A DATA COLLECTION METHODOLOGY TO PERFORM DHMS-BASED ERGONOMIC ANALYSIS OF MANUFACTURING TASKS

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ABSTRACT
A key stage in any simulation project is the data collection process. In most simulation-based ergonomic analysis, data from the movements performed by the operator during the task are obtained either by direct observation, video observation or by means of a Motion Capture (MoCap) System. Direct or video observation methods are quick and inexpensive, however less accurate and objective than commercial Mocap Systems. MoCap Systems are much more expensive and limited to the use in laboratories. The objective of this paper is to present a data collection methodology based on the joint employment of the per-pixel depth technology and a free open source video analysis software. The proposed system is portable, low-cost and suitable for fieldwork. A real case study is presented to explain how objective posture data of a user performing a task can be obtained and used for its workstation analysis and improvement.

Keywords: ergonomics, workstation design, work measurement, digital human modelling and simulation, motion capture systems, data collection methodology

1. INTRODUCTION
Despite the contribution of Digital Human Modelling and Simulation (DHMS) methodologies and tools in increasing both the consideration and the efficiency in the treatment of the ergonomic aspects among production engineers, the effective design –and most often, re-design- of industrial workstations heavily relies on the quality and reliability of an efficient data collection phase (del Rio et al. 2012). Over the years several data collection methodologies have been used by researchers and scientists working in the field of workstation effective design. Among the used for acquiring motion data, the following two have to be regarded as the most used ones, i.e., (i) observation based methods (video based systems, walking-through observation, video capture and playback technology) and (ii) Motion Capture Technology (MoCap).

Observation based methods consist in observing the worker while performing the manufacturing operations and collecting information about the work methods. MoCap systems can be based on sensor located on the subject like accelerometers, acoustic transmitters, electromagnetic sensors, or inertial sensors. Optical MoCap systems based on stereophotogrammetry are by far the most widespread in digital human modelling for ergonomic simulation (Ausejo and Wang 2010). Optical reflective markers are attached to a test subject, who is then digitally filmed with several infrared cameras. Then, from the 2D marker position recorded at each frame, the 3D marker positions can be estimated using stereophotogrammetric methods. Some commercial examples are Viconpeak, Phase-Space, Optotrak, or Motion Analysis Corporation. It is generally accepted that all postures from motion capture technology are realistic and accurate (Stephens and Jones 2009). However, the MoCap technology increases the cost and it is usually difficult to use in real-world applications due to complexity, bulk and space requirements (Best and Begg 2006)

When observation-based methods are used to collect data from body postures, designers must use their experience and judgment to manually posture the body and hands of human figures to simulate the tasks (Zhou et al. 2009). This method can result a limitation in the accuracy of the model as it introduces subjectivity. On the other hand, MoCap driven models may help to overcome this limitation, but they present other drawbacks, such as the cost and the intrusive technology.

This paper presents a combined methodology of observational data and motion capture system in order to develop a DHM ergonomic analysis to improve workstation design. The proposed methodology uses two simultaneous different motion capture systems; a per-pixel depth sensing camera (ASUS Xtion) and a free software tool to perform video analysis (Tracker).

Although not originally created for this purpose, the per-pixel depth sensing technology (Patent US 2010/0118123 A1 of May 2010) is capable of tracking the orientation and position of the body segments of a user at a frame rate of up to 30 fps. It is commercially available in Microsoft Kinect and Asus Xtion PRO (see Figure 1).

The depth cameras have been established in recent research studies as an inexpensive, portable and markless 3D data acquisition device for anatomical position measurement (Dutta 2012, Clark et al. 2012). In the experiments of Dutta (2012) it was concluded that the Kinect is able to capture 3D posture coordinates with acceptable errors (RMS < 1.5 cm in the three directions) when the device is placed between 1 and 3 m from the camera. As a drawback, it is stated that Kinect has trouble detecting dark, shiny or rough surfaces.

