Ergonomic Evaluation of upper limb movements in the automobile production measured by means of motion capturing

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Abstract

Concerning that many production tasks are still mainly manual, examining typical workloads at production sites is a challenging task. Currently, workspace design is evaluated by experts, filling ergonomic evaluation sheets by estimation of postures and loads. The use of motion capture systems could improve the evaluation process of body postures to achieve accurate data and detailed results on working postures. With regard to the automotive industry motion capturing should be used to analyze movements while performing assembly line tasks, to identify critical postures and to reduce risks of upper limb disorders due to suggesting enhancements of working stations as well as working tasks. This study compares the use of two different motion capture systems (one optical based system: Vicon Nexus; one inertial based system: MyoMotion Noraxon) for the automotive production. 11 participants inserted two fuel pipes and six plugs of different sizes at a selected workplace which was part of the pivot assembly line at an automotive OEM. The results of Vicon and Noraxon were implemented in an ergonomic assessment worksheet to identify critical postures of the upper limb throughout the entire working cycle. Systems were compared due to the results out of the ergonomic evaluation. Furthermore results of the wrist joint angles, calculated with the MyoMotion system, and typical plug insertion forces, measured with a load cell, are presented. Results of Vicon and Noraxon do not differ significant for the summed up value of the ergonomic evaluation. No strain of the neck is identified for the selected tasks. Percentage of work above shoulder height differs between 43 -70% for Vicon and 55-75% for Noraxon between participants. Reasons for intra-individual differences might be due to sensor attachment as well as natural variability of movements. Joint angles of the wrist exceed critical ranges of movement during some tasks, but for the plug insertion no exceeding of critical ranges was examined. Nevertheless plug insertion proved to produce muscular strains due to the high measured forces.

Keywords: Motion capturing, ergonomic evaluation, joint angles, upper limb disorders, Anybody

1. Introduction

Ergonomic workspace design gained great importance within the last ten years in the automobile production. Although automation of many processes is increasing the greatest part of production tasks is still manual which leads to high workloads on the human body (Schaub et al. 2012). Due to shorter cycle times and simplified tasks cycles are characterized through high forces as well as high repetition rates (Diaz et al. 2012). Hence the number of work incapacity days in the automotive production industry in Germany is quite above the average of the whole population (report of the health insurance agency BMW BKK 2012). Furthermore 33% of the work incapacity days are related to musculoskeletal symptoms. Figure one shows the percentage of different afflictions responsible for the work incapacity days. According to Hussain 2004 the most frequently regarded musculoskeletal symptoms among truck assembly workers are pain in the lower back, neck and shoulders. Winter 2010 confirmed these results when evaluating overhead work with 41 assembly line workers where 21% had lower back pain, 23% neck problems, 17% shoulder pain and 9% problems with their wrists and hands. Aside this common problems many authors describe high prevalence for hand and wrist symptoms among automobile assembly workers (Silverstein et al.1979; Jantree et al. 2010). Due to this most of the ergonomic evaluations concentrate on upper limb movements and resulting upper limb disorders. Currently workspace evaluation and design is done by experts, filling ergonomic evaluation sheets by estimation of postures and loads. Lawaczek 2001 gives an overview of the 130 existing methods for evaluating body postures and movements with their benefits and disadvantages. As the evaluation process by experts is known to depend on the subjective assessment of the observer this paper suggests a method for evaluating workspace design

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as well as working postures and tasks with motion capturing systems.

