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Cognitive and metabolic workload assessment techniques: A review in automotive manufacturing context

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Abstract

Ergonomics assessment in the automotive industry has, to date, focused mainly on physical ergonomics, for example, manual handling and posture. However, workload and, in particular, metabolic and cognitive workload, contributes to worker efficiency but has not received sufficient attention to yield practical guidance for industry. Successful workload assessment requires in-depth understanding of the context in which it will be conducted and of the various assessment techniques which will be applied, with consideration given to factors such as feasibility, resources, and skill of the assessor. These requirements are met with challenges within large and complex organizations and are often dealt with in a piecemeal and isolated matter (i.e., reactive workload assessment). The present paper explores these challenges within the automotive manufacturing industry and aims to develop a decision matrix to guide effective selection of workload assessment techniques focused on metabolic and cognitive demands. It also presents the requirements for time, equipment, and knowledge to implement these techniques as part of a participatory ergonomics approach. Early findings suggest that most assessment techniques reviewed require further development, for example, to establish the acceptance criteria for the specific workload scenario. However, five methods (Garg, Borg RPE, IPAQ, SWAT, and NASA-TLX) are ready to use in certain applications. Ultimately, the findings suggest that it is possible to implement a participatory workload evaluation program within large and complex manufacturing plants.

KEYWORDS

automotive manufacturing, cognitive workload, ergonomics intervention, metabolic workload

1 | INTRODUCTION

Although many people understand the concept of workload as, simply put, the effort required to complete a task versus the resources available to do so, the phenomenon is, in fact, far more complicated. The workload an operator experiences is influenced by the strategies they adopt as well as internal factors (e.g., skill, attitude, arousal, alertness, and mood), which can vary both between and within individuals. In the real-world, expertise, memory, attention, situation awareness, and social and organizational factors all contribute to an individual's experience of workload (Sharples & Megaw, 2015).

As a multifaceted concept, workload is difficult to measure, and there are no universally accepted definitions. Sharples and Megaw (2015) noted one of the main challenges for effective workload measurement processes as lack of consistent definition, a problem confounded by the fact that existing definitions are focused on piecemeal and isolated aspects of work demands. For example, to explore cognitive demands, complexity of task is assessed regardless of the individual differences, expertise, and working conditions. Likewise, to explore metabolic demand, the focus remains on physical components and not necessarily environmental conditions (e.g., temperature or the structure of shifts) which would likely affect the outcome. Further, knowledge of underlying psychological processes, especially in relation to cognitive demand, is incomplete in the academic literature, although system-based models which integrate current understanding do exist (e.g., Sharples & Megaw, 2015).

Measuring and understanding workload is an important component in many work settings. Yang et al. (2019) highlight this and note the need for increased use and development of technical measurement techniques to ensure higher reliability and validity of workload assessment techniques. Ultimately such integrated systems could inform automatic workload risk assessment (i.e., to identify the optimal level of work demand). To do so, would require in-depth understanding of available workload measures, their applicability and effectiveness in different contexts.

Workload assessment, like many other ergonomics best practices and tools, should inform design practises (Longo, 2015). Within safety critical domains, jobs are usually designed first in a virtual setting (either on paper or using more sophisticated modeling tools) and it is, therefore, preferable to be able to capture an understanding of workload measures while the design is in a developmental stage. Proactive workload assessment and workload forecasting (Dode et al., 2016; Greig et al., 2011; Herbst et al., 2014) have been utilized to ensure that the work is adaptive and to allow for integrating human factors throughout the organization and ensure employees' wellbeing. Workload cannot be directly evaluated or observed. It should be inferred from a number of factors which describe its multifaceted nature. There are different categorizations for workload assessment, which Mehler et al. (2009) document as: Performance-based measures, self-report, behavioral, observation and physiological measures. Depending on the nature of the work that is being studied, different approaches are preferred. For example, for dynamically changing work conditions, performance, and physiological measures are preferred as they collect workload objectively and continuously.

Demands that are imposed on operators/workers can include those focused on physical aspects of work and those influenced by the cognitive/mental aspects. Moreover, it is important to consider that association and dissociation occur between task demand, operator efficiency, and workload in different performance contexts. In other words, workload and performance are sensitive to multiple characterizes of the task and not just the immediate demand level (Hancock et al., 1995). The relationship between task demand, emotional arousal, and performance have been described as the inverted U-shaped model of Yerkes and Dodson (Teigen, 1994), with the assumption that with high level of arousal, information retrieval capacity will be reduced and consequently performance levels are also decreased. This is an oversimplification and disregards the influence of the wide range of cognitive functions and environmental factors on overall demand and performance levels (Hanoch & Vitouch, 2004). In addition, Warm et al. (2018) noted that tasks that allow active regulation of demands tend to promote engagement, whereas highly constrained task configurations lead to disengagement and reduced vigilance and consequently will negatively impact performance.

Analytical techniques to facilitate workload prediction are of interest as they estimate workload without requiring a human operator and a fully working system, and also allow for elimination of some design problems before the design is finalized (Vidullch et al., 1991). These analytical techniques can be further classified into five categories: (1) Comparison, (2) expert opinion, (3) math models, (4) task analysis, and (5) simulation.