Figure 1. Depth Sensing Device. (Source. Wikipedia Commons file "The Microsoft Kinect Peripheral for the Xbox 360")

Clark et al (2012) compared its accuracy to a commercial 3D commercial motion capture system in an experimental setup where different subjects performed postural tests. They concluded that commercial systems and the depth camera have similar reliability for the majority of the measurement of postural coordinates. Two important limitations have been noticed in their experiments, the presence of biases for outcome measures in pelvis and sternum and the inability to assess internal/external joint rotations in the limbs.

Tracker is a free and open source video analysis and modelling tool built on Java, able to track position, velocity and acceleration of point mass particles and two-body systems, intended for aiding in Physics education. It has been built as a part of the awarded Open Source Physics (OSP) Project sponsored by the National Science Foundation and Davidson College (comPADRE 2012). The strategy of most of the video analysis tools, including Tracker, consists in tracking discrete objects within the field of view of the camera and accounting for changes in position through time. Although the accuracy depends on the analyst's individual skills, the quality of the video and the size of the objects being tracked, it is generally considered acceptable (Bryan 2004; Hedrick 2008). The tracker interface to automatically follow (track) a mass point is presented in Figure 6.

In sections 2 and 3 the data collection methodology to develop Digital Human Modelling and Simulation (DHMS) is explained. In section 4, an illustrative real case study in the slate industry in which the data collection has been used is then introduced.

2. THE PROPOSED METHODOLOGY

The proposed methodology for data collection has been designed to fit a general DHMS improvement procedure. Usually in this analysis schema, the workstation improvement approach is divided into two phases. The descriptive analysis has the purpose of obtaining an ergonomic diagnosis of the task as it is in the present. The predictive stage implies the proposal of modifications (if needed) to the present workstation configuration, and the assessment of the level of improvement achieved by them. The data collection system described in this paper has been applied to both stages –descriptive and predictive- at the laboratory. However, in principle it could be easily used in real manufacturing environments because it is portable and it does not need to attach markers to the skin or clothes of the user being tracked.

The following steps are included:

1. **Observation of the real task.** By means of videos or in situ observation, general information can be determined such as work content, objects and layout main dimensions, and worker characteristics.
2. **Definition of work elements.** From the task observation, the main activity can be divided in fundamental tasks ("subtasks") that are repeated into the work cycle. The main plane of movement in which the subtask occurs should be taken into consideration to the division.
3. **Motion Data.** For each subtask, position of the MoCap system has to be adapted, so that postural data can be best recorded.
    a. Per-pixel depth camera. Usually the best location for the device is in front of the operator.
    b. Conventional camera. Placed on the main movement plane. If the movement mainly includes arms abduction or trunk lateral bending, the best camera position is in front of the subject. If the movement mainly implies neck, arms or trunk flexion over the sagittal plane, the camera is better placed 90˚ on the side.
4. **Information analysis and posture modelling** Raw data coming from the depth device has to be filtered and combined to obtain available data to perform the manikin training in the DHMS software. The following section describes with more detail this procedure. Tracker post-processing of the videos has to be performed to obtain the necessary data to validate and complete the angles characterized with the depth device. Finally, the information recorded (positions along the time) are the input data for the posture modelling of the manikin, and the basis to perform the biomechanical and postural analysis of the task.

The motivation for using both data collection systems is derived from the fact that some limitations of the depth camera have been detected apart from the ones above mentioned. Some of them, such as the inaccuracy to detect abduction movements of the extended arm or the trunk bending movements when the subject is turned 90˚ can be solved by breaking the task in fundamental elements in which the movements occur in the same plane (and so the device can be always placed oppositely). Some other limitations, such as the inaccuracy to detect arm positions in movements of extreme flexion (more than 80˚) when the subject stands in front of the device, can be solved by using a conventional camera placed perpendicularly to the depth device to check the movements on the Tracker post-process.

In the following section, the filtering techniques and the parameters configurations are discussed. In section 4, an illustrative case study is presented.

