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A lightweight approach for human factor assessment in virtual assembly designs: an evaluation model for postural risk and metabolic workload

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Abstract

The assessment and optimisation of postural stress and physical fatigue can be challenging and is typically conducted only after the design of manual operations has been finalised. However early assessment of manual operations and identification of critical factors that are deemed outside of an appropriate envelope can avoid the time and costs often associated with re-designing machines and layout for operator work processes. This research presents a low cost software solution based on a simplified skeleton model that uses operator position and workload data extracted from a simulation model used for virtual manufacturing process planning. The developed approach aims to assess postural stress and physical fatigue scores of assembly operations, as they are being designed and simulated virtually. The model is based on the Automotive Assembly Worksheet and the Garg's metabolic rate prediction model. The proposed research focuses on the integration of virtual process planning, ergonomic and metabolic analysis tools, and on automating human factor assessment to enable optimisation of assembly operations and workload capabilities at early design stage.

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Keywords: Assembly ergonomics; Postural stress; Physical fatigue; Virtual human model.

1. Introduction

In manual and semi-automatic workstations, the role of human operators is crucial as it directly impacts the operation cycle time, quality and feasibility as well as operational safety and health [1]. Due to the increase in average employee age, the probability of the occurrence of musculoskeletal disorders (MSDs), especially among workers who perform physically demanding tasks has increased [2]. As a result, legislation has been passed in many industrial countries to ensure manufacturers maintain worker health and prevent work-related safety issues [3]. Recent studies have revealed that processes and workplaces designed according to ergonomic principles both improve occupational health and enhance productivity [4]. It is important to evaluate process ergonomics at the early design stage as the re-design during try-out phase can incur significant costs and the loss of production [5]. Thus there is a need to develop tools and methods that evaluate human factors at the planning phase. Nowadays, digital human models (DHM) integrated computer aided tools (CATs) are considered a promising proactive approach to the evaluation of ergonomics. In general, DHM integrated CATs use three dimensional anthropometric manikin representations and simulations to evaluate the safety and performance of manufacturing operations, and can contribute to reducing overall design and engineering costs [6]. They allow rapid virtual prototype development without putting the operator at risk and negate the need for physical mock-ups and production trials [5]. Also, intuitive 3D representation provided by the DHM tools can improve cooperation between designers, engineers and operators by providing a common understanding of design alternatives [7].

In the last decade, a large variety of academic projects have been conducted using DHM for proactive evaluation of ergonomics issues and many commercial tools have also been introduced to the global market (e.g. Dassault Systèmes' SAFEWORK, Siemens/Technomatix's JACK, RAMSIS, MAthematical DYnamic MOdels (MADYMO), 3D Static Strength Prediction Program (3DSSPP) and SANTOS). Common methods integrated into the DHM tools include;

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Rapid Upper Limb Assessment (RULA) [8], the National Institute for Occupational Safety and Health (NIOSH) [9], European Assembly Worksheet (EAWS) [10], Job Strain Index (JSI) [11] and Rapid Entire Body Assessment (REBA) [12]. Despite the potential benefit of DHM, several limitations may impede their effective deployment and use in a real production environment:

- Most tools only allow the analysis of static scenes using ergonomic assessment methods that are developed for a particular risk factor group [5]. For example, RULA focuses only on body postures whereas the NIOSH is used for the manual material handling.
- Identification and interpretation of ergonomic issues require expert skills, which means that designers with insufficient knowledge regarding the specific methods and their limitations, may conclude to inaccurate results [13].
- According to Backstrand et al. [14], a language gap between method used by DHM tool and the company-specific ergonomic knowledge exists. An integration between DMH tool and company specific CAE software environment is therefore required.
- Most tools currently used in the industry are relatively expensive for small and medium enterprises (SMEs). Therefore, development of the low cost and lightweight solutions to enable SMEs to assess human factors is highly valuable.

To address these limitations, a DHM based human factor assessment approach offers a stand-alone, lightweight and quickly deployable design analysis for supporting of operator work sequences is designed and developed in the current article. The developed model uses simplified virtual manikin skeleton and has the ability to rapidly evaluate both working postures and physical work fatigue using intuitive and non-specialist software function and GUI. This has a significant impact on the time and skill required to edit a virtual model/simulation of a manual operation, hence allowing to contribute to the 100% virtual modelling and validation target.

