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Sonographers' Workplace Improvement: Ergonomics Evaluation using Modelling and Simulation Software

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Abstract

The aim of this paper is to carry out an ergonomic assessment of sonographers' activity by means of advanced modelling and simulation software and to verify the relative literature evidences. The objective is to arrange a support tool for the risk assessment that permits a preventive analysis and the identification of the best working conditions. Modelling and simulation of abdominal ultrasounds (about 9 minutes long) allowed to analyse the anthropometric and biomechanical risk exposure of the workers using tools and features available in a software.

Keywords
Human factors; ergonomic design; digital human; Jack; ultrasound

1. Introduction
The authors started a research project on ergonomics assessment of sonographers' work activities [1] with two objectives. The first one is to carry out a multicriteria and integrated ergonomics evaluation of sonographer activity. The second one is to define guidelines for workplace design, identifying the best working conditions. The research project began with a critical and systematic literature review mainly finalised to characterise the investigation level of sonographers' activity. The literature highlights the main symptoms and disorders experienced by sonographers. The body areas with pains most prevalent and frequently quoted in technical-scientific publications are neck, shoulder, wrist, upper back, and low back [2-12]. These are mainly due to static flexion of the head, frequent flexion and torsion of the body, uncomfortable postures for long time periods and inadequate sitting. The analysed papers rarely study the relationship between risk factors and prevalence of symptoms and pains, as well as the effect of corrective measures and improvements on the disorders prevention. Furthermore, the assessments indicated in literature are based almost exclusively on self-reported information from interviewees and they are not supported by specific diagnoses. The literature also provides recommendations to prevent injuries and ergonomics guidelines to design workstations and to carry out tasks [10-14].

2. Materials & Methods
Digital Human Modelling (DHM) can be considered a digital representation of the human inserted into a simulation or virtual environment to facilitate prediction of safety and/or performance [15]. DHM is intended to support and facilitate the new product and process design and enables engineers of various disciplines to incorporate ergonomics science and human factors engineering principles in the workplace design process. Using realistic digital human in computer simulation is a method to take the early consideration of ergonomics issues in the design and to reduce the design cycle time and cost [16,17]. The digital human model, also called manikin, is an essential part of human modelling software. According to Badler [16], manikins can be characterised in a general way along five dimensions: appearance (two-dimensional graphics, three-dimensional wireframe, etc.), function (cartoon, skeleton with joints, kinetic model, force limits, etc.), time response (off-line simulation, interactive manipulation, etc.), autonomy (interacting, making decisions, etc.) and individuality (gender and age, anthropometric data, etc.). The function seems to be the most important of these dimensions in ergonomics and several studies have been performed

to build human biomechanical models [18]. The ergonomics evaluation presented in this paper has been developed with the software Jack (version 7.1) commercialised by Siemens Product Life Management Software Inc.

The University of Pennsylvania, in the late 1970s, developed this digital human model (Jack) to perform ergonomics assessments. After a decade, Jack had an enfleshed 3D avatar and a sophisticated set of inverse kinematics routines to allow a user to easily manipulate simple movements and object-grasping tasks [19]. The software enables users to create virtual environments by modelling them, inserting human figures, assigning tasks to digital humans, and obtaining information about the interaction between the digital human and the environment. Jack is based on a high-fidelity human model with accurate joint limits, a fully defined spine and flexible anthropometric scaling. It allows to consider strength requirements, visibility, multi-person activity, reach zones, grasp and manipulation of tools or objects, foot pedal operation, and injury risk. Jack provides a range of tools to conduct an ergonomic assessment of the task. According to Lämkull et al. [20], these tools could be divided in three groups: quantitative evaluation tools, semi-quantitative tools, and tools for discomfort, anthropometry, human performance and cognition. Quantitative tools are used to evaluate working postures and physical workloads, considering specific risk factors related to a single posture/movement or to a complete task. Quantitative evaluation tools are listed below and in Jack they are grouped in a separate add-on module called Task Analysis Toolkit (TAT).