3. DATA CONFIGURATION

There exist several approaches to obtain kinematic data from the sensing technology. The developers of the depth sensor made available the Natural Interaction (OpenNI) middleware which provides position and orientation data of 20 body joints of the body. Windows also provided freely the Kinect for Windows Software Development Kit (Windows SDK version 1.6) with similar tracking features. MS Kinect or Asus Xtion can recognize six people appearing at a time and can track two users simultaneously. It is optimized to track standing or sitting users facing the device. (MSDN 2013). The visualization of the user being tracked is presented in Figure 2 (right).

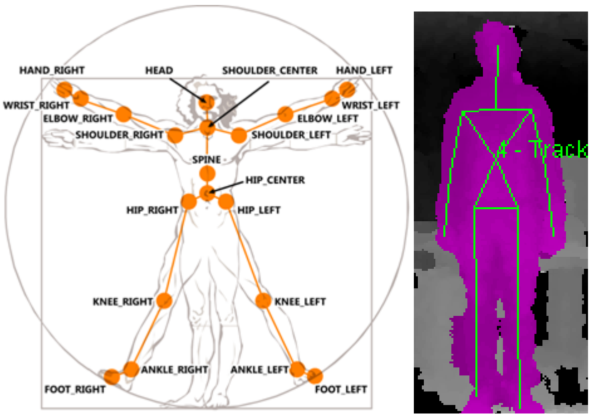

Figure 2. Skeleton Positions that are Tracked by the Depth Sensor (Source: Microsoft Kinect http://msdn.microsoft.com/)

Our experimental setup includes the use of the ASUS Xtion Pro with the OpenNI middleware (estimated price, 130 €) and Tracker 4.7x, Copyright (c) 2012 Douglas Brown and Wolfgang Christian, freely available at www.cabrillo.edu/~dbrown/tracker/.

The hip center joint provides the absolute orientation of the user. The position and orientation of each segment (child) is relative to the position and orientation of its parents. A Java application has been developed to store and combine the raw data to calculate the relative angles of the body. To do so, we had in mind the parameters that are the basis of the posture definition in Delmia V5R20, a commercial CAM software to develop DHMS. A simplified set of the degrees of freedom (without the fingers movement definition or the legs) available to set a posture is shown in Table 1.

Table 1. Degrees of Freedom that Define a Posture in Delmia V5R20 (A reduced set)

	DOF 1	DOF 2	DOF 3
Neck (N)	Flexion / Extension	Lateral R/L	Rotation R/L
Full Spine (FS)	Flexion / Extension	Lateral R/L	Medial / Lat. Rot
Right Arm (RA)	Flexion / Extension	Abduction / Adduction	Medial / Lat. Rot
(RF)Right Forearm	Flexion / Extension	Pronation / Supination	-
Right Hand (RH)	Flexion / Extension	Radial / Ulnar Deviation	-
Left Arm (LA)	Flexion / Extension	Abduction / Adduction	Medial / Lat. Rot
(LF) Left Forearm	Flexion / Extension	Pronation / Supination	-
Left Hand (LH)	Flexion / Extension	Radial / Ulnar Deviation	-
Clavicular (C)	Flexion / Extension	Elevation / Depression	-

The tracking joint information can be smoothed across different frames to minimize noise and stabilize the joint positions over time. One approach for smoothing the time series is to replace each value of the series with a new value which is obtained from an n-order polynomial fit to the 2n+1 neighbouring points (including the point to be smoothed).