2. Module descriptions

2.1. The vueOne VM tool and V-Man module

The research conducted by the Automation Systems Group (ASG) at the University of Warwick is focusing on the design and implementation of automation systems tools and methods that contribute in supporting both throughput and life cycle of automation systems. As a part of research, the ASG developed an engineering environment, called vueOne for assembly sequence planning and validation. The vueOne tool is currently being used to support virtual engineering activities at several companies operating in the sectors of automotive powertrain and battery production. The vueOne offers a set of software modules that target key engineering domains of automated production systems design. The work presented in this paper relates to the *V-Man* (Virtual Manikin) module of the vueOne toolset (Figure 1).

Manual operations in vueOne are modelled using the *V-Man* module (Fig 2) which provides a set of functions and a user interface to design, simulate and validate human operator work sequences. The *V-Man* module offers intuitive posture and move sequence editing capabilities and includes different sizes of anthropometric digital manikins (5th, 50th and 95th percentile for male and female). Currently, the *V-Man* is using a 13 independent joints skeleton with 3D interactive jog controls and is able to perform predetermined motions as defined by the MODAPTS (see [15]), such as; crouch, kneeling, torso rotation, foot rotation and move. In vueOne, a *V-Man* operation is described as a finite state machine (FSM), which outlines the production process that the *V-Man* will follow. A *V-Man* FSM consists of static and dynamic states. In each dynamic state, the V-Man completes the corresponding pre-determined sequence of moves. The *V-Man* timeline displays all the virtual manikin movements. Each row within the timeline corresponds to a part of the body such as feet position/rotation, left/right hand and left/right hand actions, and carries specific information such as walking distance and working arm distance. These data can be exported to an XML formatted file that can be used as input to additional engineering processes such as discrete event simulation and energy analysis. In this research, postural stress and fatigue assessment modules have been introduced that are fed by this data. To integrate these modules with vueOne, a set of data recording, processing and reporting mechanisms are also described.

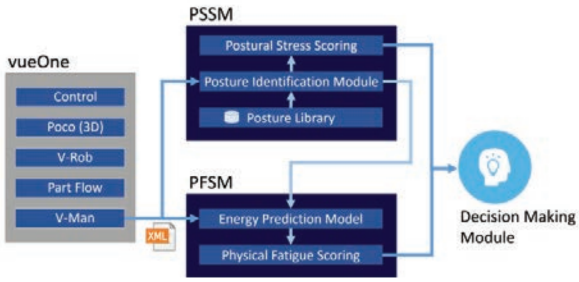

Fig. 1. Interaction between proposed modules and vueOne virtual manufacturing tool.

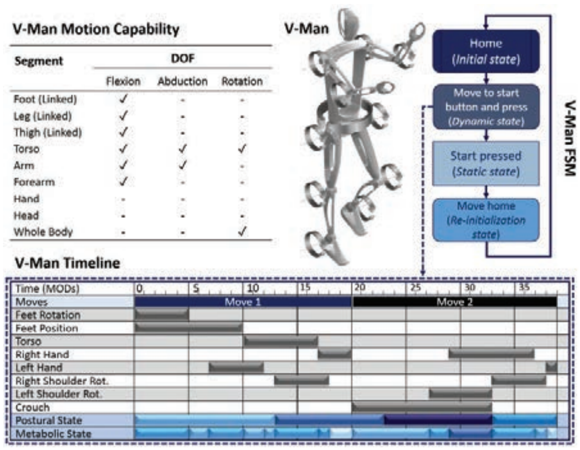

Fig. 2. Virtual manikin module; V-Man motion capability, V-Man FSM and V-Man operation sequence timeline.

2.2. Postural stress screening module (PSSM)

PSSM provides dynamic postural stress scoring which can be seen in the *V-Man* operation editing timeline. This practically means that designer can detect and correct high risk operator movements very early in the design. The module consists of two sub-modules (i.e. posture identification and stress scoring). Posture identification sub-module aims to identify and assess the current posture of the V-Man (e.g. standing, sitting, kneeling, bending, arms above shoulder level etc.) at a specific simulation time *t*. To recognise and report time-dependent *V-Man* postures, following inputs are fed into the PSSM:

- *V-Man* dimensions:

  $$D_i = [l_1, l_2, \dots , l_K] \quad (1)$$

  where, D_i is the dimension matrix of *i*th anthropometric digital manikin type, l_k is the length of the *k*th body segment in the *V-Man* ($k \in [1, \dots, K]$) and K is the total number of segments.
- *Local coordinates of body parts of the V-Man*:

  $$S_t = [(X_1Y_1Z_1)_{(t)}, (X_2Y_2Z_2)_{(t)}, \dots , (X_KY_KZ_K)_{(t)}] \quad (2)$$

  where, S_t is the local coordinate matrix at simulation time *t*, $(X_kY_kZ_k)_{(t)}$is the local position of the *k*th body segment at the simulation time t.