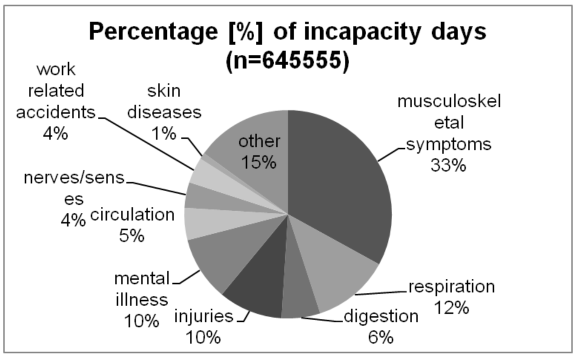

Figure 1: Percentage of musculoskeletal disorders accounting for the work incapacity days in 2012 (report of the health insurance agency BMW BKK 2012)

Motion capture systems are well known for their use in medical and sports studies for capturing movements of patients as well as athletes. Nevertheless they could be useful to analyze movements while performing assembly line tasks, to identify critical postures and to reduce risks of upper limb disorders due to suggesting enhancements of working stations as well as working tasks (Gudehus 2008; Lawaczek 2001).

2. Materials and Methods

2.1. System and Setup for motion capturing

Motion capturing at production sites was done before by Gudehus 2008 who defined benefits and disadvantages of several capturing systems. Furthermore Gudehus analyzed few ergonomic evaluation tools for their use with motion capture data. Due to his requirements he decided to use a gyroscopic based system for motion capturing in combination with the established OWAS method for ergonomic evaluation. Different needs in the current study leaded to another study design than presented by Gudehus. Two different motion capture systems are compared for their use in the automotive production concerning specified assessment criteria, like usability, flexibility, system accuracy etc. The optical based system - Vicon MX T10- and the inertial based system - MyoMotion Noraxon- are evaluated at a common assembly workspace which was part of the pivot assembly line in a German OEM.
Standardized Plug-In-Gait marker positioning for the upper body, using 21 retro reflective markers, and six infrared cameras sampling at 100 Hz, were used for data acquisition with Vicon. Cameras were arranged in a semicircle around the workspace with three cameras in a low position and three cameras adjusted in a higher position (figure 2). The system was calibrated once a day before recording. Data was collected with Vicon Nexus software. After reconstructing and labeling with the Plug-In-Gait guideline Vicon provides 3-D coordinates of each marker for the upper body.

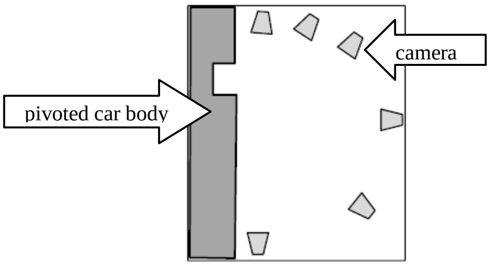

Figure 2: Camera positions for collecting motion data with Vicon

Ten inertial sensors at the subject's upper body were used to capture data with the MyoMotion system. Sensors were fixed with the help of special stripes. Three sensors had to be positioned at each segment of the arm, three sensors were used for torso motion and one sensor detected the head movements (figure 3).

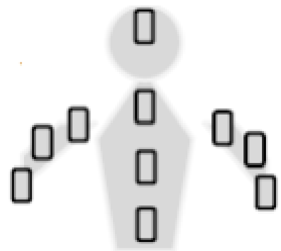

Figure 3: Positions of the ten inertial sensors located at the upper body

Calibration of the system was performed once for each participant with a defined calibration pose. One inertial sensor unit consists of three orthogonal arranged acceleration sensors as well as three gyroscope sensors and one magnetic sensor which could be switched off optional in case of magnetic disturbance. A receiver recorded the wireless sensor signals. Data was analyzed with the User Interface MR3. MyoMotion provides raw data of acceleration and gyroscope sensors as well as joint angles between two segments.
Finally 3-D coordinates and joint angles were transferred to an excel tool for further analyzing and in Matlab.

2.2. Study design

11 unimpaired and untrained male participants (mean age 25,4 years, SD 4,5, body height 183cm, SD 5,53) inserted two fuel pipes and six plugs of different sizes at a selected workplace which was part of the pivot assembly line at an automotive OEM. Mean time to perform one assembly cycle was 60 s (SD 10,6). Participants were marked

before starting the record. All trials started at a defined point by picking up the first fuel pipe and inserting it. The equal process was repeated to fix the second fuel pipe. Finally six plugs were crimped in different heights at the car body before taking up the final pose for signalizing the end of the record. Due to occlusion problems and to ensure exact marker and sensor positions, motion was captured in separated trials for Vicon and MyoMotion. Randomizing the order avoided learning effects. Each participant had to conduct the assembly task twice equipped with each system. All trials started and ended with a defined posture. T-Pose was used for Vicon (left side of figure 4). MyoMotion uses a standing pose with straight or flexed arms (right side of figure 4) which counted as calibration position simultaneously.