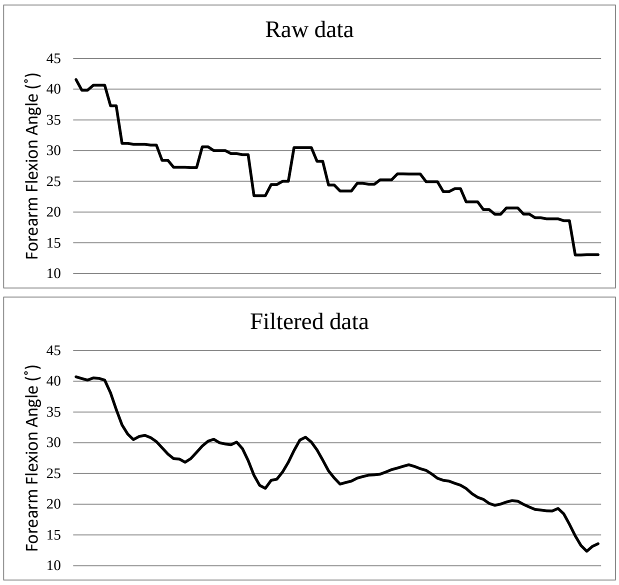

Figure 3. Forearm Flexion Angle Before and After the Savitzky and Golay Filter Application

This technique, known as the Savitzky-Golay Filter was proposed in 1964 and it has the advantage of preserving features of the distribution such as relative maxima, minima and width (Savitzky and Golay, 1964). Figure 3 presents the original right forearm flexion angle variation obtained from the depth device during some trials and the same data treated with a second order filter over seven points.

Once the different limbs of the body have been characterized, this information can be used as input into the postures modelling (by using the angles defined in Table 1). Although the angles variation is very detailed (data are acquired every 0.033 seconds), for the ergonomic analysis it is not of practical interest modelling 30 postures per second. Instead, we assumed that an input modelling of 3 postures per second was more appropriate to perform the modelling in reasonable time, as well as to conserve a realistic visual quality of the movement sequences.

4. CASE STUDY

This section presents the data collection methodology applied to a real case study of ergonomic analysis in a Spanish company devoted to the extraction and manufacturing of roofing slates. This ergonomic analysis is a part of a general improvement project which applied Lean Manufacturing, Modelling and Simulation to the proposal of standardization procedures for statistical control (del Rio, 2008), redefinition of the layout (Crespo et al. 2011) and the ergonomic analysis of other tasks (Rego-Monteil 2010).

The slate process is highly dependent on manual operations. One of them, at the end of the process is the packing station. Their work implies lifting, bending, performing repetitive work and working under pressure. These activities are extremely undesirable in terms of ergonomic impact as they will most likely provoke musculoskeletal disorders (MSD) in the long term. In addition, packers sometimes become the bottleneck of the process, blocking the exit of the final product.

4.1. Data collection methodology

The four steps of the proposed methodology to collect process data in the packers' case will be described in the following sections.

4.1.1. Step 1. General information

The first step is to characterize the work, the environment, and the worker.

The packers are responsible for performing one by one inspection of every single tile produced and packing them on crate pallets. Quality is assessed in terms of roughness, colour homogeneity, thickness and presence of imperfections - mainly quartzite lines and waving. Crate pallets are directly put on the ground so classifiers have to bend their back and extend their arms every time they place a lot of tiles. The operation is repeated until the pallet is full (around 2,300 tiles in three layers). The cycle starts with the classifiers taking a pile of tiles (a number between 10 and 12 tiles, depending on their thickness and geometry, and weighing circa 10 kilos) and walking to place them inside crate pallets.

In this company, packers usually are medium-aged men or women in the same proportion. They have been represented by the P50 of French population for proximity with their physical conditions. Their physical workstations include a table from which slates are picked up and several pallets for different thickness and qualities of slate. Geometrical information has been acquired in situ.

Figure 4. Packing Task in the Slate Process. (Source. Asociación Gallega de Pizarristas)

4.1.2. Step 2. Work elements

The second step of the data collection methodology is to define the work elements or subtasks. In particular, we can divide the entire classifier task in three subareas, to facilitate the analysis of each part:

1. Inspect, pick up and lift a group of slates
2. Transportation (turn around and walk up to the pallet)
3. Placement into the pallet and counting process. The placement of the piles occurs around 65 times per layer. For the purpose of this analysis, the placement operation has been divided in type I (worst ergonomic conditions, place tiles in the center of the first layer of the pallet), type II (all the rest of the placements in the first layer or any placement on the second layer), or type III (third layer)

4.1.3. Step 3. Motion data acquisition

The next step is the motion data acquisition, performed with the proposed system in our laboratory. A subject has been recorded performing the operations of pick up, transportation of slates and placement into a crate pallet. The experimental setup for the placement operation (type II) is shown in Figure 5. In this case, the disposition of the system cameras has been frontal to the user for the depth device and lateral (90˚) for the conventional camera. Both devices have been placed at a horizontal distance of 2 m and 1 m height.

