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Physical risk factors identification based on body sensor network combined to videotaping

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Abstract

The aim of this study was to perform an ergonomic analysis of a material handling task by combining a subtask video analysis and a RULA computation, implemented continuously through a motion capture system combining inertial sensors and electrogoniometers. Five workers participated to the experiment. Seven inertial measurement units, placed on the worker's upper body (pelvis, thorax, head, arms, forearms), were implemented through a biomechanical model of the upper body to continuously provide trunk, neck, shoulder and elbow joint angles. Wrist joint angles were derived from electrogoniometers synchronized with the inertial measurement system. Worker's activity was simultaneously recorded using video. During post-processing, joint angles were used as inputs to a computationally implemented ergonomic evaluation based on the RULA method. Consequently a RULA score was calculated at each time step to characterize the risk of exposure of the upper body (right and left sides). Local risk scores were also computed to identify the anatomical origin of the exposure. Moreover, the video-recorded work activity was time-studied in order to classify and quantify all subtasks involved into the task. Results showed that mean RULA scores were at high risk for all participants (6 and 6.2 for right and left sides respectively). A temporal analysis demonstrated that workers spent most part of the work time at a RULA score of 7 (right: $49.19 \pm 35.27\%$; left: $55.5 \pm 29.69\%$). Mean local scores revealed that most exposed joints during the task were elbows, lower arms, wrists and hands. Elbows and lower arms were indeed at a high level of risk during the total time of a work cycle (100% for right and left sides). Wrist and hands were also exposed to a risky level for much of the period of work (right: $82.13 \pm 7.46\%$; left: $77.85 \pm 12.46\%$). Concerning the subtask analysis, subtasks called 'snow thrower', 'opening the vacuum sealer', 'cleaning' and 'storing' have been identified as the most awkward for right and left sides given mean RULA scores and percentages of time spent at risky levels. Results analysis permitted to suggest ergonomic recommendations for the redesign of the workstation. Contributions of the proposed innovative system dedicated to physical ergonomic assessment are further discussed.

Keywords

Physical Ergonomics, Inertial Measurement Unit, Manual Tasks, Risk of Exposure, Musculoskeletal Disorders

1. Introduction

According to the International Ergonomics Association, “ergonomists contribute to the design and evaluation of tasks, jobs, products, environments and systems in order to make them compatible with the needs, abilities and limitations of people” (IEA, 2016). From a physical point of view, an ergonomic intervention aims at detecting and evaluating the disequilibrium between workplace requirements and workers physical abilities in order to prevent work-related musculoskeletal disorders (MSDs). After a physical ergonomic analysis, recommendations may be provided for the primary design of a workplace (Sanchez-Lite et al., 2013) or for the redesign of a workplace (Greene et al., 2005). Thus, developing supportive tools for the identification and assessment of potentially hazardous motor tasks and postures appears crucial for ergonomic research.

Different methods and tools have been developed for assessing exposure to risk factors for work-related MSDs. These methods can be classified in three groups: self-reports observational methods and direct measurements (Li and Buckle, 1999; David, 2005). Self-reports involve worker diaries, interviews and questionnaires. Despite their ease of implementation, self-reports have been associated with subjective drawbacks like the unreliability of exposure perception or interpretation according to the worker’s literacy.

The aim of observational methods is to evaluate workplace exposure by assessing the worker’s motor behavior on paper sheets either while observing in the field or replaying videos (Engström and Medbo, 1997). One of the most cited observational methods is the Rapid Upper Limb Assessment (RULA) index, which is based on postures observation (biomechanical and postural load parameters) to provide a score of exposure to MSDs, with particular attention to the neck, trunk and upper limbs (McAtamney and Corlett, 1993). Reliability of this method adapted to specific contexts has been assessed through different studies (Takala et al., 2010; Dockrell et al., 2012; Levanon et al., 2014). Observational methods have been implemented into videotaped specific softwares (Yen and Radwin, 1995; Chang et al., 2010; Radwin, 2011) even though this process is usually time-consuming. More simply, videotaping is a standard tool in ergonomics as it permits to divide a work cycle in different key elements, denoted as subtasks (Hernandez-Arellano et al., 2016). The amount of time spent during each of these subtasks can also be deduced as a percentage of the work cycle (Armstrong et al., 2014). Although observational methods are affordable and practical for use in a wide range of professional situations, the scoring system may suffer from a lack of epidemiological data (David, 2005).

Finally, direct methods aim at measuring the risk of exposure in real-time by using sensors attached to the worker's body (Radwin and Lin, 1993; Freivalds et al., 2000; Breen et al., 2009; Bernmark and Wiktorin, 2002; Sanchez-Lite et al., 2013; Peppoloni et al., 2014). Although this kind of methods have been known to require complex implementation and cost-intensive hardware setup (David, 2005), low-cost systems based on inertial measurement units (IMU) have been introduced by manufacturers, e.g. MTx (XSens, Netherlands), Trigno (Delsys, USA), or CAPTIV Motion (TEA, France). In 2013, some researchers presented an IMU system able to provide a real-time ergonomic assessment of the upper body into an industrial environment (Vignais et al., 2013). Based on the RULA method, this system computed both a standard global risk score and several local risk scores (one per segment). This evaluation was fed back to the user in real-time by using a see-through head mounted display coupled to auditory warnings, thus allowing reducing the risk of MSDs in industrial settings. Along the same lines, Battini and colleagues introduced a full-body system dedicated to real-time ergonomic evaluations of manual material handling tasks and composed of 17 inertial measurement units (Battini et al., 2014). Although the feedback was only visual (portable screens or personal computers), this system integrated some of the most used methodologies, such as RULA, OCRA, OWAS, or the Lifting Index, thus given the possibility to the user/ergonomist to select the suitable methodology (Andreoni et al., 2009). In the aerospace manufacturing industry, an inertial measurement system has been used to capture human activity for ergonomic assessment and digital modelling (Fletcher et al., 2016). Compared to traditional ethnographic methods, inertial data demonstrated a better suitability for human performance monitoring and digital human modelling.