- Lower Back Analysis (LBA): it determines the forces acting on the low back by evaluating postures and load conditions.
- Static Strength Prediction (SSP): it estimates the percentage of the working population able to perform (in terms of muscular static strength) a task.
- NIOSH: it calculates a recommended weight limit and a lifting index for a given manual lifting/lowering action or an overall index in the case of multiple tasks.
- Predetermined Time Standards (PTS): it quantifies the time required to perform a task by dividing it into a set of elementary movements.
- Rapid Upper Limb Assessment (RULA): it identifies the manual tasks, mainly of handling of low loads at high frequency, which expose workers to increased risk of upper limb disorders, taking into account posture, muscular strain, weight, duration and frequency of the tasks.
- Metabolic Energy Expenditure (MEE): it characterises the requirements of tasks in terms of metabolic energy expenditure.
- Manual Handling Limits (MHL): it assesses tasks that require carrying, lifting, lowering, pushing or pulling in relation to the percentage of working population able to execute the tasks.
- Fatigue Analysis (FA): it determines whether, after each task, there is an adequate recovery time able to avoid excessive physical fatigue for the worker.
- Ovako Working Posture Analysis (OWAS): it estimates the possible discomfort related to the posture taken by the worker.
- ForceSolver (FS): it predicts the maximum acceptable force that a human could exert under the prescribed conditions.

These tools are used in Jack by first positioning the human model and then modelling its postures before the analysis can be performed [21]. Semi-quantitative tools are used to visualise or analyse the manikin's interaction with the environment. Examples of such tools are Eye View (EV), View Cones (VC), Reach Zones (RZ), Collision Detection (CD), and FootPrints (FP). The tools for discomfort, anthropometry, human performance, and cognition are used for many applications, such as to support vehicle interior design or to create manikins with specific anthropometric measurements, but they are not adopted in this study. The quantitative evaluation tools used in this study and detailed below are: RULA, OWAS, LBA, SSP, and FS. RULA [22] is a survey method developed for investigation of workplaces where work-related upper limb disorders are reported. It is a screening tool that assesses biomechanical and postural loading on the upper body, with particular attention to neck, trunk, and upper limbs. It assigns a score that determines if the task presents a risk of an upper limb injury. This method evaluates a posture and rates it on a scale of one to seven (one being most comfortable). Jack divides the human body in two groups; group A for upper arm, lower arm, and wrist position, group B for neck and trunk position. A rating system is used to assign values at every level, with a score of one indicating the best posture/case. The data required by the RULA tool include: the joint angles and the twist of arms, wrist, neck, trunk, and legs; nature and weight of the load and whether it is static or repeated; number of task (repetitions) per minute. The scale for the score is as follows:

- Level 1 (score 1 or 2): acceptable posture if not maintained or repeated for long periods.
- Level 2 (score 3 or 4): further investigation needed; changes may be required.

- Level 3 (score 5 or 6): investigation; changes required soon.
- Level 4 (score 7): investigation; changes required immediately.

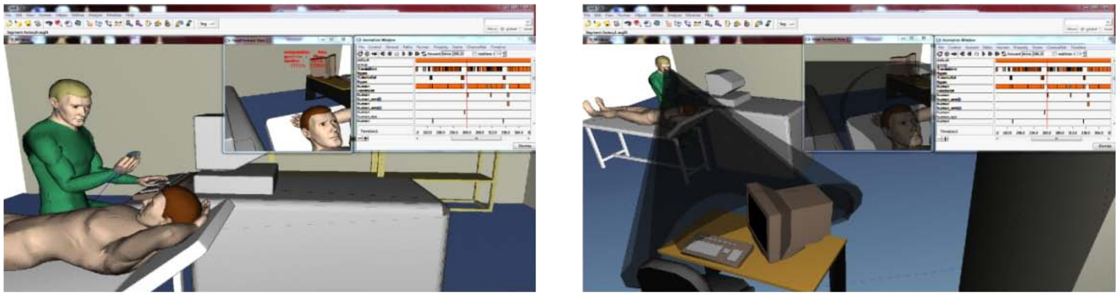
OWAS, first reported by Karhu et al. [23], identifies the most common work postures for the back, arms, and legs. It estimates the weight of the loads handled or the extent of the strength (effort). A rating system categorises different postures in terms of discomfort caused and effect on health. According with the OWAS method, for a specified posture, the Jack's OWAS tool assigns a score for back position, arm position, leg position, and load requirements. These scores are presented in a dialog box, along with the "corrective measure" rating identified for the working posture. A four-level scale of harmfulness is proposed, where each level indicates the urgency to correct harmful postures. These four levels are:

- Level 1: posture is normal; no corrective action is required.
- Level 2: posture may have some harmful effect; no immediate action is required, but may be necessary in the near future.
- Level 3: posture has a harmful effect; corrective measures must be taken as soon as possible.
- Level 4: posture has a very harmful effect; corrective measures must be taken immediately.