PSSM reports the sequence of postures along with the start and end motion times, and also records the time value at which the postural state change has happened. Aforementioned dynamic motion information is extracted from the corresponding *V-Man* module XML work sequence output and is converted into a series of work postures as defined in the posture library designed for this project and containing predetermined ergo-zones (Fig 3). In vueOne, the operations outside of zone 1, zone 4 and zone 5 are always simulated with fully stretched arms which is imposed by design limitation of the *V-Man* skeleton module. Posture identification is carried out based on internally coding a set of IF-THEN-ELSE rules. For example, the following pseudo-code defines a kneeling bend forward position:

READ Hip position at time *t* (H_t); Arm position at time *t* (A_t);
IF -600 < y value of H_t < -200,
AND ZONE2 ⊇ A_t,
THEN posture at time *t* is 'kneeling bend forward', **END IF.**

In the next step, a modified version of the AAWS (see original method [16]) is used to screen the postural stress involved during the operations. The AAWS was originally developed for automotive car assembly and (contrary to methods such as RULA) contains physical exposures by accounting their intensity, duration, frequency and possible concurrent occurrence [5]. In the AAWS, static postures i.e. standing, sitting, kneeling and lying, either upright or bent, arms above/at shoulder or head level are rated according to their durations (Table 1). Moreover, additional posture scores i.e. lateral bending of the trunk, twisting of the trunk and far reach of the hands, are also considered in the AAWS calculations (Table 2). It is important to note that the Action Force Score sheet, the Material Handling Score sheet and Extra Forces are not addressed in this article. These scores will be considered in future work.

Table 1. Evaluation of basic postural scores [13].

	Posture of trunk / arms	Static postures/movements in % of cycle time 2…10	10…20	20…33	33…66	66…100
Standing	Upright standing & walking	0	0	0	0	0
	Bend forward	3	7	12	23	40
	Bend deeply forward	5	12	21	38	63
	Upright arms at/above shoulder level	5	12	21	38	63
	Upright arms at/above head level	8	19	33	60	100
Lying	Lying	9	21	37	68	113
Sitting	Upright slightly bend forward	0	0	0	0	0
	Bend forward	1	2	4	8	13
	Upright arms at/above shoulder level	4	10	16	30	50
	Upright arms at/above head level	6	14	25	45	75
Kneeling	Upright slightly bend forward	5	9	15	27	45
	Bend forward	6	14	25	45	75
	Arms at/above shoulder level	9	23	43	80	135

Table 2. Evaluation of torso twist, lateral torso bending and far reach posture scores [13].

Twist Level Score (°)					
0-30	30-60	+60			
0	2	4			
Twist Time Score (%)					
1-6	6-15	15-20	20-100		
1	2	2.5	3		
Lateral Level Score (°)					
0-10	10-15	15-20	20-25	25-30	+ 30
0	1	2	3	4	5
Lateral Time Score (%)					
1-6	6-15	15-20	20-100		
1	2	2.5	3		
Far Reach Level Score (%)					
0-60	60-80	80-100			
0.5	1	4			
Far Reach Time Score (%)					
1-6	6-15	15-20	20-100		
0.5	1.25	1.75	2		

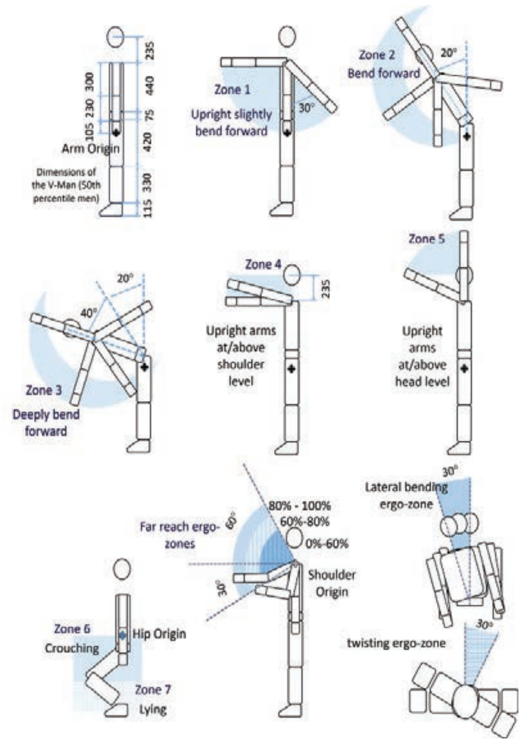

Fig. 3. Predetermined ergo-zones for *V-Man* operations.