While promising, previous studies did not exploit the whole potential of continuous data provided by IMU system, even offline. Thus the aim of this study was to conduct an ergonomic analysis of a manual material handling task by associating videotaping and RULA computation implemented continuously through a motion capture system combining IMU and electrogoniometers. This in-field apparatus permitted to identify awkward subtasks and thus orientated the ergonomic recommendations for the redesign of the workstation.

2. Materials and Methods

2.1. Subjects

Five experienced workers took part to this study. Participants' mean age, height and mass were 41.2 ± 11 , 1.69 ± 0.14 m and 70.8 ± 23.56 kg, respectively. All participants gave their informed consent before participating to the study. It has to be noticed that all participants were traditionally in charge of the workstation studied.

2.2. Workstation

The workstation described in this study aims to clean filters dedicated to medical material (see Fig. 1). More precisely, the worker had to clean each subpart of the filter, to put subparts together, to vacuum the filter, and then to check the quality of the vacuuming. Then, each filter was placed inside a packet and sealed using a vacuum sealer.



Figure 1: Workstation dedicated to filter cleaning and description of the filter.

2.3. Materials

In this section, the data collection process based on IMUs and electrogoniometers have been introduced. From those data, the subsequent offline ergonomic computation based on RULA sheet has been described.

2.3.1. IMU system

This system was composed of seven wireless CAPTIV Motion IMUs (TEA, Nancy, France). Each lightweight sensor (32 g, 60 × 35 × 19 mm) contains a tri-axial accelerometer, a tri-axial gyroscope and a tri-axial magnetic sensor. All sensors were sampled at 64 Hz. The IMUs were placed on the worker's body using manufacturer's guidelines and specific adjustable straps: one IMU for each upper arm, one IMU for each forearm, one IMU for the head, one IMU for the trunk, located on the chest, and one IMU for the pelvis, placed on the sacrum (see Fig. 2). This last IMU was necessary to define the movement of the trunk with respect to the pelvis segment.

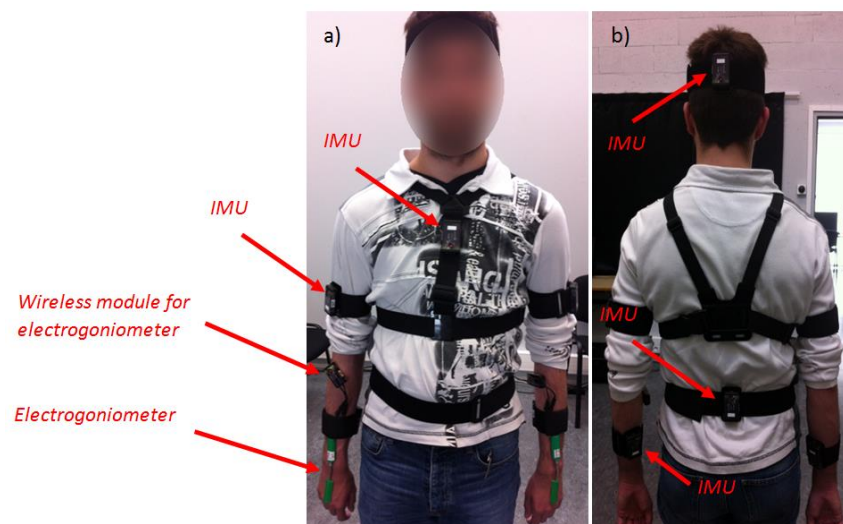


Figure 2: Placement of IMUs, electrogoniometers and their wireless modules in the front (a) and back views (b).

2.3.2. Goniometers

To record wrist angles (flexion/extension, radial/ulnar deviation), two bi-axial electrogoniometers (Biometrics Ltd., Newport, UK) have been added to the on-body sensor network (see Fig. 2) and placed on both sides of the wrist using medical tape and straps. They were sampled at 32 Hz and synchronized with the IMUs during the post-processing through CAPTIV software (TEA, Nancy, France).

2.3.3. Camcorders

Two camcorders have been used to film worker's activity. One camcorder was fixed on a tripod placed to the rear up of the worker (see viewpoint in Fig. 1). One camcorder was hold by the experimenter during the whole recording to capture postures of the worker's forearms

and hands, especially on the right side of the workstation while the worker opened and closed the vacuum sealer (see Fig. 1).