Traditionally, OWAS can be quite time consuming because it requires direct observation [24]. One of the advantages of using this Jack's tool is that, during the simulation, the postures set by the user are analysed in "real-time" and the effects are shown visually. The LBA tool evaluates the spinal forces acting on a digital human's lower back, under any posture and loading condition. This tool is used to determine whether newly defined or existing tasks expose workers to a high risk of low back injury. It calculates compression and shear forces at the L4/L5 vertebral joint and the sagittal, lateral and axial spinal reaction moments (torques) at the L4/L5 disc. It is possible to evaluate the forces on Jack's lower back while he's in static posture or "continuously" throughout a task sequence. As the manikin moves while carrying out the task, LBA automatically alerts the user when forces and moment at the L4/L5 joint exceed admissible limits. The SSP tool evaluates the percentage of working population that has the strength to perform a task based on posture, exertion requirements and anthropometry. This tool aids in analysing physical tasks involving lifts, lowers, pushes, and pulls requiring complex hand forces, torso twists and bends. It evaluates jobs in "real-time", flagging postures where the requirements of a task exceed the strength capability limits defined by the user. It also calculates joint torques and angles using the Jack manikin posture, anthropometry, and hand loads. The provided results can be used to design or modify manual tasks that all workers are likely to have the strength to perform.

The FS tool allows the user to assign a posture and to define task specific parameters, such as support forces and standing strategy, in order to predict the maximum acceptable force that a human could exert under the prescribed conditions. Using thresholds fixed by the user, the tool will iterate through joint moments and low back forces until a limit will be reached for a particular joint. Hand forces can also be an output making the FS suitable for executing what-if scenarios or assessing design proposals and providing force specifications. The semi-quantitative evaluation tools used in this study and detailed below are: EV, VC, and RZ.

According to Chengalur et al. [25], an important rule that should be considered in workplace design is a clear line of sight for the operators. Several authors have stated that visual requirements influence working postures [26-28]. The possibility to accurately and by easy actions direct the field of vision area is of major importance for assessing workplace design [29]. EV and VC tools provide an approximation of the manikin view. The view does not represent the complete field of view available to a human (typically extending to about 200° in the horizontal), but only the central portion of it [30]. Figure 1 shows the field of view and the view cones of a sonographer during the task.



(EV) (EV + VC)

Figure 1: Application of EV and VC tools

The RZ tool gives to the user the ability to visualise the areas of maximum and comfortable reach for a specific digital human in a definite location. It generates polygonal surface geometry that graphically depicts areas of maximum and comfortable reach for various joints and constraint conditions. In addition, it is possible to define comfortable reach zones for shoulder, elbow, wrist, hip, knee, and ankle joints based on recognised comfort data.
To use the selected Jack's tools, the authors had to define how to:

- characterise and model the work environment and the work activities;
- measure the force applied during ultrasound execution.

To characterise and model the work environment, it was necessary to inventory the equipments relevant for ergonomics assessment and to recognise their size or to acquire technical data sheets when available (e.g. examination table and ultrasound equipment).
To model the work activities, the authors decided to video record the execution of ultrasounds with the aim to have always available the information related to tasks and sonographer postures and movements.
Due to the peculiar characteristics of the analysed situation and to the problems concerning privacy protection, the authors video monitored ultrasounds accomplished on other sonographers avoiding to involve real patients.
This choice was also supported by the need to interview the "patient" with the aim of assess his perception of the forces applied by sonographer during ultrasound execution.
The equipment used for video recordings was composed of two digital video cameras each placed on a tripod and located to adequately frame the movements of the upper limbs and the torso of the sonographer and his whole body posture.
The authors video recorded two abdominal ultrasounds, each about 9 minutes long, executed on male patients. The sonographer was 45 years old, weighting 78 kg and 1.75 m tall. Age, height and weight of patients were respectively: 33 and 39 years, 1.71 and 1.77 m, 74 and 82 kg.
The work environment is a room with plan dimensions 3.50 m × 4.00 m and with a low illumination level to enhance the visibility of the monitor. The equipments in the work environment are:

- examination table;
- seat for the sonographer, backless and with five supports;
- ultrasound equipment that mainly consists in:
    - input/output devices: monitor, keyboard, transducer;
    - further accessories like gel tube.