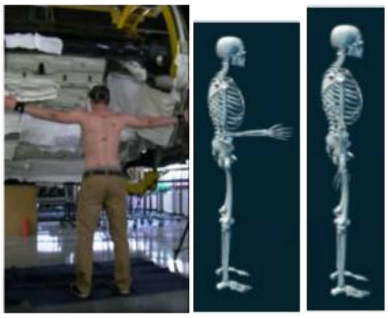

Figure 4: calibration pose; left side: Vicon; middle: MyoMotion: arms flexed; right side: MyoMotion: standing straight

2.3. Ergonomic Evaluation

A software tool for assessing body postures was developed using Matlab (MathWorks, Inc., Natick, MA) software package. The tool requires joint angles as the input for conducting the ergonomic evaluation. Due to this MyoMotion data could be imported directly from the excel file whereas Vicon data needed further analysis, which was performed in Matlab as well.

This intermediate step included the calculation of joint angles from the 3-D coordinates of the Vicon data. For analysis, planes each one characterized by three markers were built. When calculating the angular movement between two planes a vector normal to each plane is defined. The scalar product between the two normal vectors is build to examine angle movement between planes. An example for the calculation of the angle between head and upper body is given in figure 5. All other joint angles were calculated similarly.

The developed software tool is performing an ergonomic evaluation of body postures based on the evaluation sheet AbaTech which consists of 19 characters. The attributes one till then analyze the body posture. Feature eleven assesses the handling of loads and features 12 till 19 take environmental conditions into account. Each assessment criteria is analyzed by the amount and the duration of exposure. The risk assessment is based on a three-zone-concept (green, yellow, red). Risk assessment is done for each single attribute. An overall result, called EBI (ergonomic value index), is calculated additionally.

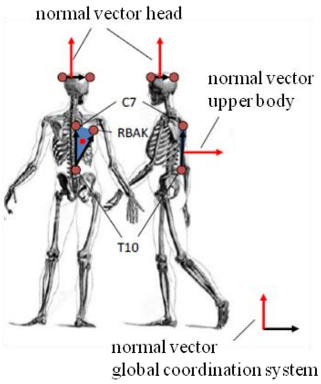

Figure 5: Joint angle calculation from 3-D coordinates in Matlab

AbaTech is a commonly used tool at a German OEM to evaluate ergonomic loads of different workplaces and is therefore utilized in this study. Plus a pretest showed good results for implementing the motion data of both systems in AbaTech, whereas implementing the data in other well known ergonomic evaluation sheets (for example EAWS) was difficult. The current study analyzed the percentage of the following assessment criteria for one assembly cycle (60 s):

- working height when standing
- exposure at the neck
- Standing erect, elbow at/above shoulder height
- Torso twisting and bending

The 15 remained assessment criteria are not evaluated due to the task. Methods for analyzing the criteria differed between the motion capture systems depending on sensor output information.

Working height

Working height was estimated for both hands of the participants independent. Based on this procedure the amount of time, for tasks performed at one defined working height (for example between 85 and 120 cm) is summoned up for both hands. This leads to the possibility of higher time percentages than 100%. Limiting values for the working height are the following:

- Green= heights between 85 and 120 cm
- Yellow= heights between 55 and 85 or 120 and 155 cm
- Red= beyond the other values

Evaluating working height causes no difficulties with Vicon as the data allocates 3-D coordinates of each marker and therefore positions within the calibrated volume. It was not possible to estimate working height with MyoMotion data as MyoMotion does not provide information about marker position in the room.