2.4. Procedure

The workstation being in a sterile environment, the worker was equipped with the IMU system and goniometers in the gowning room. At this time she/he was also informed with the aim of the study. Then the worker was asked to wear the professional clothes (coat, charlotte, goggles, and gloves) and go to the workstation situated 30 m away from the gowning room. At the workstation, all sensors were zeroed using a calibration posture (standing posture with upper limbs along the body, hands turned inside). This posture was also used at the end of the experiment to verify that the IMU signals have not been disturbed through the work cycles. Both camcorders were synchronized to the IMU system and goniometers through a specific step into CAPTIV software. The worker was asked to perform 30 cycles of the task, which corresponds to 20 min of work.

2.5. Post-processing

The analysis was conducted on the 10 cycles situated in the middle of the work done. Wrist, elbow, shoulder, neck and back joint angles were deduced from the on-body sensor network through a biomechanical model developed by the manufacturer (TEA, 2014). This model was composed of 20 degrees of freedom.

Joint angles were then used to compute automatically a global risk score based on the RULA method (McAtamney and Corlett, 1993). For a current posture, this global score ranged from one to seven as follow: 1-2 corresponded to an acceptable posture; 3-4 meant that the current posture needed further investigation and that a change may be needed; 5-6 meant that the current posture needed further investigation and that it had to be changed soon; 7 meant that the movement could lead to MSDs, that it had to be investigated and changed immediately. By computing the RULA scores at each time step, the percentage of time spent at each range was deduced.

Some specific parameters of adjustments were also necessary to compute the RULA score:

- Shoulder raising: as the worker did not raise his arm upward during the task, the ‘shoulder raising score’ was fixed to 0.
- Upper arm abduction: the upper arm adduction/abduction angle was computed by the IMU system so a score of +1 was added to the ‘upper arm score’ when this angle was superior to 45° (in the frontal plane).

- Arm supported: during the whole task, the worker did not support her/his arms so the 'arm supported score' was fixed to 0.
- Arm working across midline or out to side of body: it was deduced from the video analysis that either worker's arms were working across midline of the body, either worker's arms worked out to side of body, throughout most of the task. Thus we added +1 to the 'lower arm score'.
- Wrist bending from midline: the IMU system computed the radio-ulnar deviation angle so a score of +1 was added to the 'wrist score' when this angle was inferior to -10° (radial deviation) or superior to 10° (ulnar deviation).
- Neck and trunk twist: the IMU system provided these angles so a score of +1 was added to the 'neck score' and/or 'trunk score' when these angles were inferior to -10° or superior to 10° .
- Neck and trunk side bending: similarly, a score of +1 was added to the 'neck score' and/or 'trunk score' when these angles were superior to 10° laterally.
- Legs and feet supported: as legs and feet were supported during the whole task, the 'leg score' was fixed to 1.
- Muscle use score: this score was fixed to 1 as the worker repeated some subtasks more than four times per minute.
- Force/load score: this score was fixed to 0 as the filter held by the worker was small and light (largely under 2kg).

In addition to the global risk score, an articulation-based analysis was conducted based on the following predefined local scores thresholds (Vignais et al., 2013):

- Shoulder and upper arm: 5
- Elbow and lower arm: 3
- Wrist and hand: 5
- Neck and head: 4
- Pelvis and trunk: 4

For each articulation generating a local score higher than the corresponding predefined value, the frequency of appearance was computed.

Concerning the subtask identification, a research technician, with more than 20 years of experience on ergonomic analyses, used both video observations to manually code each worker's activity. This process was performed through CAPTIV software.

3. Results

3.1. Mean RULA scores and percentage of time spent at each RULA range

On average, participants performed the 10 work cycles with a global RULA score of 6 ± 0.87 for the right side and 6.2 ± 0.78 for the left side, meaning that the average posture used by the workers needed further investigation and it had to be changed soon (McAtamney and Corlett, 1993).

Percentages of time showed that the workers spent the biggest part of their time at a range of 7 (right: $49.19 \pm 35.27\%$; left: $55.5 \pm 29.69\%$) (see Fig. 3). At ranges 5-6, they spent $35.63 \pm 14.13\%$ for the right side, and $34.82 \pm 13.62\%$ for the left side. Finally, the percentage of time a low risk of MSDs (ranges 3-4) was $15.18 \pm 9.21\%$ for the right side and $9.67 \pm 7.38\%$ for the left side.