Despite these benefits of proactive workload assessment, within large organizations, ergonomics involvement and intervention are often in response to an issue raised by the workforce or in response to diminished performance in the workplace (i.e., reactive). Participatory ergonomics approaches, in which workers are actively involved in developing and implementing workplace changes (Burgess-Limerick, 2018) have been found to be highly effective in enhancing workplace safety (Hignett et al., 2005; van Eerd et al., 2010). The goal of such an approach, as indicated in Rost and Alvero (2020), is to allow personnel at all levels of an organization to have the information and skill to be effective change agents in their own work. In doing so, end users as part of the participatory approach will be given problem solving tools to identify and address challenges within their own workplace. The present paper aims to explore such tools, namely, a decision matrix that can guide appropriate level of workload assessment within the automotive industry.

Participatory ergonomics interventions can be conducted at a micro or macro level. Micro ergonomics is mostly focused on individual aspects of work (i.e., workload assessment) and macro ergonomics attempts to review and influence work and end users' wellbeing at an organizational level (Hignett et al., 2005). A key first step to implement participatory ergonomics (at either level) is to understand the scope, available resources, and limitations within the organization. Rost and Alvero (2020) defined the three core elements of a participatory ergonomics framework as: Ongoing involvement, context-specific involvement, and end-user influence. Ongoing involvement will ensure that users are part of the ongoing process to identify and address ergonomics issues. Context-specific involvement suggests the importance of a best-fit approach and the value of contextual consideration when designing an ergonomics intervention. End-user influence focuses on the need for user engagement and recognizes the need for supporting works in delivering an effective ergonomics program in their workplace. These three elements are adopted throughout the present research to explore what workload assessments are feasible in the workplace and to develop a framework to guide participatory workload evaluation within the automotive manufacturing sector (i.e., a decision matrix).

This is not the first work to support the decision making around ergonomics interventions; previous works have looked at optimizing workplaces in a diverse range of industrial sectors. For example, Battini et al. (2011) developed a theoretical framework to assess concurrent engineering approaches to assembly system design problems. They explored the context, technological and environmental variables, and developed a series of qualitative cross-matrices to inform decision making. Similarly, Nurmianto et al. (2015) present a decision matrix to identify manual handling problems within the mining industry. Their decision matrix (taken from Cornelius et al., 1997) captured contextual insights from stakeholders to determine relevant manual handling risk factors. The present paper adopts a similar approach to understand the specific needs of the automotive manufacturing context and determining appropriate and feasible ergonomics intervention for cognitive and metabolic workload assessment.

A number of participatory ergonomics programs have previously considered workload assessments, examples include mining (de Jong & Vink, 2000), office ergonomics (Vink et al., 1995), and installation work (de Jong & Vink, 2002). However, these are mostly focused on physical (and in particular *musculoskeletal*) workload and generally adopt the definition of participatory to incorporate and involve end-users within the organization during the design and implementation of the workload evaluations. Similarly, much work has been done in cognitive workload assessment, in a range of applications areas, such as driving (Reimer & Mehler, 2011; Zhang et al., 2004), air traffic control (Ayaz et al., 2010; Marchitto et al., 2016) and rail (Krehl & Balfe, 2014; Pickup et al., 2005) but not within automotive manufacturing. The present paper explores the process adopted to develop/propose a participatory workload assessment program within automotive manufacturing.

Any manual activity, such as that found in manufacturing jobs, is conducted through the conversion of food and oxygen to energy (i.e., metabolism) in the muscles responsible for movement. Maximum aerobic power is a threshold beyond which energy expenditure exceeds energy production. In metabolic workload assessment, the energy required to perform jobs (total job metabolism) is compared to the worker's maximum aerobic power (Garg et al., 1978; Gasser et al., 2018; Williams, 2017). Garg et al. (1978) reports that 16 kcal/min is the maximum aerobic power of a normal healthy young male, and estimates that the sustainable value for an 8-h shift is 33% of this value: 5.2 kcal/min.

In comparison, mental workload (MWL) can be defined as a ratio between task complexity and a person's cognitive capacity to meet the task demands (Kantowitz, 1987). In other words, MWL is the cost put upon the operator's information processing capacity (Sanders & McCormick, 1998). It not only relies on task specificities, its complexity, and human computer interaction, but it also takes into account individual differences and characteristics (Da Silva, 2014). Stanton et al. (2005) considered MWL as a combination of interacting stressors on an individual.

In the present research, the focus was on metabolic and cognitive workload evaluation. This was in response to needs arising from the automotive manufacturing. Physical workload was not the main focus of the present research as there is existing knowledge available regarding the physical workload measurement techniques in industrial settings (e.g., Ivarsson & Eek, 2016, Mazloumi et al., 2014; Greig et al., 2018) and these findings are already embedded within the Jaguar Land Rover (the industrial collaborator) work practices. However, Jaguar Land Rover, identified a need for more clarity in the application of cognitive and metabolic assessment, and at all stages of the manufacturing lifecycle, from design through to implementation in the factory. Moreover, this need was exacerbated by current manufacturing jobs, which may involve complex assembly procedures in a short assembly cycle (i.e., cognitive demand) and/or considerable metabolic effort. Thus, the aim of this study was to inform participatory ergonomics interventions and in doing so allow for embedding workload considerations throughout the design and evaluation of work settings.

Therefore, the key research questions explored in this paper are:

1. What common workload assessment techniques are applied to analyze metabolic and cognitive workload?
2. What are the limitations and benefits of the different workload assessment techniques for industrial applications?
3. What are the appropriate workload assessment techniques (if any) to guide analytic (virtual) or empirical (physical) workload analysis?
4. Where no suitable technique exists, what is needed to address this shortfall?