Exposure at the neck

To evaluate the exposure of the neck, the time percentage when the neck was more than 4 s in one static position was taken into account.

- Green= between 0 and 5% of the time
- Yellow= between 5 and 30% of the time
- Red= above 30% of the time

The exposure of the neck is characterized due to the movements of the head in relation to the upper body. Limiting values for the static positions were:

- > 55° for rotational movements
- > 37,5° for bending forward
- > 55° for bending sideward

Analyzing the Vicon data shows reciprocal influences of the forward and sideward head angle when evaluation angles with the help of a normal vector at the head. MyoMotion provides direct information about the head angles.

Standing erect, elbow above shoulder height

Risk assessment for over head work depends on the handled loads. This study relies on the case handling without substantial loads (< 10 N) where:

- 0-10% of the time is characterized by green
- 10-30% of the time is characterized by yellow and
- 30-100% of the time is characterized by red.

For Vicon data work above shoulder height could not be evaluated with help of the shoulder joint angle directly. It was therefore calculated with the z-coordinate of elbow and back. If the z-coordinate of the elbow marker was above the marker at the participant's back the elbow must be suited above the shoulder. For MyoMotion data work above shoulder height was calculated with the shoulder and elbow angle. It was therefore possible to calculate x and y with the know relation between upper and under arm (figure 6). Work above shoulder height was considered when x exceeded y.

Torso twisting and bending

Movement of the torso is subdivided in three areas depending on the amount of the twisting and bending angles. The current study relies on rotation movements characterized by more than 15° as well as bending forward movements ranging from 30 till 90°. Limiting values for this case are:

- Green: 0-15% of the time
- Yellow: 15-35% of the time
- Red= above 35% of the time

Time percentages of torso movement could be analyzed with both systems.

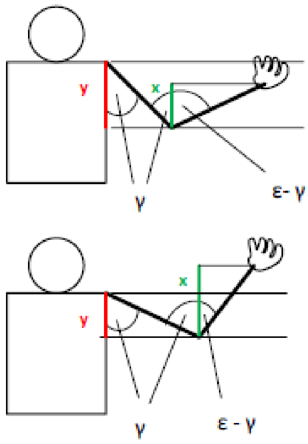

Figure 6: Estimation of work above shoulder height for MyoMotion data

Results of the analysis are presented in Matlab. The analysis provides time percentages of each body posture within the characterized values as well as the maximum and minimum joint angles for each analyzed body segment. The final output of the ergonomic workspace evaluation with AbaTech is an overall score which differs from red to green the higher the better. No loads are considered for this special working task as there occurred little weights only. Plug insertion forces which are known from objective measurements with a tensile testing machine were taken into account additionally. Joint angles for the wrist were analyzed while inserting plugs. Wrist angles were evaluated similar to the other assessment criteria. Joint angles for flexion extension, radial/ ulnar deviation and supination/ pronation of the wrist were recorded. This study presents the results of flexion and extension angles. Furthermore the joint angles are only analyzed for the time of plug insertion due to the fact that especially the combination of extreme wrist angles and high applied forces could lead to upper limb disorders.

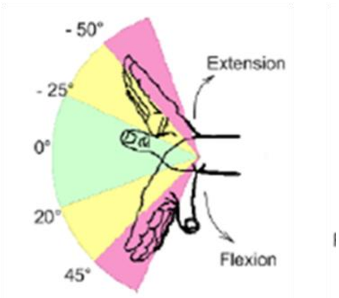

Figure 7: Characterization of flexion and extension angles in three areas

As there occurred to be different movement strategies – participants used the right as well as the left hand for plug insertion – both hands were analyzed equally. The areas for characterizing flexion and extension angles are shown in figure 7.

3. Results

Due to different body heights, abilities and experiences the results of the ergonomic evaluation differed slightly between subjects. It is therefore not possible to perform a between subject comparison. Hence the motion capture systems were compared individually for each participant. Assembly times varied from 45 up to 81 seconds for all participants.