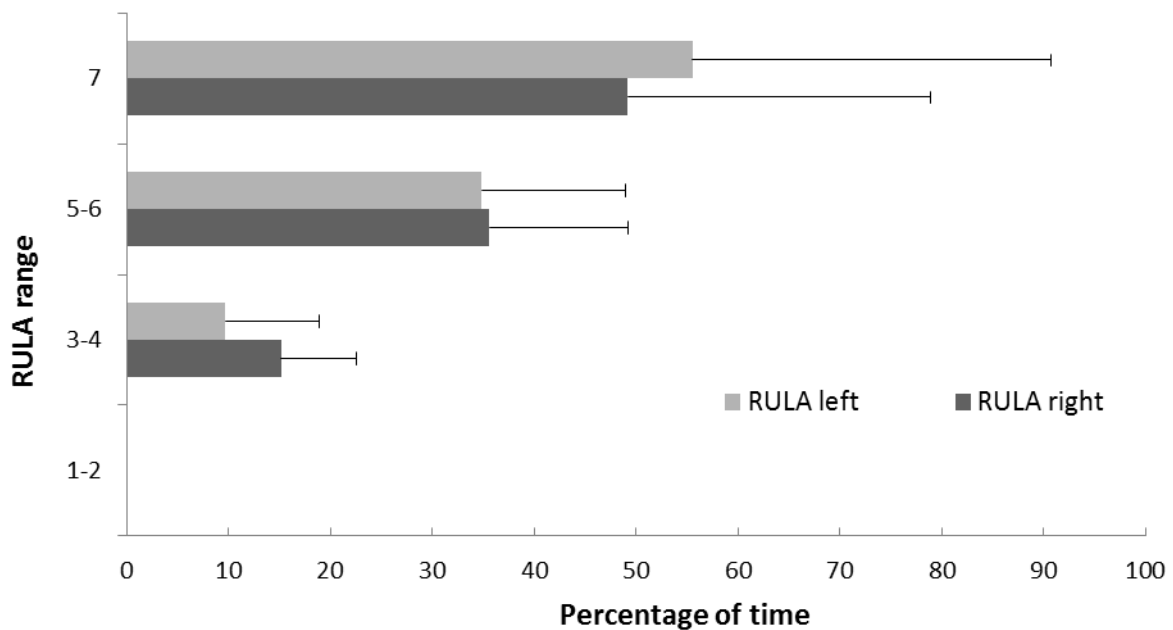


Figure 3: Percentage of time spent at each RULA range.

3.2. Mean local scores and percentage of time spent at a risky level

Workers' local scores have been summarized in Table 1. According to predefined values (see section 2.5), 'Shoulder and upper arm', 'Neck and head' and 'Pelvis and trunk' scores were under the risky threshold, 'Elbow and lower arm' scores were over the threshold as well as 'Wrist and hand' scores.

Table 1: Mean local scores and standard deviations (SD).

	Shoulder and upper arm score		Elbow and lower arm score		Wrist and hand score		Neck and head score	Pelvis and trunk score
	<i>Right</i>	<i>Left</i>	<i>Right</i>	<i>Left</i>	<i>Right</i>	<i>Left</i>		
Local scores	2.91*	3.38*	3.27**	3.34**	5.16	5.05	2.51	3.2
SD	0.75	0.9	0.43	0.44	0.83	0.78	1.29	0.53

* Prior hypotheses: shoulder was not raised, upper arms were not supported or the worker was not leaning during a work cycle.

** Prior hypothesis: lower arms were working across midline or out to side of body (+1).

Based on the same predefined values, the percentage of time an articulation/segment spent at a risky level was deduced (see Fig. 4). Results demonstrated that elbows and lower arms were at a high level of risk during a work cycle (100% for right and left sides). Wrist and hands were also exposed to a risky level for much of the period of work (right: $82.13 \pm 7.46\%$; left: $77.85 \pm 12.46\%$). It has to be noticed that the pelvis and trunk spent $41.47 \pm 40.34\%$ of the work time at a risky level, followed by the neck and head ($23.08 \pm 11.98\%$) and shoulders and upper arms (right: $0.2 \pm 0.29\%$; left: $12.45 \pm 5.03\%$).

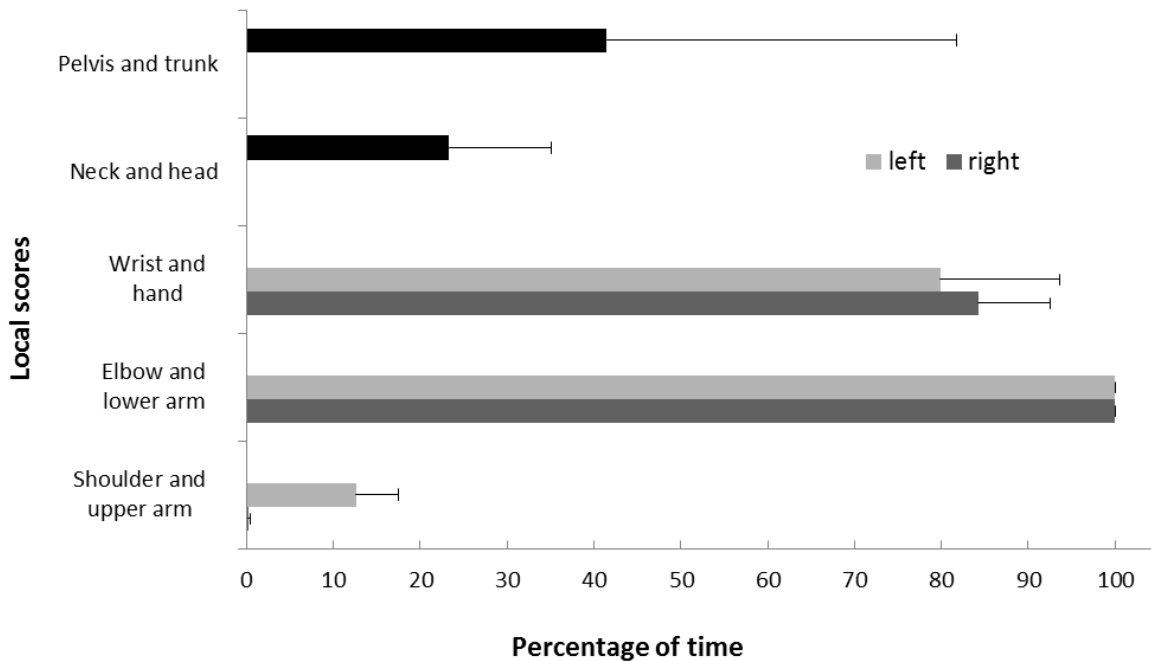


Figure 4: Mean percentage of time an articulation/segment spent at a risky level for all work cycles.

