
\] (21)

Roll: \( \gamma = \tan^{-1}\left(\frac{-a_x}{a_z}\right) \)  

Pitch: \( \alpha = \tan^{-1}\left(\frac{-a_x}{a_x\sin(\gamma) + a_y\cos(\gamma)}\right) \)  

\[
X(\alpha)Z(\gamma)m = Y(\beta)\left( \begin{array}{c}
B\cos(\delta) \\
B\sin(\delta) \\
0
\end{array} \right) = B
\] (24)

\[
\left( \begin{array}{ccc}
m_x\cos(\gamma) & m_y\sin(\gamma) & 0 \\
-m_x\sin(\gamma)\cos(\alpha) & m_y\cos(\alpha)\cos(\gamma) & m_z\sin(\alpha) \\
m_x\sin(\alpha)\sin(\gamma) & -m_y\sin(\alpha)\cos(\gamma) & m_z\cos(\alpha)
\end{array} \right) = \left( \begin{array}{c}
B\cos(\beta)\cos(\delta) \\
B\sin(\beta)\cos(\delta) \\
B\sin(\beta)\cos(\delta)
\end{array} \right) = \left( \begin{array}{c}
B_x \\
B_y \\
B_z
\end{array} \right)
\] (25)

Yaw: \( \beta = \tan^{-1}\left(\frac{-B_z}{B_x}\right) \)  

\( a, B, m, G = \) accelerometers, earth’s magnetic field, magnetometers and Gravity vectors in \( \mathbb{R}^3 \)

Kalman filter:

\[
x_{t+1} = Ax_t + w_t
\] (27)

\[
z_t = Hx_t + v_t
\] (28)

\( x_t = [\omega]^T, \omega = \) angular velocity, \( \phi = \) rotation angle, \( A = \left[ \begin{array}{cc} 1 & -\Delta t \\ 0 & 1 \end{array} \right] \) temporal changes of the system, \( w_t = \) state transition noise at time \( t \), \( z_t = \) measurement at time \( t \), \( H = \left[ \begin{array}{cc} 1 & 0 \end{array} \right] \) relation between measurement and state variable, \( v_t = \) measurement noise at time \( t \).
B. Protocol for validation experiment

Protocol for validation experiment

Positions of IMUs and markers on the torso: IMUs on Sternum, Cervical vertebrae 7 (C7), Thoracic vertebrae 4 (T4) and Lumbar vertebrae 5 (L5). Markers placed on each Acromion right and left, one marker at C7, one 10 cm below C7, one at L5/S1, one 10 cm above L5 and each side of femur greater Trochanter right and left.

Before start: Wait until all IMUs are online. Set metronome at 20 BPM with 3 seconds between beats.

Start:

1. Postural test
   a. Start the recording and when everything is online, jump three times.
   b. Full flexion (1 beat). Wait 1 beat. Return to natural posture (1 beat).
   c. Full extension (1 beat). Wait 1 beat. Return to natural posture (1 beat).
   d. Full lateral bending left (1 beat). Wait 1 beat. Return to natural posture (1 beat).
   e. Full lateral bending right (1 beat). Wait 1 beat. Return to natural posture (1 beat).
   f. Full rotation left (1 beat). Wait 1 beat. Return to natural posture (1 beat).
   g. Full rotation right (1 beat). Wait 1 beat. Return to natural posture (1 beat).
   h. Repeat all postures with trying to bend the spinal column only without help of the hip.
   i. Stop recording OMC and IMU

2. Work-task tests
   a. Start the recording and when everything is online, jump three times.
   b. A box is put on the floor 0˚ (in front) of the participant. Lift the box up (1 beat) from the floor (don’t bend legs) onto a table (in front of the participant) (1 beat waiting). Then lift the box again and place it back on the floor (1 beat). Repeat 3 times. Wait a few beats (2-3) before you continue with next task.
   c. A box is put on the floor at 45˚ to the side of the participant. Lift the box up from the floor (don’t bend legs) (1 beat) onto a table (in front of the participant) (1 beat waiting). Then lift the box again and place it back on the floor 1 beat. Repeat 3 times. Wait a few beats (2-3) before you continue with next task.
   d. Stop recording OMC and IMU
C. LPMS-B2 specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LPMS-B2</th>
<th>LPMS-B2 OEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output range of Euler angle</td>
<td>Roll: ±90°, Pitch: ±180°, Yaw: ±180°</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>400Hz</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>0.01°</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>&lt;0.5° (Static), &lt;2° RMS (Dynamic)</td>
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</tr>
<tr>
<td>Max. instant impact (0.1 ms)</td>
<td>10,000g</td>
<td></td>
</tr>
<tr>
<td>Output data type</td>
<td>Raw data/Euler/Quaternion/Linear acceleration/Air pressure/Altitude/Temperature</td>
<td></td>
</tr>
<tr>
<td>Latency</td>
<td>15 ms</td>
<td></td>
</tr>
<tr>
<td>Internal sampling rate</td>
<td>400Hz</td>
<td></td>
</tr>
<tr>
<td>Communication interface</td>
<td>Bluetooth Classic 2.0 (BLE4.1 Optional)</td>
<td></td>
</tr>
<tr>
<td>Max. baudrate</td>
<td>921600 bps</td>
<td></td>
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<tr>
<td>Communication protocol</td>
<td>LPBUS</td>
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</tr>
<tr>
<td>Size</td>
<td>39x39x8 mm</td>
<td>16x31x4 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>12 g</td>
<td>2g</td>
</tr>
<tr>
<td>Communication distance</td>
<td>&lt;20m</td>
<td></td>
</tr>
<tr>
<td>Max. data update rate</td>
<td>400Hz</td>
<td></td>
</tr>
<tr>
<td>Power consumption</td>
<td>110mW @ 3.3V</td>
<td></td>
</tr>
<tr>
<td>Power supply</td>
<td>Lithium Battery &gt; 6h (3.7V@230mAh)</td>
<td>3.3-5.5V DC</td>
</tr>
<tr>
<td>Working temperature</td>
<td>-20–+60 °C</td>
<td>-40 – +80 °C</td>
</tr>
<tr>
<td>Connector*</td>
<td>Micro USB, type B</td>
<td>SM02B-SURS-TF</td>
</tr>
</tbody>
</table>

Figure 23. The specifications of LPMS-B2 from the LPMS-B2 manual.
Figure 24. The specifications of LPMS-B2’s accelerometers, gyroscopes and magnetometer from the LPMS-B2 manual.

LPMS-B2 manual:
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