2 | UNDERSTANDING THE JAGUAR LAND ROVER CONTEXT

It is widely recognized within Jaguar Land Rover that, to optimize the manufacturing process, it is beneficial to focus on virtual processes to facilitate predictive review of work settings and embed that understanding early on in the design process. The Ergonomics team at Jaguar Land Rover is responsible for empowering and equipping various parts of the design and manufacturing process with relevant and appropriate tools, frameworks, training, and guidelines that allow them successful delivery. That is, the Ergonomics team empower others to consider the ergonomics of their processes; this is different from other parts of the organization where specialists are embedded within the various functions.

Currently, the guidelines and standards within Jaguar Land Rover are mostly focused on physical aspects including, for example, virtual representations of hands to check access in computer aided design (CAD) and reach envelopes that can be used as a decision aid. Risk factors that are currently reviewed include access, clearance, posture, manual handling, and vision. Examples of workload-related factors captured using CAD include reviewing accumulative manual handling, and comparing distances walked by individuals. That is, if two individuals who work on the same assembly line differ greatly in the number of steps taken during any given shift, the ergonomist would then review the work elements and suggest modification to the tasks to balance the workload. The CAPTIV[1] system is being used by some locations to explore job categories. These are not currently focusing on workload assessment and the research work presented in this paper was conducted to address this gap.

The majority of manufacturing simulations that may be potentially used to facilitate predictive workload assessment are available during the early phases of design (i.e., the concept phase). The process engineer would define the assembly process from the specification, these specifications are outlined by the product development team. Very early phases are documented in PLM software (Product Lifecyle Management). Next, the assembly process information is compiled in process definition software, the elements should be well-defined and should have all of the specific tooling or equipment associated with them. Jaguar Land Rover use an Excel spreadsheet and review work elements and allocate time variations to each of the elements. This is more detailed and may have potential to be utilized for capturing metabolic or cognitive workload.

The information about walking and movements are not captured (e.g., walking distances) and the work elements listed are to cover the work as a single unit and is not focused on the parts that have to be completed by a single individual. An additional system is linked to process definition software and covers the industrial engineering part of the system. Industrial engineers can inform different aspects of work elements based on the reference engineering operational definitions (i.e., work assignment).

Early ergonomics reviews of work will most likely include a review of textual information regarding processes and tasks and explore the actions and elements that are required to complete these tasks. Simulating the work (e.g., through Jack) allows review of posture, currently, this is mostly done to review and simulate high risk postures. The information from digital human models is then exported to an internal tool which processes the posture data and conduct an assessment.

At the operational level, tools like Jack (Blanchonette, 2010) are being used. At the macro level, tools like Witness™ are being used, which simulates the flow of the material through the whole system and identifies the functional codes to define the human role. This is not very detailed but provides higher level information. It reviews work from the human perspective and explores the capacity of the allocated person and may also include data associated with distance that they have to walk. The data documented is quite subjective and representing the system can be quite resource intensive (i.e., need to write detailed codes). Workload is not particularly assessed within Witness™ and the individual positioned in the simulated environment is assumed to have capacity to conduct the allocated functions.

From the design perspective, it would be ideal to have all of the information defined in one system and have all of the tasks allocated to the built workstation aligned with a three-dimensional version of the factory, as well as potential human movements required to conduct the activities. However, this detailed information is often unavailable during the early phases of the design. This is partially due to the fact that process engineers may not have sufficient resources (i.e., time) to develop this level of detail early on and data is mainly getting populated if it is serving a very clear purpose and not to facilitate potential synthesis or assessment.

Elements of cognitive load may be captured through review of complexity; however, this does cover elements associated with root cause analysis and to explore the impact of demand on error and quality of work.

Some of the considerations and recommendations are summarized below:

- Tools adopted at earlier phases of design (i.e., predictive) should be self-explanatory for nonspecialists.
- Important to have a mechanism to flag potential problematic aspects before any detailed assessment and to facilitate prioritization.
- Assessments conducted by nonspecialists should be based on checklists to ensure that all reviews are consistent and individual preferences of the non-ergonomist evaluators are mitigated.
- It would be useful to have local liaisons (Ergonomics Ambassadors) at each of the teams to ensure effective and consistent implementation of any proposed assessment. Currently, there are provisions for having ergonomics liaisons to comment on process designs.
- Ideally all of the simulation models should operate and interact within the same environment, but this is not the case at the moment.
- It is important to understand elements (non-value-added work) in allocated process timing (e.g., walking) and merge them with work steps as well in the predetermined time management system timing patterns.
- For metabolic load assessment, it is important to have an understanding of the whole range of work conducted by an individual whereas for cognitive load assessment can be more focused on specific (highly cognitive demanding) tasks.
- Currently, no metabolic or cognitive assessment is conducted at Jaguar Land Rover except limited work conducted at the Jaguar Land Rover site.

Workload assessment is needed to predict demand or to assess ongoing work in the physical environment. To utilize existing resources efficiently, it is possible to allocate early assessments to Ergonomics-aware operators and allow Ergonomics specialists to focus on more in-depth reviews. The question is what types of workload assessment techniques are sufficiently informative for their intended purposes and feasible to be conducted by different levels, as shown in Figure 1.