3.3. Subtask analysis

A subtask analysis was performed based on the videotaping of all subtasks inside each work cycle. Thus each subtask was associated to mean RULA scores (right and left) and mean local scores (see table 2).

Table 2: Mean RULA scores and mean local scores (\pm standard deviation) associated to each subtask.

	Mean RULA score		Shoulder and upper arm score		Elbow and lower arm score		Wrist and hand score		Neck and head score	Pelvis and trunk score
	<i>Right</i>	<i>Left</i>	<i>Right</i>	<i>Left</i>	<i>Right</i>	<i>Left</i>	<i>Right</i>	<i>Left</i>		
Assembly	5.64 ± 1.2	5.90 ± 1.09	2.59 ± 0.82	2.93 ± 0.72	3.10 ± 0.07	3.29 ± 0.32	5.09 ± 0.23	5.15 ± 0.11	2.41 ± 0.43	3.00 ± 0.89
Bell jar holding	6.15 ± 1.00	6.25 ± 0.79	3.32 ± 0.46	3.49 ± 0.52	3.24 ± 0.42	3.49 ± 0.22	4.98 ± 0.51	5.09 ± 0.41	2.41 ± 0.85	3.21 ± 0.79
Cap holding	6.15 ± 0.76	6.56 ± 0.46	2.62 ± 0.92	3.68 ± 0.28	3.10 ± 0.22	3.54 ± 0.18	4.94 ± 0.33	5.05 ± 0.31	2.91 ± 1.09	3.04 ± 0.94
Cleaning	5.92 ± 1.14	6.06 ± 1.00	2.85 ± 0.27	3.28 ± 0.46	3.03 ± 0.03	3.23 ± 0.22	5.38 ± 0.14	5.04 ± 0.26	2.35 ± 1.01	3.16 ± 0.84
Closing the vacuum sealer	6.45 ± 0.45	6.59 ± 0.45	2.76 ± 0.58	3.91 ± 0.61	3.45 ± 0.30	3.60 ± 0.19	5.21 ± 0.15	4.96 ± 0.27	2.72 ± 0.81	3.57 ± 0.39
Filter holding	6.06 ± 1.24	6.04 ± 1.33	2.51 ± 0.59	2.58 ± 0.89	3.09 ± 0.07	3.35 ± 0.18	5.23 ± 0.24	5.01 ± 0.25	2.73 ± 0.39	3.36 ± 0.78
Miscellaneous	6.25 ± 0.51	6.35 ± 0.46	3.09 ± 0.47	3.49 ± 0.96	3.47 ± 0.36	3.39 ± 0.31	4.93 ± 0.13	4.71 ± 0.68	2.48 ± 0.43	3.33 ± 0.46
Opening the vacuum sealer	6.23 ± 0.84	6.73 ± 0.22	3.58 ± 0.51	4.60 ± 0.39	3.83 ± 0.10	3.76 ± 0.17	4.79 ± 0.56	5.08 ± 0.39	2.58 ± 1.64	3.32 ± 0.81
Pack checking	6.28 ± 0.80	6.42 ± 0.66	2.71 ± 0.58	3.45 ± 0.43	3.24 ± 0.47	3.06 ± 0.05	4.74 ± 0.33	5.05 ± 0.66	3.09 ± 0.96	3.39 ± 0.76
Packaging	5.75 ± 1.11	5.96 ± 0.97	2.63 ± 0.80	3.09 ± 0.42	3.23 ± 0.32	3.23 ± 0.30	5.34 ± 0.22	5.03 ± 0.58	2.37 ± 0.61	3.11 ± 0.69
Removing from the vacuum sealer	6.06 ± 0.73	6.34 ± 0.66	2.66 ± 0.74	3.59 ± 0.35	3.34 ± 0.22	3.15 ± 0.22	4.98 ± 0.40	5.21 ± 0.48	2.55 ± 0.74	3.32 ± 0.69
Snow thrower	6.57 ± 0.46	6.65 ± 0.51	3.60 ± 0.34	3.62 ± 0.61	3.52 ± 0.46	3.30 ± 0.38	5.29 ± 0.30	4.85 ± 0.58	3.21 ± 0.77	3.35 ± 0.63
Storing	6.51 ± 0.44	6.62 ± 0.37	2.98 ± 0.24	3.60 ± 0.69	3.38 ± 0.28	3.33 ± 0.16	4.99 ± 0.26	5.24 ± 0.19	3.12 ± 0.35	3.61 ± 0.50

From Table 2, one can observe that the posture associated to the highest RULA score was ‘snow thrower’ for the right side, and ‘opening the vacuum sealer’ for the left side. Thus, shoulder and upper arm were most exposed during these two tasks for the right and left sides, respectively. Concerning elbow and lower arm, there were more at risk during ‘opening the vacuum sealer’ for the right and left sides. The ‘cleaning’ subtask was the most awkward for the right wrist and hand, the ‘storing’ subtask being the riskiest for the left wrist and hand. The neck and head were most exposed during the ‘snow thrower’ subtask, whereas pelvis and trunk were most at risk during the ‘storing’ subtask.