Typical configuration of the workplace during ultrasound execution can be detailed as follow:

- sonographer seated near a long side of examination table;
- monitor and keyboard located in front of the sonographer, perpendicularly to the examination table (as shown in Figure 3 JACK);
- patient supine on the examination table in position depending on the organ to be checked.

Usually the sonographer did not provide for an accurate adjustment of the workplace before starting his activity.
To complete data entry in Jack, after work environment and activities modelling it has been necessary to measure the forces applied by the sonographer using an electronic dynamometer (mod. DIN ERGO 81-08 PRO-X). The dynamometer states a full scale limit of 50 kg_f and an accuracy of ± 0.1 % of full scale. It is specifically stated suitable for the measurement and evaluation of the efforts during the exposure to biomechanical overload of the

musculoskeletal system, such as pulling, pushing, and carrying, as well as lifting and/or lowering of loads. The dynamometer has the functionality of recording data during the task. Data are sampled with a period of 200 ms and they are stored in a common USB flash driver. Then, data are managed by custom software that allows a graphical time representation and an automatic finding of the reference values of the evaluation (peak value and average value). In order to better simulate the forces exerted by the sonographer and perceived by the patient, the dynamometer was equipped with a special "in house" adapter that recalls shape and hardness of the ultrasound transducer head (Figure 2).

Figure 2: The adapted dynamometer and the original ultrasound transducer

To validate this procedure, after the ultrasound execution the patient was interviewed in order to verify the experienced sensation due to the pressure exerted by the sonographer during ultrasound.

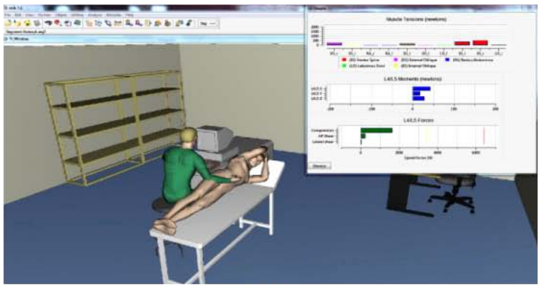
3. Results & Discussion

To model with Jack the real work activity, the authors used two monitors side by side, one dedicated to videotape reproduction and the other to Jack simulation. First it was modelled as realistic as possible the work environment and after the activity; sonographer and patients manikins were scaled with the same body dimensions of the real humans. To set the load applied by sonographer during ultrasound execution, the data measured by means of adapted dynamometer were used. The authors performed several measures, also to verify the correspondence with the literature data; for example, Burnett and Campbell-Kyureghyan indicate the evaluated push force in right and left abdominal scan: average values are 32.9 and 36.5 N respectively, standard deviations are 12.8 and 11.9 N respectively [2]. Among all the graphs representing the force exerted by the sonographer on patients, the authors selected the two containing the maximum peak value detected for men and women. Figure 3 REAL shows the portion of the graphs including the peak values (4.3 and 3.2 kg for male and female respectively). In comparison, also the force exerted on female patients was detected during the execution of further tests useful for future analyses; a trend is drawn in the same Figure 3 REAL. The measured force is acting in the axial direction with respect to the pivot of the dynamometer. Consequently, the authors set load acting in this direction due to the peak value of 4.3 kg detected during the force measuring activity (Figure 3 JACK). Loads acting in planes orthogonal to the force direction and loads due to friction were neglected.

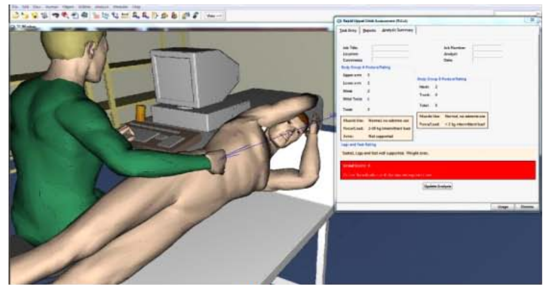
(REAL) (JACK)

Figure 3: The REAL force and the JACK load

For the entire duration of simulated ultrasound, it was decided to monitor the progress of significant tools available in the Task Analysis Toolkit as OWAS, RULA and SSP. Contrariwise, due to the relatively low efforts required by the activity, tools as MEE, MHL and FA were not adopted. In this paper the authors analyse some positions identified as particularly relevant, while less critical positions (e.g. as shown in Figure 4) are not discussed in detail.