- Level 1: Only aims to identify a problem, and mostly consists of a checklist or design criteria. The aim is for operators with limited training and basic ergonomics knowledge to conduct preliminary review of the work and comment on metabolic and cognitive demands.

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[1] https://www.teaergo.com/?lang=en

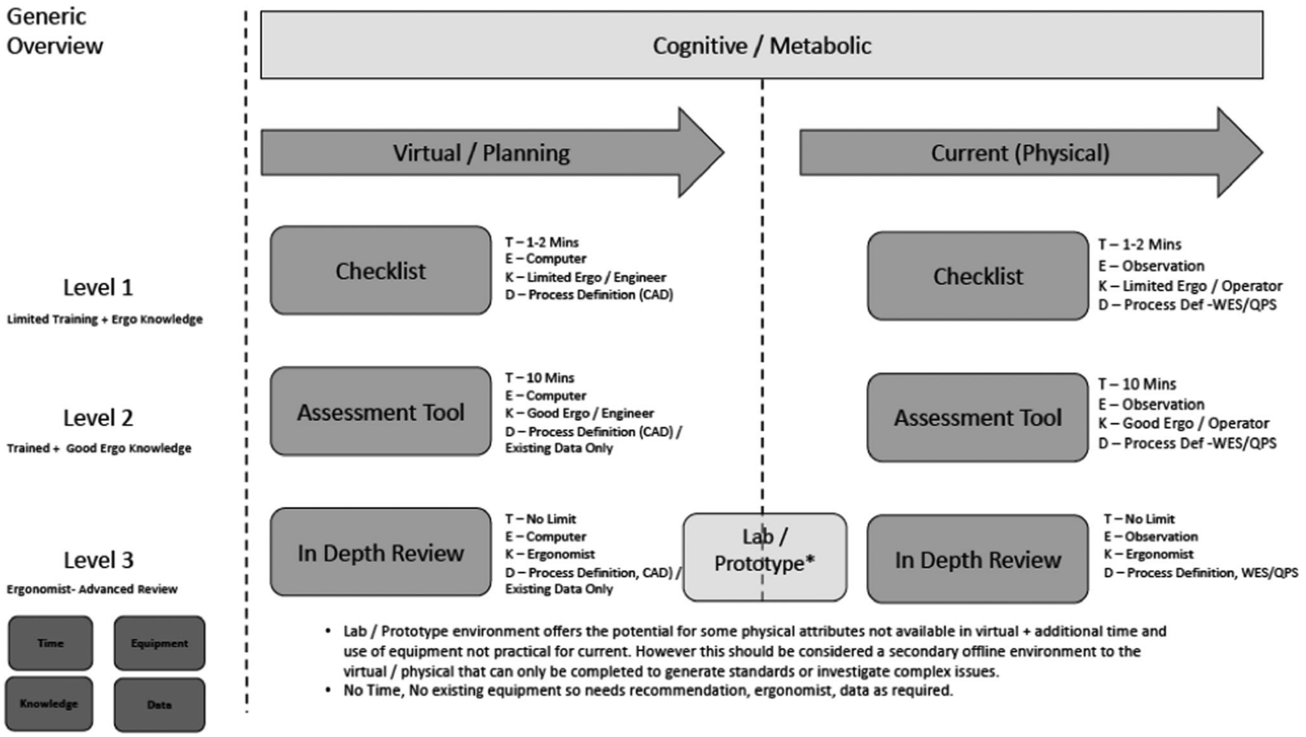

FIGURE 1 Levels of Ergonomics review/intervention (virtual and physical environment)

- Level 2: This level will be conducted once an issue is flagged during level 1 and it may contain a framework for review or application of standard methodology. Evaluators with some ergonomics knowledge will conduct the review. It concerns metabolic and cognitive load.
- Level 3: This level contains administration of a complex methodology and relevant interpretation. An in-depth review often accompanied with observation and field studies to develop a detailed understanding of the work setting, in addition outcomes of level 3 reviews will later provide a knowledge base (e.g., database of cognitive and metabolic loads) to be utilized during level 2 and level 1 evaluations.

The present research conducted a review of availabile workload assessment techniques along with contextual limitations, capabilities and resources available to Jaguar Land Rover to advise approproate workload assessment techniques within each of these levels to inform a participatory workload assessment program. In addition, the techniques are reviewed in terms of a select assessment criteria to ensure their effectiveness, Section 4 presents this assessment criteria in further detail.

3 | APPROACH

The research presented in this paper adopted a mixed method approach, which involved data collection from the industrial partner, a systematic review of workload assessment within manufacturing and a high-level exploratory literature review informed by and discussed with project partners. This mixed approach led to the development of a decision matrix that was further reviewed and would inform a participatory workload assessment program.

First, an introductory meeting was conducted with stakeholders to explore the context of work and to scope the workload assessment that would form the focus of this study. The meeting also identified the resources (e.g., staff time, expertise, and workplace representations) available for conducting workload assessment, and the dichotomy between physical and virtual assessment (Figure 1). Following this meeting, further review of the academic literature (Section 4) and a systematic review of workload assessment techniques (Section 5) was conducted. The primary purpose of the systematic review was to develop an understanding of the range and applicability of different workload assessment techniques with a focus on cognitive and metabolic workload assessment within the manufacturing industry. The secondary purpose was to identify areas in need of further research. The outcomes of the literature review specifically explored the techniques which are appropriate for metabolic and cognitive workload assessments and their relevant considerations that further informed the development of the decision matrix.