In the AAWS, the basic posture score is the summation of all individual basic scores for identified postures whereas the additional scores are calculated by multiplying the value of the level score with the identified time score of the corresponding posture type. For overall postural stress score, the individual scores of basic posture, lateral bending of the trunk, twisting of the trunk and far reach of the hands are summarized to a total score indicating the risk for a particular assembly operation according to the traffic light principle (i.e. *green* (*0-25*): low health risk, operation design is valid, *amber* (*26-50*): moderate health risk, re-design may be required, *red* (*+50*)): High health risk, immediate intervention is required).

2.3. Physical fatigue screening module (PFSM)

Manual assembly tasks may include intense physical activities. When metabolic energy expenditure rate exceeds worker's energy production capability, physical fatigue compromises workers' productivity and safety, occurs [17]. Several methods for assessing metabolic energy demand for a specific task have been proposed. In this research, a physical fatigue scoring module (i.e. PFSM) based on Garg's model [18] is integrated into vueOne. Garg's model offers empirical metabolic energy prediction equations for a series of typical industrial material handling motions such as; walking, lifting, carrying, and reaching based on motion (e.g. speed of walking and horizontal movement of work piece), load (e.g. weight of the load) and operator specific (e.g. body weight and gender) parameters [19]. The mathematical model allows an estimate of human operators' energy consumption during their work in kcal/min. According to Garg's model, average energy expenditure rate of the entire job can be described as follows;

$$\sum E_{op} = (\sum^{nt} E_{pos}\, t_i + \sum^{n} \Delta E_{taski})/T \qquad (3)$$

where, $\sum E_{op}$ is the average energy expenditure rate for the entire operation (kcal/min), E_{pos} is the metabolic energy expenditure due to maintenance of *i*th posture (i.e. sitting, standing and standing bent position)(kcal/min), t_i is the time duration of *i*th posture (min), nt is the total number of body postures employed in the operation, ΔE_{taski} is the net metabolic expenditure of *i*th task in steady state (kcal), n is the number of total tasks in given operation and T is the total cycle time (see [20] for detailed information and equations for maintenance of body postures and net metabolic cost of tasks).

The main function of PFSM is to calculate the predicted metabolic energy, using the Garg's model, for any given operation designed using the *V-Man* tool. Several types of data input, that can be obtained either manually or automatically, are required for the calculations. Part of this data, the operational data (i.e. vertical height of lift and lower, horizontal movement of work piece, grade of the walking surface, speed of walking and time) is extracted from a *V-Man* XML work sequence output. An interface between the PFSM and the *V-Man* module, and an XML parsing tool are implemented for this purpose. Additional data such as; operator body weight (kg), operator gender (m/f), operator age average pushing (pulling) force applied by hands (kg) and average work hours (mins) can be defined manually in the PFSM. Moreover, time durations for individual posture types are achieved from the PSSM. In order to reveal the degree of physical fatigue of a manual assembly operation, PFSM findings are compared against the designated worker population's maximum physical work capacity (PWC). If the total metabolism calculation (based on the PFSM analysis) exceed the PWC for a given gender, age and work duration, the operation will most likely generate physical fatigue. In this research, a theoretical PWC model introduced in [21] is used. This model provides a universal PWC calculation which is derived for a variable time period of work and variable fitness level. Adaptive polynomial fitting with cross validation is applied to the tables provided by PWC model to obtain equations that reflects the maximum aerobic capacity of female and male populations between ages of 20 to 65 and for time durations comprised between 120 mins up to 510 mins. PWC for male and female workers can be defined as follows;

$$PWC_{female} = 2.8295\ 10^{-4} a^2 + 5.0873\ 10^{-5} a\, w - 0.08\, a + 1.2677\ 10^{-5} w^2 - 0.0163\, w + 10.039 \qquad (4)$$

$$PWC_{male} = 3.697\ 10^{-4} a^2 + 6.8741\ 10^{-5} a\, w - 0.1061\, a + 1.6853\ 10^{-5} w^2 - 0.0217\, w + 13.8393 \qquad (5)$$