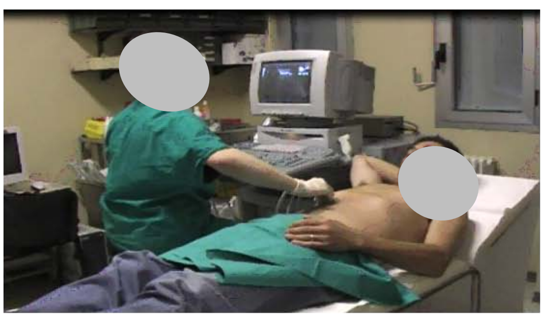
(LBA)



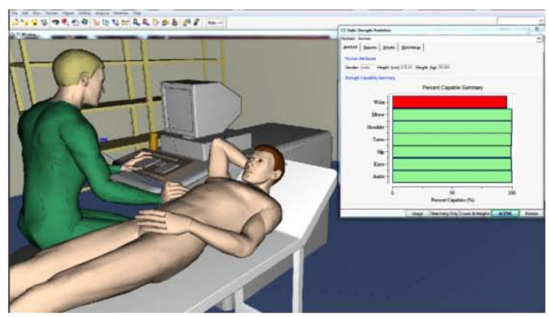
(RULA)

Figure 4: Example of a less critical position

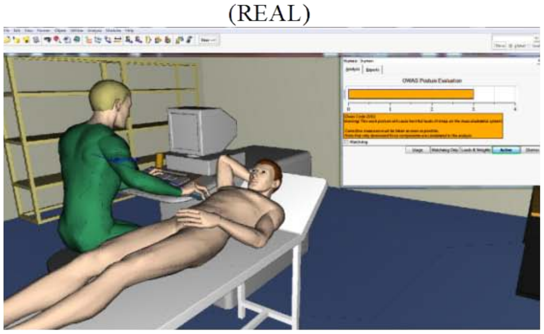
During the first part of the ultrasound, sonographer assumes a posture called “comfortable” in this paper (Figure 5 REAL). Figure 5 SSP illustrates a wrist problem because of the posture and the force exerted. The Jack’s RULA tool provides a Level 2 (score 4) in “comfortable” position; this suggests additional investigations, and changes of work system may be required. Furthermore, Figure 5 OWAS posture evaluation shows a Level 3 but the authors highlight some problems related to this result. Indeed, the authors are currently working on a project to check the reliability of software Jack and they found an error in the Jack’s OWAS tool.



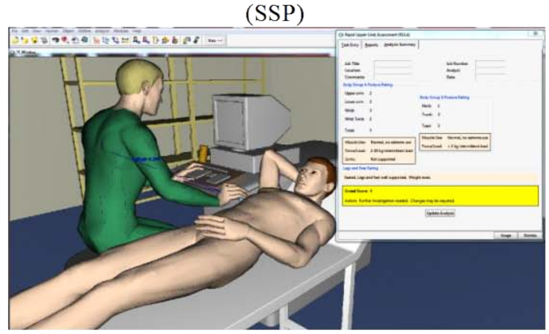
(REAL)



(SSP)



(OWAS)



(RULA)

Figure 5: The REAL “comfortable” posture and some related TAT results

With reference to that error, Figure 6 presents a comparison between the results offered by Jack and calculated using an appropriate Microsoft Office Excel sheet on the basis of original method. It is therefore clear that Jack's OWAS considers the sitting position like a squatting position. Note also that in Jack "comfortable" position is Level 3 while "uncomfortable" position is Level 4 (the position called "uncomfortable" is shown in Figure 8 REAL). However, using "REAL OWAS" both positions are Level 2. The authors have reported this problem to the developers of the software and they are providing to make the necessary corrections; further considerations might be published in a paper.