Moreover, each subtask was associated to the percentage of time spent at each RULA range, and the percentage of time an articulation/segment spent at a risky level (see Table 3). We can observe that the subtask which exposed the worker to a RULA score equal to 7 during the largest proportion of time was ‘storing’ for the right side, and ‘snow thrower’ for the left side. Elbows and lower arms clearly appeared the most at risk during the task as these articulations and segments spent 100% of time at a risky level. For the wrists and hands, the ‘cleaning’ and ‘assembly’ subtasks induced the largest proportion of time at a hazardous level for the right and left sides, respectively.

Table 3: Duration, percentage of time spent at each RULA range and percentage of time an articulation/segment spent at a risky level, per subtask.

	Mean duration (s)	Percentages of time at each RULA range								Percentages of time each articulation/segment spent at a risky level							
		Right RULA ranges				Left RULA ranges				Shoulder and upper arm		Elbow and lower arm		Wrist and hand		Neck and head	Pelvis and trunk
		1-2	3-4	5-6	7	1-2	3-4	5-6	7	Right	Left	Right	Left	Right	Left		
Assembly	21.3 ±12.8	0	29.46 ±38.8	26.02 ±24.14	44.52 ±40.54	0	17.75 ±31.83	34.92 ±41.23	47.32 ±37.25	0	1.43 ±2.18	100	100	85.30 ±15.38	88.99 ±6.19	8.49 ±4.90	0.71 ±1.60
Bell jar holding	6.7 ±1.6	0	14.12 ±30.8	28.79 ±36.78	57.10 ±39.75	0	9.28 ±17.08	33.22 ±39.88	57.51 ±38.79	0.09 ±0.19	5.12 ±8.87	100	100	78.95 ±23.90	80.28 ±18.74	21.66 ±24.66	0
Cap holding	8.5 ±6.5	0	13.14 ±14.2	35.93 ±22.24	50.93 ±38.33	0	4.18 ±3.84	26.13 ±15.92	69.69 ±29.62	0	4.60 ±10.28	100	100	84.46 ±27.29	78.15 ±15.00	33.66 ±34.67	5.25 ±11.73
Cleaning	56.5 ±29.2	0	18.33 ±16.25	31.73 ±18.52	49.94 ±45.28	0	9.43 ±8.45	40.05 ±23.03	50.52 ±44.87	0.03 ±0.06	1.64 ±2.64	100	100	93.89 ±3.15	85.07 ±10.65	7.69 ±12.00	0.77 ±1.72
Closing the vacuum sealer	7.9 ±4.8	0	5.06 ±4.23	32.56 ±13.01	62.39 ±26.8	0	5.20 ±5.69	19.46 ±6.85	75.34 ±16.38	0	47.06 ±19.43	100	100	89.24 ±6.84	75.85 ±14.59	11.26 ±17.92	0.74 ±1.21
Filter holding	9.2 ±7.1	0	21.64 ±21.57	27.81 ±16.7	50.54 ±43	0	20.14 ±20.14	20.31 ±10.09	59.56 ±40.46	0	1.47 ±2.95	100	100	91.00 ±8.58	72.98 ±11.78	4.15 ±11.10	0
Miscellaneous	21.4 ±65.8	0	10.99 ±4.15	28.65 ±10.13	60.36 ±26.43	0	7.43 ±4.24	30.01 ±11.38	62.56 ±27.03	0.26 ±0.52	28.22 ±35.49	100	100	76.23 ±9.88	61.52 ±35.46	8.76 ±6.05	1.12 ±1.97
Opening the vacuum sealer	18.9 ±8.7	0	8.00 ±5.87	36.67 ±20.05	55.33 ±43.69	0	0.77 ±0.69	21.20 ±10.97	78.03 ±17.75	1.15 ±2.50	74.73 ±24.28	100	100	61.58 ±24.73	79.13 ±21.03	17.68 ±34.95	1.53 ±3.41
Pack checking	4.4 ±7.3	0	8.32 ±6.88	37.35 ±21.78	54.33 ±49.51	0	2.19 ±2.19	42.05 ±30.38	55.76 ±49.12	0	0	100	100	71.61 ±23.70	72.99 ±34.62	17.27 ±22.72	3.22 ±5.41
Packaging	31.2 ±23.3	0	20.24 ±15.54	41.56 ±14.92	38.20 ±40.11	0	11.64 ±10.46	34.44 ±11.73	43.07 ±41.28	0	4.61 ±8.09	100	100	88.79 ±5.97	73.72 ±23.85	5.09 ±9.22	0.87 ±1.94
Removing from the vacuum sealer	7.7 ±5	0	9.89 ±8.11	48.44 ±17.35	41.67 ±38.2	0	5.59 ±6.09	41.94 ±22.08	52.47 ±40.78	0	0	100	100	74.18 ±15.76	84.96 ±21.91	3.45 ±4.17	1.40 ±3.02
Snow thrower	13.1 ±12.3	0	0.69 ±0.77	34.18 ±22.32	65.13 ±40.87	0	1.50 ±1.53	20.18 ±15.06	78.32 ±24.37	0	16.24 ±32.27	100	100	90.85 ±8.14	66.67 ±31.76	34.49 ±28.90	0.70 ±0.96
Storing	11.8 ±7.6	0	3.09 ±2.16	31.75 ±12.71	65.16 ±26.84	0	1.06 ±0.53	28.12 ±13.78	70.82 ±28.15	0.47 ±1.06	14.00 ±22.45	100	100	70.91 ±12.01	86.59 ±10.72	22.31 ±21.81	5.07 ±7.01