Figure 5. Experimental Setup for Data Collection during Placement Operation

4.1.4. Step 4. Data Post-processing and postures definition

The depth camera opposite the subject performed a good control of each subtask movement. The lateral conventional camera provided a second set of angles to compare and complete the angles from the depth camera (especially trunk, arm and neck flexion, as shown in Figure 6).

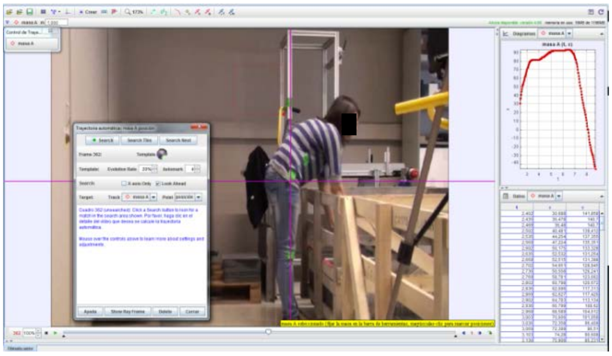

Figure 6. Tracker GUI over a Task Video during the Experimentation

Motion data have been used to perform the set of models that are presented in next section.

4.2. Task analysis

The workplace physical layout has been modelled with the geometrical information obtained in the first step. The model has been reproduced for male and female manikin when performing each of the subtasks defined on the second step. Each subtask is made up from the different postures. The posture definition included the motion data obtained in step three.

The descriptive analysis of the task includes the modelling of the inspection and pick up, the transportation and the placement from different types. The key performance indicators included to perform the ergonomic evaluations have been the RULA score and the L4/L5 vertebrae moment on the spine. RULA is a well-known ergonomic index, proposed in 1993 (McAtamney 1993). It has been especially designed for the assessment of tasks that mainly imply the upper limbs as is the case with the packers. The Spine Compression value is a complementary measure of risk of MSDs. According to NIOSH guidelines, compression force on the intervertebral disk over 3.4 kN may eventually lead to injuries. Both RULA scores and L4/L5 values are provided by Delmia V5R20.

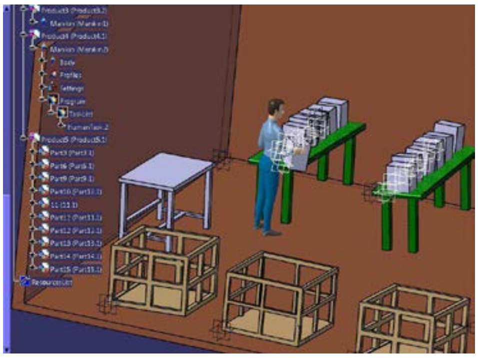

Figure 7. Model Capture of the Inspection and Pick up Operation

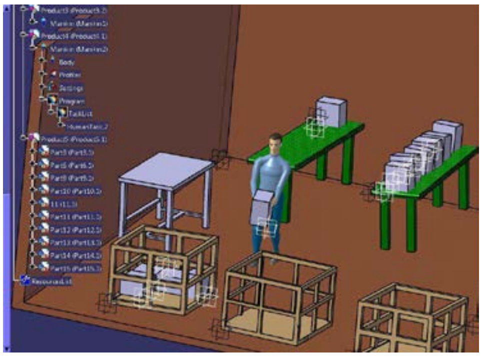

Figure 8. Model Capture of the Transportation of a Group of Slates

The pickup operation model is shown in Figure 7. This task is performed at the beginning of the cycle. Each tile is inspected to assess its quality and the group of tiles (around 10 or 12) is then picked up. The transportation is presented in Figure 8. The placement operation has been modelled for the worst (type I), intermediate (type II) and best conditions (type III), as it can be seen in Figure 9, Figure 10 and Figure 11 respectively.