POSITION: COMFORTABLE	
BACK	2-bent forward , backward
ARMS	1-both arms are below shoulder level
LEGS	4-standing or squatting with both knees bent
USE OF FORCE	1-weight or force needed is 10 kg or less
OWAS	**3**

(JACK)

POSITION: COMFORTABLE	
BACK	2-bent forward , backward
ARMS	1-both arms are below shoulder level
LEGS	1-sitting
USE OF FORCE	1-weight or force needed is 10 kg or less
OWAS	**2**

(REAL)

POSITION: UNCOMFORTABLE	
BACK	4-bent and twisted forward and sideways
ARMS	1-both arms are below shoulder level
LEGS	4-standing or squatting with both knees bent
USE OF FORCE	1-weight or force needed is 10 kg or less
OWAS	**4**

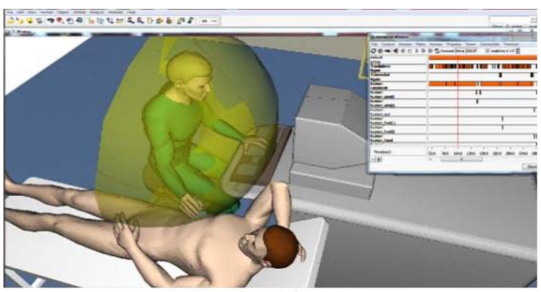
(JACK)

POSITION: UNCOMFORTABLE	
BACK	4-bent and twisted forward and sideways
ARMS	1-both arms are below shoulder level
LEGS	1-sitting
USE OF FORCE	1-weight or force needed is 10 kg or less
OWAS	**2**

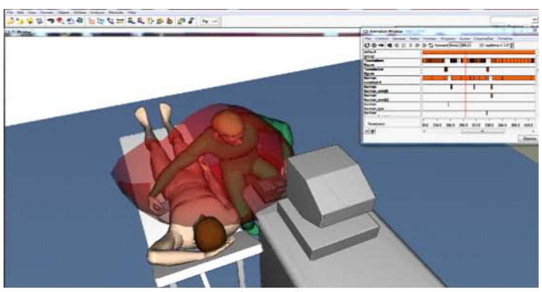
(REAL)

Figure 6: OWAS evaluations

After scanning the closest side of the patient (the right side in Figure 7 RZ-1), the sonographer has also to investigate the other side (the left side in Figure 7 RZ-2).



(RZ-1)



(RZ-2)

Figure 7: RZ in "comfortable" and "uncomfortable" postures

To scan the farthest side the sonographer changes his posture, assuming a posture called "uncomfortable" in this paper (Figure 8 REAL); note that in the "uncomfortable" posture the sonographer twists and bends back to scan the patient and to type on the keyboard at the same time. In addition, as highlighted by the EV and VC tools, the sonographer must rotate the neck in uncomfortable position to watch the monitor.

In the "uncomfortable" position, it is observed the presence of high stress areas such as the erector spinæ (Figure 8 LBA) involving upper and low back. On the contrary, compression and shear forces at the L4/L5 vertebral joint and sagittal, lateral and axial spinal reaction moments (torques) at the L4/L5 disc do not exceed admissible limits due to the low applied load. The Figure 8 RULA points out a Level 4 (score 7), suggests investigation, and requires immediate changes to reduce the highlighted problems to neck and trunk.