where, *a* is the age of employee ($a \in [20, \dots, 65]$) and *w* is the work duration per shift ($w \in [120, \dots, 510]$). Similarly to AAWS postural stress scoring, a traffic light principle indicating the risk of designed assembly operation is applied to the PFSM analysis i.e. *green* (PWC > 105% $\sum E_{op}$): operation energy demand is acceptable, *amber* (95% $\sum E_{op} \leq$ PWC $\leq$ 105% $\sum E_{op}$): operation energy demand is at physical limits of the operator, re-design may be required soon, *red* (PWC < 95% $\sum E_{op}$): operation energy demand is beyond acceptable physical limits, immediate intervention is required).

3. Use case

The PSSM and PFSM modules were tested by designing a basic drilling operation that used the *V-Man* to carry out pick, place, and drilling processes. The workspace is illustrated in Fig 4a. The operation was designed such that the location of the workpiece and drill tool were at positions that were non-optimal, requiring crouching and reaching up respectively (Fig. 4b and Fig. 4c). The aim of the case study was to therefore determine whether the model would flag these processes to inform the designer that further analysis, or potentially, a redesign was required.

The operation was designed using the 50th percentile male *V-Man* model (1742.5mm height, 76.1kg weight) and 50th percentile female *V-Man* model (1626 mm height, 62.5kg weight). The cycle time of the operation was 37.518 seconds (222 MODs). The weight of the workpiece and drill tool were 5kg and 1kg respectively. Typically, the AAWS method uses a threshold of 3 seconds per minute to define a static posture. However, due to the relatively short cycle time used in this case study, the threshold was set to 2% of total cycle time to ensure sufficient sensitivity. The results of the PSSM and PFSM for male model are presented in Table 3 and 4 respectively with Fig. 6 describing the operation's timeline and corresponding PSSM and PFSM outputs. The PSSM module flagged the workpiece picking (30-73 MODs) and drill picking (138-156 MODs) as those that required further analysis (Fig. 6a) for both models. According to the AAWS criteria, the operation is in the amber area for both models (Scores of 41.25 for male and female models). This indicates that, as expected, there is a need to redesign the operation to reduce postures that pose health risks.

The PFSM predicted a total energy expenditure of 5.52 and 5.49 kcal/min for male and female models where ~70% of which was caused by vertical arm movements highlighting the relatively high metabolic load of this process and indicating a need for redesign. This load could be reduced by reducing workpiece and tool mass, and by placing the workpiece in an area that is less strenuous on the operator to reach. Prediction of physical fatigue of PFSM for 50th percentile male and female worker populations are illustrated in Fig. 5. This data can be used either optimising the current workstation or selecting the suitable worker and work duration.

4. Conclusion and future work

This research stemmed from the identification of the need to fill the gaps between ergonomic analysis, fatigue analysis and virtual engineering tools used to design production processes. The presented work has focused on describing how theoretical models used for human posture and fatigue analysis *i.e.* AAWS and Garg's model, are integrated with a virtual engineering tool to specify, design and prototype engineering support modules that extend the capabilities of an existing VM software solution.

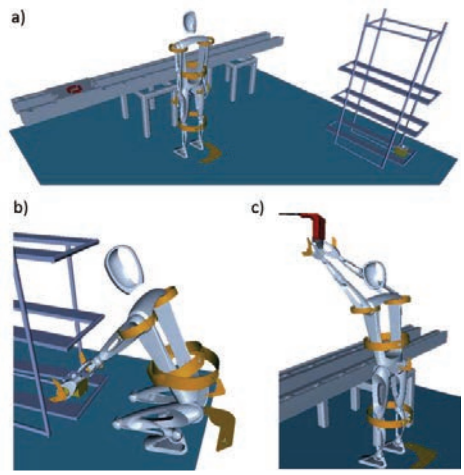

Fig. 4. a) Designed workspace, b) A snapshot posture from picking workpiece task, c) A snapshot posture from picking drill task.

Table 3. PSSM Results (50th percentile male).

Posture Description	Time (MODs)	Posture Score	Twist Score	Lateral Score	Reach Score
Standing & walking	161	0	0	0	2
Standing bend fwd.	15	3	0	0	5
Std. deeply bend fwd.	13	5	0	0	2
Std. arms at/above shoulder	4	0	0	0	0
Std. arms at/above head	8	8	0	0	0.25
Kneeling upright	5	5	0	0	0
Kneeling bend forward	16	6	0	0	5
Total	222	27	0	0	14.25
Postural Score	**41.25**				

Table 4. PFSM Results (50th percentile male).