An initial set of recommendations for cognitive and metabolic assessment and the preliminary version of the decision matrix was presented back to stakeholders before a 1-day workshop session, which allowed for refinement of the proposed workload tools and their feasibility for application in the automotive context. In addition, two interviews were conducted with members of the Ergonomics team and process engineers at

Jaguar Land Rover (one ergonomist and one process engineer). The synthesis of these findings informed the development of a final version of the decision matrix (Section 6) for metabolic and cognitive workload assessment, including analysis of the assessment methodologies' readiness to be adapted within an industrial context and any potential gaps (in requirements for resources, knowledge, equipment, and time).

4 | SYSTEMATIC REVIEW

As mentioned above, a systematic review was conducted to understand what common workload assessment techniques are applied to analyze metabolic and cognitive workload in the manufacturing industry. A systematic review was chosen as this could be used to determine empirical factors pertaining to the research, such as date of publication, gender of participants, sample sizes, and sector.

4.1 | Data collection

The keywords used to facilitate an initial search from web of science (conducted in July 2020) are summarized in Table 1 below.

Relevant literature was imported to the Dedoose™ analysis software, and after removing duplicated papers, a total of 33 papers were imported. Following a preliminary review, the following inclusion and exclusion criteria were determined:

Inclusion criteria:

- Articles in English
- Primary research studies where data has been collected regarding metabolic and/or cognitive workload
- Standalone studies that present application of a single- or multiple-workload assessment technique to evaluate and review workload
- Studies conducted to facilitate review of a particular workload assessment technique
- Studies conducted to shed light on workload within a specific context
- Studies conducted to introduce and guide development of new workload assessment techniques
- Studies solely conducted to facilitate comparison of workload assessment techniques

Exclusion criteria:

- Conference papers
- Reports and instructional documents that describe various workload assessment techniques
- Literature reviews summarizing workload assessment techniques

4.2 | Coding and collation

The criteria for coding the imported papers were selected to facilitate descriptive and thematic content analysis. The descriptors included: Year (year of publication), type of publication (conference, journal, or report), industry (construction, laboratory, healthcare, process manufacturing, transport, and energy) purpose (purpose of the workload study: Proactive, reactive, or to test a method), gender (gender of participants who took part in the workload study: Mixed, male, female, or not specified), sample size (number of participants who took part in the workload study: 0–10, 11–20, 21–30, or 31+), and level of experience (participants' experience in their respective sector: Expert or novice).

4.3 | Synthesis

Looking through coding associated with descriptors (Figure 2a–d) suggest that majority of workload assessment research was conducted in the previous 5–6 years (2015–2020). Process manufacturing, transport, and construction were the three main sectors, although this is likely influenced by the "manufacturing" keyword used in the search criteria. The majority of the studies used a mixed sample (both male and female participants) and the majority had more than 31 participants and mostly involved experts.

Papers identified were coded (with a sample and checked by a second reviewer to ensure inter-rater reliability) to facilitate a thematic content analysis. Key findings are:

TABLE 1 Keywords utilized to guide the web of science search

Keyword	Results (*n*) including duplicates	Articles	Manufacturing/manufacture/Industry	Inclusion criteria
Cognitive workload assessment	542	363	3/4/15	2
Cognitive workload measurement	313	204	3/3/13	7
Mental workload assessment	786	570	11/11/27	20
Mental workload measurement	477	307	6/6/18	13
Metabolic workload assessment	92	85	0/0/1	1
Metabolic workload measurement	152	144	0/0/4	3
Workload assessment	4648	3434	49	