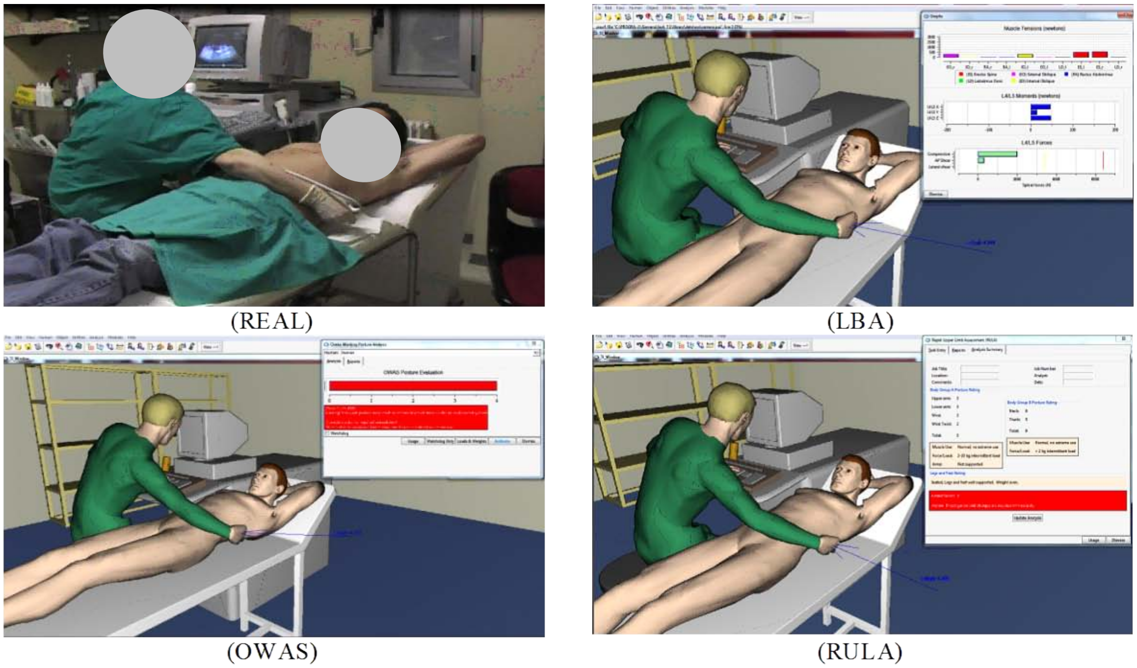


Figure 8: The REAL “uncomfortable” posture and some related TAT results

In addition to the Task Analysis Toolkit, during the simulation the authors monitored the percentage of industrial population capable of performing the task (% Capable) in ForceSolver tool to check for any relevant issues (Figure 9 FS) and the angle values in Static Strength Prediction real time graphs (Figure 9 SSP). These tools were also applied to positions intermediate between “comfortable” and “uncomfortable” ones.

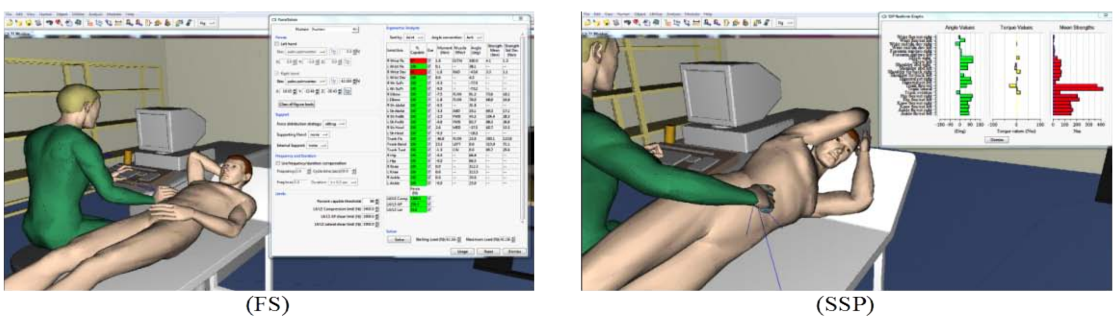


Figure 9: FS and SSP in intermediate positions

Note that during the simulation, critical angles of shoulder abduction and extension, and of elbow rotation for prono-supination of forearms were emphasised.

4. Conclusions

The paper is oriented to the ergonomics evaluation of sonographers’ activity to verify the evidences arising from the literature and to highlight most significant postures and problems related to sonographers’ health and well-being. To reach these objectives the authors video recorded ultrasound executions, arranged a procedure to measure the force applied by the sonographer, and used the modelling and simulation software Jack.

Applying both quantitative and semi-quantitative evaluation tools implemented in Jack, the literature evidences were confirmed; in fact the main body areas exposed to risk were found to be neck, wrist, back, trunk, shoulder, and elbow.
Furthermore, OWAS and RULA analyses state that the ergonomic problems have mainly postural origin and it may be improved redesigning the workplace layout. The relevance of an adequate regulation of the workplace, at least at the beginning of the activity, is also confirmed.
Due to the useful support offered by Jack in the ergonomics assessment of sonographers' activity, the authors are evaluating redesign interventions aimed to point out guidelines for sonographers activity and work environment organization. For example, a first step in this direction will be to verify the ergonomics effects of: to bring near the equipments present in the work environment (examination table, seat for the sonographer, ultrasound equipment, etc.) in order to reduce flexo-extention of trunk and upper limbs; to adjust the relative position of seat and ultrasound equipment in order to support upper limbs during typing and to reduce their static strength; to adequately orientate the monitor in order to reduce neck rotation; etc. Subsequently, the authors will also simulate in Jack the interventions reported in the literature with the aim to verify their effectiveness to the workplace improvement and to ultimately reduce the prevalence of musculoskeletal symptoms among sonographers.
Likewise, the evaluation will be extended to female patients by repeating the procedure of modelling and simulation. All these activities should provide more useful information to use Jack as an effective way to consider human factors in first design phases, in the case of a new sonographers' workplace.

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