Ergonomic value index (overall score)
The ergonomic value index showed insignificant differences in the results for each subject when comparing the results of both motion capturing systems. Nevertheless the index differed greatly between subjects from 32 up to 55 points (yellow area) which leads to the suggestion that the index depends on the abilities of the participants to fulfill the tasks.

Working height
Participants performed tasks most of the time within the "red area". Figure 8 shows that ten out of eleven participants worked during 50-60% of the assembly cycle time within the red area. Due to the design of the selected workstation fuel pipes as well as a number of plugs needed to be inserted at or above shoulder height causing the high time percentages in the red area. There was just one participant working in the green area most of the time. This might be due to different abilities or movement strategies of the participant.

Exposure at the neck
Data provided almost no exposure of the neck for the selected workspace. This is most reasonable because the tasks demand small movements of the neck and head only. Therefore the exposure is located within the green area.

Standing erect, elbow above shoulder height
Both motion capture systems showed small differences when evaluating over head work for each participant (figure 9). Differences could be caused by slight different movements between the trials. Measurement errors and inaccuracy might be another reason. It should be noticed that the assessment criteria is located in the red area for every participant.

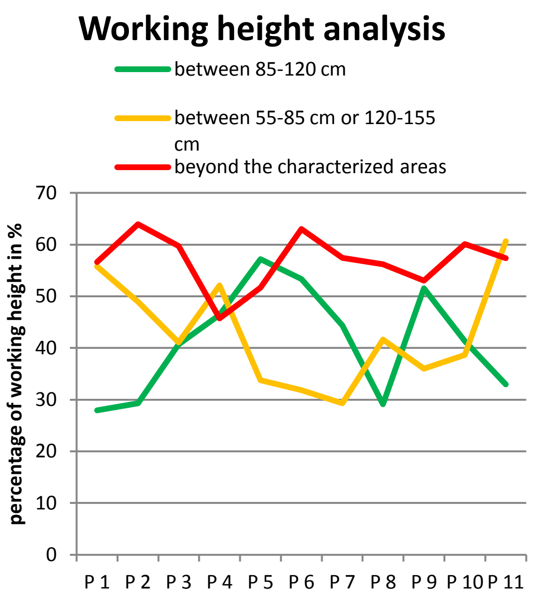

Figure 8: Working height analysis based on motion capture data from the Vicon system

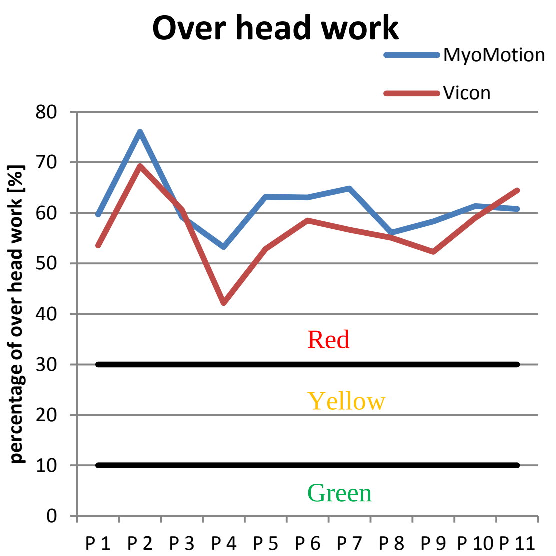

Figure 9: Results for the percentage of over head work for both capture systems and each participant

Torso twisting and bending
The results of the torso movement analysis include torso bending as well as twisting. Results show great differences in the values of some participants for both measurement systems. Especially participant number 2, 8 and 10 got differing values concerning the MyoMotion and the Vicon data. This might be due to variability of movement between trials. Furthermore it can be said, that most of the torso movements are considered to be in the yellow area (figure 10). There is only one participant where about 38% of the torso

movements extended 15° of rotation and/or 30-90° of torso bending movement.