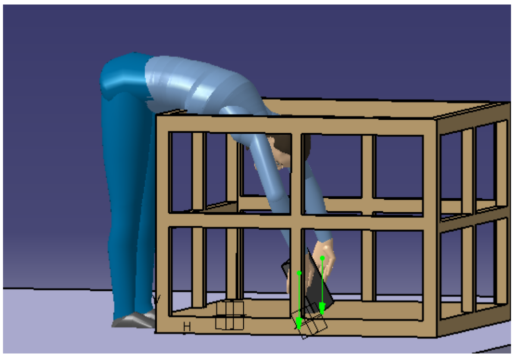

Figure 9. Model Capture of the Placement Operation in Worst Conditions (Type I)

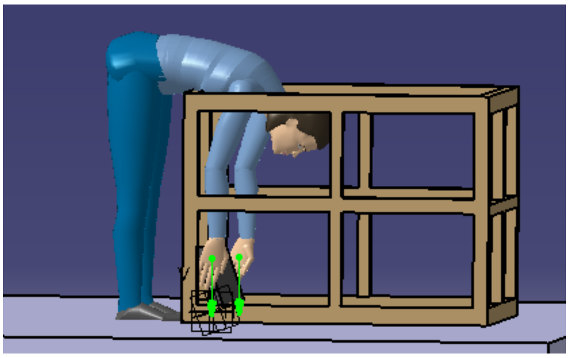

Figure 10. Model Capture of the Placement Operation, Intermediate Conditions (Type II)

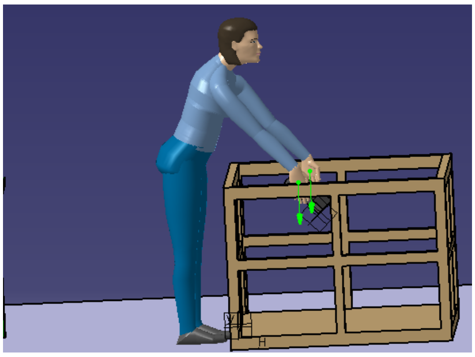

Figure 11. Model Capture of the Placement Operation, Best Conditions (Type III)

Ergonomic analysis results are summarized in Table 2. The postural risk is measured by the RULA index, which classifies the risk of developing MSD's from 1 (no risk at all) to 7 (urgent need of change). The L4/L5 compression on the spine accounts for the spine stress during the task. The NIOSH limit of 3,400 N has to be regarded as a reference for safe or unsafe task. Both maximum values and average are useful to describe the risk profile of the task. On the one hand, the maximum gives an idea of the pick forces achieved during the subtask. On the other hand, the average is a measure of cumulative stress.

Table 2. Ergonomic Results of the Packer's Task

	RULA		L4/L5 Compr. (N)	
	Average	Max	Average	Max
Pick up	3.54	6.00	748.92	1511.11
Transport	2.58	5.00	1168.96	1328.26
Placement (type I)	7.00	7.00	2852.00	4647.00
Placement (type II)	6.42	7.00	1693.63	2798.00
Placement (type III)	3.14	5.00	1168.63	1328.00

The pickup, transport and type III placement operations remain in relatively safe levels of postural risk and spine compression. Types I and II placements show a high risk profile in terms of RULA score. In the case of type I placement, the task is also very hard when considering the spine compression (that exceeds the NIOSH safe limit).

For the packers, trunk and arms are very likely to suffer MSD and therefore, these results suggest the need to redesign the task to alleviate their work conditions. The overall placement risk has been obtained by calculating a weighted average, in which the weigh is the frequency of each type of placement (Table 3)

Table 3. Overall Assessment of the Placement Operation

Type I	Type II	Type III
12%	55%	33%
Overall RULA = 5.34		
Overall L4/L5 = 1640.51 N		

Therefore, the objective of the workplace improvement is to reduce the overall RULA and L4/L5 values of the present workstation configuration.