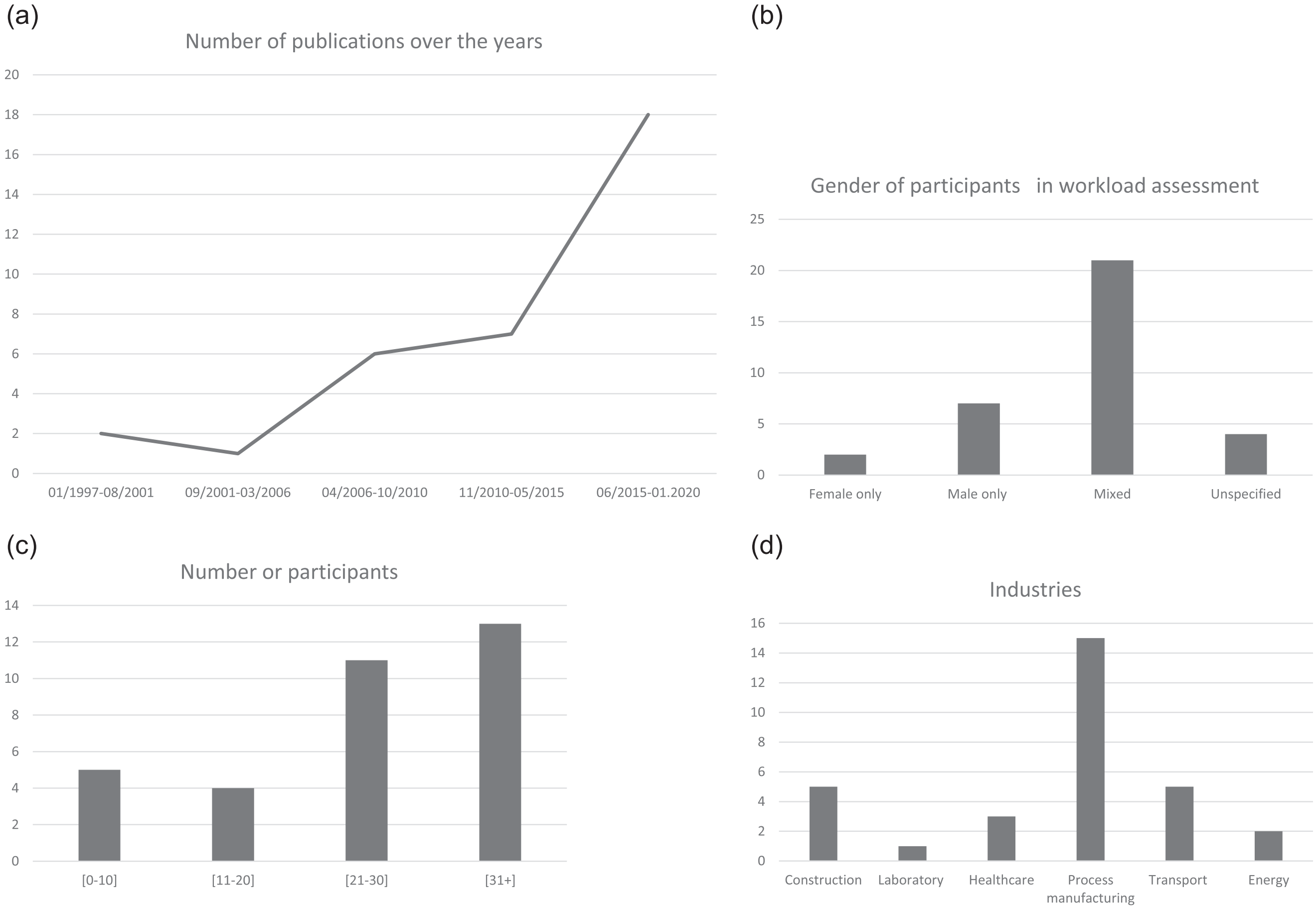

FIGURE 2 (a) Date of publication. (b) Gender of participants in workload assessment (number of studies). (c) Number of participants who took part in the workload assessment. (d) Industries where workload assessment was performed

- Assessment criteria:

  Very little information was noted regarding the knowledge requirements for implementing workload assessments. In some cases, information regarding simulated scenarios were listed, these included designing simplified cognitive processes to be utilized as potential secondary task performance indicators. Time of the workload assessment sessions were varied with no consistent pattern being observed. Equipment (especially those used to record physiological measures) were listed and ranged from everyday electroencephalograms (EEGs) to sophisticated eye tracking equipment.
- Demand:

  The majority of the work reviewed focused on cognitive workload assessment, only two papers were identified to explore metabolic demands within the search criteria.
- Workload assessment and quality of techniques:

  All four categories of assessment techniques (secondary, primary task performance, physiological measures, and subjective assessments) were utilized in the reviewed papers. Subjective measures were fairly common possibly due to their feasibility in use; the validity of methods such as NASA-TLX were also discussed. Physiological measures were the second highly utilized group of workload assessment techniques and were noted as being reliable (specifically with regard to capturing cognitive demands). However, the arguments regarding reliability and sensitivity of different methods were not consistent and varied greatly from one context of use to another.
- Expertise level

Almost no study reported any insights regarding different levels of ergonomists expertise required to conduct the workload assessments. The workload assessments reported were all designed and implemented by ergonomics experts and provisions for participatory workload evaluation were not discussed.

5 | WORKLOAD ASSESSMENT

5.1 | Establishing the assessment criteria for measuring workload

In a review conducted by Verwey and Veltman (1996), two major criteria for selecting appropriate workload assessment techniques were noted as sensitivity (to discriminate between levels of workload) and diagnosticity (distinguish between types of workload).

Sharples and Megaw (2015) also defined the criteria for assessing MWL techniques and measures, extending Verwey and Veltman's (1996) criteria to include: validity, reliability, generalizability, sensitivity, diagnosticity, selectivity, granularity/bandwidth, feasibility of use, acceptability, and ethics. These criteria can be expanded to methodologies to capture any type of demands (i.e., cognitive or metabolic workload) as follows:

- *Validity*: Measuring what the method is set to measure and includes: face validity, concurrent/convergent validity.
- *Reliability*: Consistency in outputs when repeating the data collection and workload assessment. For example, a checklist to document signaller's workload showcased over 75% inter-rater reliability (Balfe, 2010).
- *Generalizability*: Transferability of the findings to other applications. This is very hard to achieve for workload assessment as the findings are often domain specific.
- *Sensitivity*: Appropriately detecting changes in the task demands. The degree to which a given measure can distinguish among different levels of workload (Wierwille & Eggemeier, 1993).
- *Interference*: To be unobtrusive to the performance of the primary task, particularly when this can cause an obstacle to safety critical tasks.
- *Diagnosticity*: Refers to the capacity of a measure to discriminate among different types of workload and the cause of variation to be identified. Often a mixture of workload assessment techniques will be adopted to ensure diagnosticity.
- *Selectivity*: Relevant to construct validity to ensure that variations in workload (in particular, MWL) is appropriately distinguished.
- *Granularity/bandwidth*: tracking workload in real-time and consider the dynamic nature of work (i.e., interrupt driven).
- *Feasibility of use*: Appropriate for the context of use and in-line with capabilities of those who will be administering the workload assessment techniques.
- *Acceptability and ethics*: Participant awareness of the extent of data recorded regarding their performance and their detailed measurements.