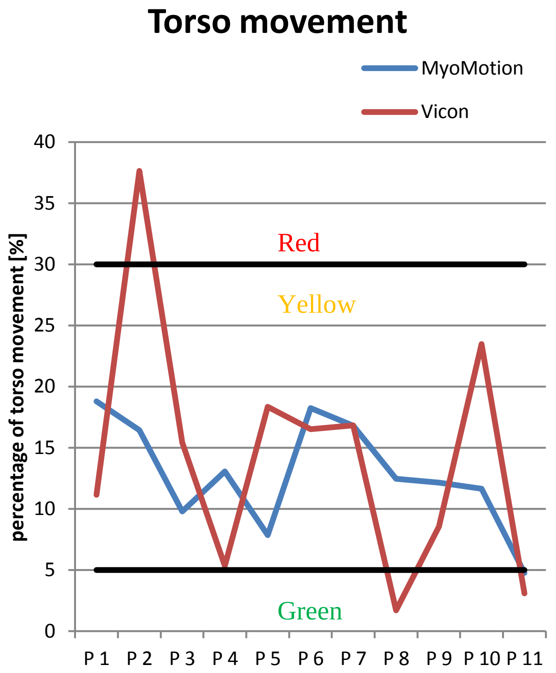

Figure 10: Torso movement characterized by rotational movements > 15° and bending movements from 30-90°

Wrist joint angles
During the whole assembly cycle participants capture wrist positions between -30° flexion for minimum and 80° extension for maximum. Most of the assembly cycle time the wrist is extended up to 40°. Flexion movements do rarely occur. Figure 11 shows an example for the wrist joint angles of one participant of both right and left hand.
It can be seen, that the participant extended his wrist most of the time. Extension joint angles varied from 5-45° for both hands most of the time. Analyzing the joint angle course for the right hand of the participant (red line, figure 11) shows joint angle deviations varying from 20 up to 49° when inserting the six plugs (Table 1).

Table 1: Joint angles for the plug insertion process

time when plug was inserted	Joint angle deviation
53 s	27°
57s	20°
62s	28°
65s	24°
71s	47°
75s	49°

Plugs were inserted with the right hand, beginning with the first plug after 53s and finishing with the last one after 75s. The first four plugs appeared to be in good reach at the height of the participant's torso. Therefore extension angles differed from 20 up to 28°. The last two plugs were located in a lower area which seems a reason for higher extension angles (47° and 49°).

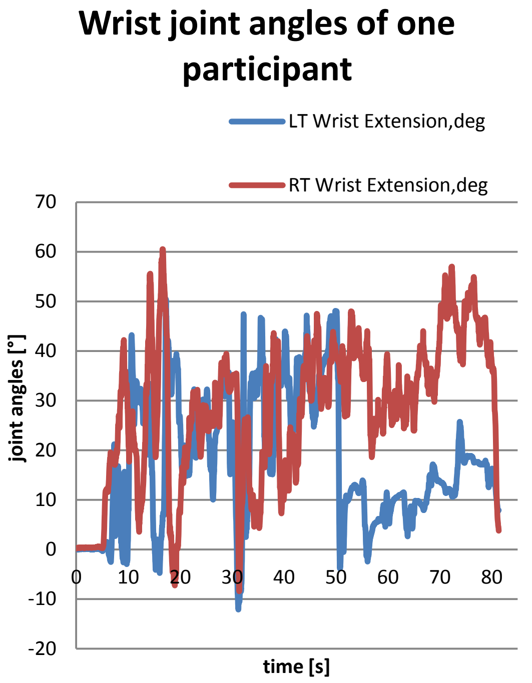

Figure 11: Wrist joint angles (Flexion and Extension) of both hands of one participant representatively

Joint angles for the other participants proved to be similar. Plug insertion forces vary depending on the size and material of the plug from 50 up to 150 N. The mean value for five different plugs (10 mm, 12 mm, 20 mm, 25mm and 35 mm) is 134 N when each plug was inserted five times.