4.3. Improvement measures

The proposed improvement for this task implies to use a modified crate pallet with an accesible lateral part to help its fill. It is initially placed on an automatic lifting platform at the corresponding ergonomic standard height avoiding problems to the worker (70 cm from the ground in our case). As the classifier fills the pallet with a row of plates, he can operate the automatic mechanism of the platform so that it is lowered and he can continue to fill the pallet with the slates always at the same height, which would not involve any physical effort that might cause ergonomic risks in the long time.

The analysis of this task implies predicting the postures that the new workstation would produce. The experimental setup has been also used to obtain motion data of the proposed modification.

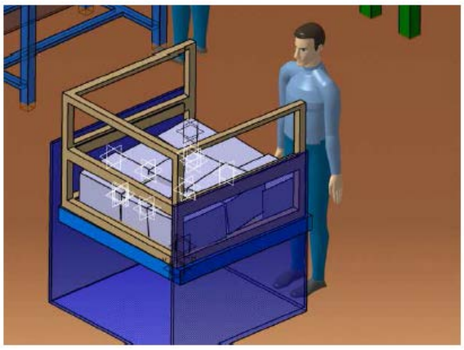

Figure 12. Proposed Workstation to Reduce the Ergonomic Risk of the Placement Operation.

In this case the filling process of each layer is equivalent. However, there still exists a difference in the placement of the slate blocks closer to the free part of the operator or the farthest possible. The ergonomic analysis of this workstation proposal is provided in Table 4.

Table 4. Ergonomic Results of the Modified Placement Workstation

	RULA		L4/L5 Compr. (N)	
	Average	Max	Average	Max
Placement (closest)	2.47	5.00	627	2495
Placement (farthest)	4.56	7.00	1153	2650
Overall	3.52	-	890	-

As it can be noticed in Table 4, the maximum value of the global score in RULA is still high. However, the average value in the improvement is much lower and so, better. For this reason it can be said that the proposed improvement would actually reduce the ergonomic stress of the operator.

5. CONCLUSIONS

A general methodological description for the motion data collection to perform ergonomic analysis and improvement projects of manufacturing tasks has been presented. The proposed methodology is portable, markerless and very affordable, especially when compared to other MOCAP systems. An illustrative case study has also been described.

During the experiments, it became clear that the error of the depth device was motion dependent and for large range of motion the errors were larger. Although there are several references that had studied the accuracy of the device to track 3D measurements, these practical considerations seem to be systematically not considered in the studies yet. More research has to be performed to clearly establish the practical limitations to obtain reliable posture information in the field.

This work supposes an improvement compared to the traditional observation of videos for estimation of postures when performing a task. However, a limitation of this approach is that, until now, the posture input modelling into the DHMS tool is still a manual task, and therefore there is a limitation on the number of postures per second to be introduced for practical reasons. We are currently working on the automation of the postures definition to solve this problem. To do so, a different but supplementary issue has to be regarded. The postural information needed to simulate a task is dependent on the speed of the movement. Variation between consecutive data should be considered as a factor to determine the appropriate number of postures that have to be introduced on the model. This is directly related to the tracking frequency of the depth device. The optimal solution would be an adjustable recording in which frequency is established according to the motion observed. Our future work lines also include this approach to the problem.

Another important advantage of the use of this methodology compared with the traditional visualization of videos is the possibility to obtain other useful information to define the task. The tracked data can be used to obtain information of the speed, acceleration, cycle time, frequency, rest time, within-minute range variation, between-minute variation, etc. However, dynamic aspects of the task are often disregarded (Wells et al. 2007). Probably this is related to two main factors. On the one hand, there used to be a need of more sophisticated tools to obtain speeds and accelerations. On the other hand, because of the lack of standardized criteria (such as speeds, work pace or repeatability) of the maximums to establish whether the risk exists in the task or not. The potential of a data collection methodology such as the one proposed is also linked to the development of dynamic ergonomic standards.

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