These criteria, in addition to "resources" (one criterion borrowed from Wilson & Sharples, 2015), will be utilized to further evaluate the selected workload assessment techniques and to identify their relevance and applicability to the industry context and inform the decision matrix.

In addition, following consultation with the project team, it was apparent that the criteria which must be considered against the adoption of different techniques are:

- Time: Time required to administer the workload assessment technique.
- Equipment: Any specific apparatus that are necessary to collect and analyze workload data.
- Knowledge: Specific ergonomics knowledge required by the evaluators for effective data collection.
- Data: Data required to facilitate workload assessment (e.g., in-depth understanding of activities to inform an algorithm, etc.)

These were utilized to facilitate selection and exploration of different workload assessment techniques specified in the decision matrix. First, we conducted a more general review on the literature on the assessment of metabolic and mental/cognitive demand. This served to provide a more wide-reaching review of topics not included in the systematic review above, for example, the assessment of workload in nonmanufacturing applications.

5.2 | Metabolic demand

Physical and metabolic workload share common traits, explore demands from different perspectives. Physical demand focus on the strain on the individual caused by physical activity and metabolic demand focus on the amount of oxygen consumption while conducting the activity. Garg et al. (1978) described the main three techniques to measure metabolic workload as: Measurement of oxygen consumption on the job, macro studies and micro studies. Oxygen consumption is a physiological measure and has been greatly expanded in recent years with technological advancements. Macro studies focus on the general population and attempt to get a sense of the average user energy expenditure when doing certain tasks. On the contrary, micro studies focus on particular tasks and activity elements and the energy required by specific individuals.

In terms of the first group of techniques, oxygen consumption, there are a wide range of physiological measures to facilitate establishing metabolic status of individuals. Headley (2003) explored oxygen consumption (VO_2) and carbon dioxide production (VCO_2) to provide routine assessment of metabolic changes and found them effective and feasible thanks to recent technological advancements that facilitate continuous capturing and monitoring of the relevant data, examples include MediSense Exact Blood Glucose sensor, g.tec medical, NeuGraph Software to name only a few.

Macro studies as described by Garg et al. (1978) aim to explore metabolic energy by "average"[2] people, and consequently these techniques can often be too simplistic. In macro studies, approximation of metabolic load for a given manual activity will be documented, but this is generic and does not take into account specific circumstances. For example, the height of the table where a load will be lifted from will influence total net metabolic cost, but this is not considered as part of macro studies, which would just treat this as a "lifting task." On the contrary, micro studies adopt statistical approaches (e.g., analysis of variance, regression) related to the magnitude of the metabolic energy expanded by a person to the magnitude of various common physical parameters of the manual activity. Depending on large data sets to facilitate robust statistical analysis limits the practicality of micro studies and consequently Garg et al. (1978) propose a predictive model for metabolic assessment. This model assumes that a job can be divided into simple tasks

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[2] Garg et al. (1978) do not define average with any specificity, for example, 50th percentile, but rather use the term to imply *typical* workers who are considered within macro studies.

(activity elements) and that average metabolic energy can be predicted by knowing the energy expenditure of the elements.

Battini et al. (2016) used Garg model to assess the ergonomics of several assembly tasks. They developed the predetermined motion energy system (PMES), which can be used to estimate energy expenditure in tasks. Elementary motions (e.g., walking, carrying, squat lift, etc.) were documented along with the estimation of the PMES. The energy expenditure is defined based on basic human motions defined by Garg et al. (1978) and their estimated time. Their proposed approach was explored using a real-life case study of a simple product assembly task and it was suggested that the model could assist with informing the trade-off between time and energy optimization. This is an example of how Garg-inspired methods can be utilized with physical work environments.

Virtual settings and Digital Human Modeling can also benefit from metabolic workload assessment modules. This has been explored by Alkan et al. (2016) where a lightweight approach, based on an assembly worksheet and the Garg metabolic rate prediction model, was developed using a simplified virtual manikin skeleton and was able to rapidly evaluate working postures and physical work fatigue.

As part of Garg's method, a detailed understanding of work and the tasks associated with it, along with time required/predicted to complete each of the steps, need to be clearly documented. This includes predetermined motion time systems where the time of basic human movement to build up the time for a job is used (Battini et al., 2016). Once this in-depth understanding is achieved, it would be possible to develop software to capture and compute metabolic workload. This is particularly feasible when video recording and retrospective analysis of the workload is possible.

Borg rating of perceived exertion (RPE) developed by Borg (1998) (Table 2) is a tool for measuring an individual's effort and exertion, breathlessness, and fatigue during physical work. It is very simple and can be self-administered.

In Garg et al. (2006) a series of workload assessment techniques including objective (surface electromyography, EMG) and subjective measures (RPE-CR-10, an 11-point fatigue scale and an 11-point pain scale) were used to identify the safety threshold for fatigue. The findings suggest that there is a correlation between the EMG data and RPEs. Another study of the Borg scale (1998) is reported in Gasser et al. (2018), who use it to explore eccentric muscle activity. They conclude that Borg RPE is a valid technique to estimate heart rate during eccentric muscle activity. Williams (2017) presents Borg-CR10 that was also developed by Borg (Category-Ratio) which is anchored at number 10 (Table 3) The ratio properties of Borg CR-10 allow rate comparison between intensities as well as a determination of intensity levels (Zamunér et al., 2011). Shariat et al. (2018) conducted a study of 105 staff members in which Borg-CR-10 was self-administered twice. The findings suggest that the technique is highly reliable (0.89) to monitor perceived exertion experienced by office workers.