Description	Energy expenditure (kcal/min)	%
Walking	0.305	5.537
Carrying	0.541	9.808
Horizontal arm work	0.482	8.747
Lateral arm work	0.224	4.053
Vertical arm work	3.939	71.406
Maintenance of postures	0.025	0.449
Total	**5.516**	100

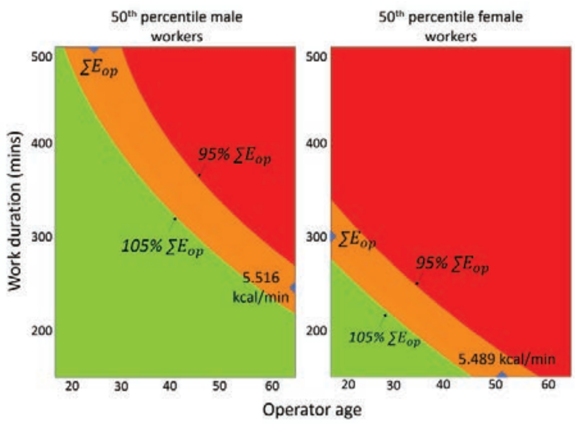

Fig. 5. Physical fatigue prediction of designed operation for a given age, gender and work duration.

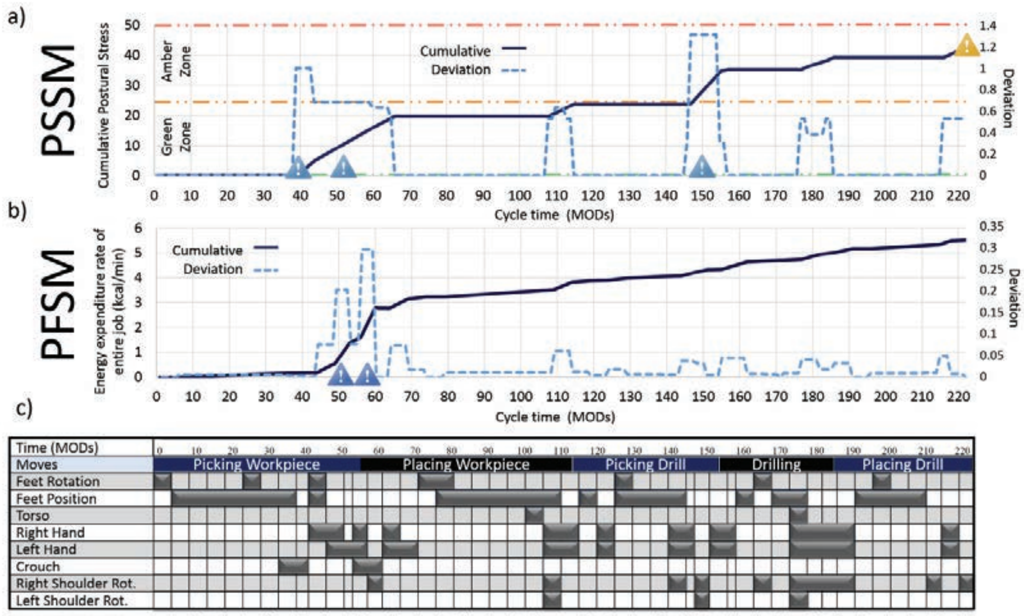

Fig. 6. a) PSSM results, b) PFSM results and c) *V-Man* timeline for designed drilling task (50th percentile male).

The PSSM and PFSM modules developed in this work automatically extract and process appropriate data from an interactive virtual manikin interacting within a virtual engineering environment to provide practical and immediately usable engineering knowledge for an assembly operation utilising a traffic light approach to flag potentially dangerous operations. The work has shown the overlap and gaps between data required by theoretical models and the data generated by virtual models and the methods to achieve mapping between those data sets (i.e. ergo zone screening methods).

This work provides a strong basis for future development of the engineering tools developed by the ASG group: The limitation of the skeleton model currently used for the *V-Man* module was highlighted and resulted in a clear set of specifications for modification to better align with critical aspects of the theoretical models. Future work will also focus on full implementation and integration of the PSSM and PFSM modules as part of the vueOne software solution. Finally, the posture and fatigue analysis models combined in this work, will be used as one component (human process) of a wider complexity model aiming at assessing complexity of manual and also semi-automated production systems.

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