4. Discussion

This study aimed to demonstrate the interest of coupling a continuous ergonomic assessment, based on IMUs and electrogoniometers, to subtask videotaping during a work cycle. This methodology was applied to a filter cleaning workstation in a biomedical material manufacture. The ergonomic assessment was based on the RULA method as operators were working in a sitting posture. Computing joint angles in continue allowed to deduce (for the right and left sides): mean RULA scores, percentages of time spent at each RULA range, mean local scores and percentages of time each articulation/segment spent at a risky level. The combination with videotaping permitted a deeper analysis based on each subtask composing the work cycle. Thus each subtask was associated to: a mean RULA score, percentages of time spent at each RULA range, a local score per articulation/segment, and percentages of time each articulation/segment spent at a hazardous level.

Results from this study showed that mean RULA scores were at a high level of risk for both sides (6 and 6.2 for right and left sides, respectively), meaning that the workstation involved hazardous postures during the work cycle (McAtamney & Corlett, 1993). These RULA scores appeared considerably higher to previous continuous RULA assessments during manual tasks (Vignais et al., 2013, Peppoloni et al., 2016). This global preliminary indication has been completed by percentages of time spent at each RULA range, which revealed the temporal aspect of the risk of exposure to MSDs. These percentages demonstrated that workers spent half of the work cycle at a RULA score equal to 7 with few differences between right and left sides. This variable was a clear indicator of the risk of MSDs, as it took into account the temporal aspect of the ergonomic assessment. Further modifications of the workstation would have to decrease those percentages to validate the future ergonomic approach.

After these global risk assessments, it was interesting to identify which anatomical region was more at risk in the worker's body. Local scores have been computed to this aim and associated to risk thresholds. These scores showed that the elbows, lower arms, wrists and hands suffered from hazardous postures used during the work cycle in average. This outcome was confirmed by the temporal variable, i.e. percentages of time each articulation/segment spent at a hazardous level, as elbows and lower arms spent the whole work cycle time at a risky level. Wrists and hands were at risk during more than three quarters of work time. As the operator had to accurately manipulate the different parts of the filter in different places of the workstation (vacuum sealer, bell jar, packaging, storing, etc.) during the task, it may explain why lower arms and hands were the most exposed. In top of giving an anatomical localization of the risk of exposure, this variable could orientate the further modification of the

workstation. Thus, the future workstation would ideally have to reduce the movements of lower arms (by decreasing the workspace and the position of the useful elements for instance) and hands (by adapting the height of the workstation to each operator for example).

It has to be noted that large standard deviations associated with the percentage of time spent at the RULA range of 7 (see Fig. 3) were probably related to high standard deviations associated with the percentage of time pelvis and trunk spent a risky level (see Fig.4). Indeed, these interindividual variations were probably due to large anthropometric differences between the five subjects of this experiment (see subsection 2.1). As an example, the smaller subject in height was 1.55m (subject 3) while the taller subject in height was 1.90m (subject 5). Therefore, subject 5 most likely had to constantly bend down his trunk while working on the workstation, thus leading to a high pelvis/trunk local score, and subsequently a high global RULA score.

The main contribution of this experiment consisted in the combination of the subtask analysis. By combining videotaping with RULA continuous assessment, we have been able to identify the most risky subtasks. The highest RULA scores were obtained for the subtasks 'snow thrower', 'storing', 'closing' and 'opening the vacuum sealer'. The significance of 'snow thrower' and 'storing' subtasks for the risk of exposure to MSDs was supported by the percentage of time spent at the 7 RULA range. Thus future ergonomic modifications of the workstation have to focus on the procedure of these subtasks, and their associated postures. For example, the 'snow thrower' subtask was currently performed by placing and holding the filter into a box in front of the worker (orange area in the middle of figure 1). One modification could be to integrate a support inside the snow thrower permitting to decrease the time where lower arms were in extension. Concerning local scores per subtask, the subtask named 'opening the vacuum sealer' appeared particularly at risk for left shoulder and upper arm. Thus the position of the vacuum sealer into the workstation might be redesigned as well as the way to open it (another activation pedal might be conceived to this aim). Local scores also demonstrated that elbows and lower arms were a high level of risk during all subtasks. Consequently, a global redesign of the workstation would have to be implemented for elbows and lower arms, e.g. permitting to easily adjust the height of the work surface to each worker's anthropometric characteristics. Concerning wrists and hands, processes under 'cleaning' and 'storing' subtasks had to be redesigned and/or explained in details through specific training in order to decrease awkward postures. Nevertheless, the subtask analysis revealed that the neck and head, and pelvis and trunk, were not concerned by a high level of risk on average.