4. Discussion

The goal of the study was, performing an ergonomic analysis with the help of two different motion capture systems. Due to low automated production tasks examining typical workloads at production sites is a still challenging. Currently workspace design is evaluated by experts, filling ergonomic evaluation sheets. Hence the evaluation process strongly depends on subjective opinions of the examiner. That is why the use of motion capture systems should be tested. Several advantages as well as disadvantages occurred for both systems preparing the measurements, recording the data and analyzing the results. Which motion capture system seems to be more valuable to gain results depends strongly on the evaluated work space, the conducting examiners and the goal of the study.

The goal of the current study was to improve the evaluation process of body postures by achieving accurate data and detailed results on working postures. Both the optical based system and the inertial based system proved to record valuable data for the analysis. Concerning the validation of joint angle data of the MyoMotion system a pretest was carried out. Joint angles examined with Vicon were used for comparison, as Vicon is a well evaluated and validated system. Pretests on a robot arm showed good correlation for the joint angles examined with Vicon and the ones calculated by MyoMotion. Joint angles evaluated with MyoMotion seemed therefore valuable. Interpretation of the joint angle results of the MyoMotion system in comparison to Vicon is still to be done for the motion data captured at the workplace.

Concerning the ergonomic evaluation both systems showed advantages as well as disadvantages. Obviously one common disadvantage appears because of the current properties of ergonomic evaluation systems. Those evaluation sheets were made for subjective evaluation whereas motion capture systems provide objective values. To analyze the existing assessment criteria varying methods of data analyzing were developed due to the differing data (Vicon: provides 3D coordinates, MyoMotion provides joint angles) of both systems. Several more ways of analyzing the data might exist. Therefore it is necessary to enhance ergonomic evaluation sheets for the use of motion capture systems as data provided by these systems is much more objective than data examined during visual examination. Furthermore there is a need of normalization of motion data to perform between subject comparisons and enable future analysis of production sites with digital human models.

The results of the ergonomic evaluation appeared to be quite similar for most of the assessment criteria except the torso movements. Stronger differences between the systems might be due to movement variability within the trials as well as measurement errors. Problems occurred for the optical based system because of marker occlusion. The most important error for the inertial system was the drifting of sensors because of the metal car body. The results of the ergonomic evaluation enable enhancements of the working station as well as the working tasks.

Because of high working heights tasks were performed between 30-100% of the time cycle over head. Hence the working height must be soon changed to a lower level to reduce risk of upper limb disorders. No exposure of the neck was examined. During five to 20% of the assembly line cycle torso movements extended the limited values including rotation >15° and bending forward between 30 and 90°. The working task could therefore be improved by a different way to facilitate parts. It might be a good opportunity to facilitate parts on a small height adjusting dolly to avoid rotations as well as bending forward when picking up parts.

The determination of the wrist angles showed an extended wrist during most of the assembly task. There occurred to be a difference when plugging in parts in good reach of the participants torso or in a lower area beyond the participants pelvis. Extension in the wrist appeared to be higher with lower assembly positions. Furthermore high forces must be applied for inserting plugs. Forces between 100 and 150 N in combination with wrist extension angles above 25° could lead to higher prevalence of upper limb disorders especially as there are high repetition rates additionally. Suggestions for enhancing the wrist angles could be higher assembly positions for plug insertion.

Further analysis of these data should be done with the help of a finger-hand-arm model based on the software package Anybody. Goals for the musculoskeletal modeling are:

- reducing strains for the fingers and wrist when inserting plugs and
- investigating movement strategies.

5. Conclusion

With regard to the automotive industry motion capturing was used to analyze movements while performing one specified assembly line task of the pivot assembly line. Both systems proved to be valuable to asses an ergonomic evaluation. Intermediate steps are needed to evaluate the assessment criteria of the evaluation sheet with motion capture data. Nevertheless ergonomic work place evaluation worked out well. Wrist joint angles and forces could be examined additionally to provide information about the possible risk of upper limb disorders. Critical postures were identified and enhancements of working stations as well as working tasks were suggested. The method was developed for one defined working station but could be easily transferred for analyzing other assembly line tasks.

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