4.1. RULA method limitations

Concerning the ergonomic assessment, unless the RULA method has been widely applied in the ergonomic literature (David, 2005), epidemiological data are missing to support the relationship between MSDs appearance and risk of exposure computation (Li and Buckle, 1999; Vignais et al., 2013). Some researchers are currently working on the developments on other objective measurements (Hansson et al., 2009) in order to assess the exposure-response relationships between occupational risk factors and musculoskeletal disorders (Nordander et al., 2016). However these types of studies have been dedicated to specific anatomical areas (neck, shoulder, forearm and/or wrist) although RULA score provided a global risk score for the whole worker's upper body. It has to be noted that some angles thresholds have to be chosen subjectively for the implementation of the RULA calculation in continue. For example, concerning the neck and head, RULA computation defined that if the neck was side bending, a local score of +1 had to be added. However, it was not detailed from which angle of the neck a side bending was considered. The same observation could be made for upper arm abduction, shoulder raising, radio-ulnar deviation, wrist twist, neck twist, and trunk twist and side bending. Some prior hypotheses had also to be done to allow the RULA score computation, e.g. the shoulder was not raised and upper arms were not supported or the worker was not leaning during a work cycle. The selection of local scores thresholds were along the same lines. Results showed that the percentage of time elbows and lower arms spent at a risky level was equal to 100%. As this threshold has been chosen subjectively, it could be suggested that it was too low to reflect the risk of exposure for this particular area. Concurrently with these calculations, the specific anatomical area of the lumbar zone, responsible for most of the MSDs around the world (Brooks, 2006), has been given little consideration through this assessment (Vignais et al., 2013). Finally, the RULA method, even if it permitted an analysis of temporal aspects in the current study, has been initially developed to focus on static postures. Thus through this method, it was not possible to analyze the influence of the cumulative time spent at each RULA range on the risk of MSDs exposure (Svensson et al., 2010).

4.2. Biomechanical limitations

Although few researches have been dedicated to temporal aspects of subtask ergonomic assessment in the literature, different points of the current applied protocol could be called into question. First of all, the biomechanical model deduced from IMUs and electrogoniometers suffered from a lack of validation, although it was certified applicable by

the manufacturer (TEA, Nancy, France). An experimental protocol is currently under progress to validate the described biomechanical model with an optoelectronic system, based on the methods from Morrow and colleagues (2016).

4.3. Sample size limitations

In the current study, the small sample size could also be questionable. However, it has to be noted that the five subjects who took part to this experiment were the only five workers dedicated to this workstation. By adding non-specialist workers, we would have taken the risk of recording non representative motion patterns associated to this workstation. Thus the current study did not pretend to be as robust and representative as a genuine laboratory experiment, but it described a valuable case-study applied into a medical material manufacturing environment.

4.4. Practical implications

As the methodology of this study showed, combining different analysis tools may lead to a deep ergonomic assessment. In practice, it requires an organized protocol involving multiple experimenters to be in charge of sensors (attachments, calibration, and continuous monitoring during data collection) and video recording. It is recommended that after the operator is familiarized with the experimental setup, the effective measurement is taken for several cycles of the task. Although the battery capacity of the sensors could dictate the recording duration, a minimum of 10 cycles should be considered as a theoretical lower limit (Samani et al., 2015). Global results concerning mean RULA scores and percentages of time spent at each RULA range provide an overview of the ergonomic recommendation. Moreover, it may later be used as comparative measures to assess the impact of an ergonomic intervention. The computation of local scores and percentages of time an articulation/segment spent at risky level allow identifying the localization of the workstation that needs to be modified, e.g. the workspace dedicated to lower arms and hands. Finally, the subtask analysis gives a better insight about processes and tools that can be improved. As an example from this study, the vacuum sealer might be opened using an activation pedal to decrease the involvement of left shoulder and upper arm in the 'opening the vacuum sealer' subtask. Identified risky subtasks may also be subject to improved detailed processes or specialized training.

5. Conclusion

This study aimed to perform an ergonomic analysis of operators working on a workstation dedicated to filter cleaning for medical materials. The main contribution of this research consisted in combining continuous RULA assessment, based on on-body sensors network, with subtasks videotaping to provide ergonomic recommendations for the workplace redesign. Thus right and left RULA scores were calculated at each time step to characterize the risk of exposure of the upper body. Local risk scores were also computed to identify the anatomical origin of the exposure. The video-recorded work activity was time-studied to classify and quantify all subtasks involved into the task. Results showed that RULA scores were at a risky level from average and temporal points of view. Mean local scores permitted to identify most exposed joints during the task, i.e. elbows, lower arms, wrists and hands. The subtask analysis allowed to detect 'snow thrower', 'opening the vacuum sealer', 'cleaning' and 'storing' subtasks as the most dangerous for the development of MSDs. Thus suggested ergonomic recommendations focused on these different subtasks. The methodology presented in this study may be transferred to other risky workstations in order to optimize redesign in an ergonomic manner and subsequently decrease the risk of exposure to MSDs.

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Tables

Table 1: Mean local scores and standard deviations (SD).

Table 2: Mean RULA scores and mean local scores (\pm standard deviation) associated to each subtask.

Table 3: Duration, percentage of time spent at each RULA range and percentage of time an articulation/segment spent at a risky level, per subtask.

Figure captions

Figure 1: Workstation dedicated to filter cleaning and description of the filter.

Figure 2: Placement of IMUs, electrogoniometers and their wireless modules in the front (a) and back views (b).

Figure 3: Percentage of time spent at each RULA range.

Figure 4: Mean percentage of time an articulation/segment spent at a risky level for all work cycles.