TABLE 2 Borg rating of perceived exertion, taken from Borg (1998), copyright Gunnar Borg www.cdc.gov/physicalactivity/everyone/measuring/exertion.html

Score	Level of exertion
6	No exertion at all
7	Extremely light
8–9–10	Very light
11	Light
12–14	Somewhat hard
15–16	Hard
17–18	Very hard
19	Extremely hard
20	Maximum exertion

TABLE 3 Borg CR10 scale (adapted from Hareendran et al., 2012)

Score	Level of exertion
0	No exertion at all
0.5	Very, very slight (just noticeable)
1	Very slight
2	Slight
3	Moderate
4	Somewhat severe
5	Severe
6–7–8	Very severe
9	Very, very severe (almost maximal)
10	Maximal

5.3 | Mental/cognitive demand

MWL can be defined as a ratio between task complexity and a person's cognitive capacity to meet task demands (Kantowitz, 1987). In other words, MWL is the cost put upon the operator's information processing capacity (Sanders & McCormick, 1998). It not only relies on task specificities, its complexity, and human computer interaction, but it also takes into account individual differences and characteristics (da Silva, 2014). Workload is not simply a function of task demand and aspects including difficulty, constraints, competing tasks, and additional and interacting stressors (e.g., environmental and organizational) need to be explored for an effective projection of operator workload (Stanton et al., 2005; Megaw, 2005). In a review of MWL, Cain (2007) points out that the concept of MWL is an applied construct that reflects the mental strain due to performing tasks under specific contextual conditions.

The brain is the most metabolically active organ in the human body (Kennedy & Scholey, 2000). Metabolic measures are hence

TABLE 4 Workload techniques—Overview of the appropriateness of required resources and readiness according to industry criteria

Metabolic/ cognitive	Virtual/ physical	Level	Criteria Option	Time	Equipment	Knowledge	Data
Metabolic	Virtual	Level 1	Job workload classification	Time to implement exceeds Jaguar Land Rover requirement for level 1. Analysis time for scenarios would take ~30 min, exceeding Jaguar Land Rover's requirement of 1–2 min allocated for level 1 reviews.	OK	OK	Two elements are needed before implementation of this technique that are not currently available at Jaguar Land Rover: 1—Classification of job categories and describing low, medium, and high. 2—Corresponding level of metabolic demand associated with each job classification and ranges of acceptability.
		Level 2	Predetermined Motion Time Analysis	Time to implement this method is likely to take several hours; Jaguar Land Rover requirement for this level is 10 min.	OK	OK	Jaguar Land Rover has access to process information where task steps are noted. The missing features that need to be in place before implementing this technique is availability of database of metabolic measures associated with each element of the task as well as range for acceptability.
		Level 3	Garg	Ok	Ok	OK	The available process data at this stage in vehicle development may not be sufficiently detailed to facilitate step by step review of motions and activity elements in a virtual setting. In addition, the Garg 28 equations may not cover the full range of task components at Jaguar Land Rover; these will need to be derived from physical measurements.
	Physical	Level 1	IPAQ	Completing the questionnaire is slightly more time-consuming than required by Jaguar Land Rover. Jaguar Land Rover requires 1–2 min for this level of analysis, whereas this questionnaire and completing it through the Excel sheet will take approximately 30 min.	OK	OK	OK
		Level 2	Borg	Completing the questionnaire is slightly more time-consuming than required by Jaguar Land Rover. Jaguar Land Rover expects this level of review to take around 10 min but applying Borg questionnaire and analyzing the data will mostly likely take around 1–2 h.	OK	OK	Borg indicates level of workload but domain specific acceptability should be determined before implementation of this assessment technique.
		Level 3	Garg + Observation	OK	OK	OK	The acceptability criteria for the Jaguar Land Rover context would need defining. As in virtual setting, the Garg 28 equations may not cover the full range of task components at Jaguar Land Rover; in this case the metabolic

TABLE 4 (Continued)

Metabolic/ cognitive	Virtual/ physical	Level	Criteria Option	Time	Equipment	Knowledge	Data
							workload will need to be derived from physical measurements.
Cognitive	Virtual	Level 1	Review against heuristics	OK	OK	OK	Relevant cognitive heuristics for the Jaguar Land Rover work domain are not currently available.
		Level 2	Cognitive task analysis	Jaguar Land Rover requires level 2 reviews to be conducted in 10 min. Exploring cognitive tasks against guidelines is more likely to take 1–2 h.	OK	OK	Breakdown of cognitive elements associated with each of the tasks should be available before implementing this technique. In addition, there is a need for acceptability range and a clear criterion to identify cognitive aspects of tasks.
		Level 3	Activity analysis timeline tool	OK	OK	OK	Breakdown of activity elements associated with each of the tasks and their corresponding workload factors should be understood before implementing this technique.
	Physical	Level 1	SWAT (Subjective workload assessment technique) (simplified)	Jaguar Land Rover requires this to be completed in 1–2 min but the presentation and capturing information about the three SWAT dimensions and compute the average will take around 10 min.	OK	OK	Acceptance criteria requires validation for the Jaguar Land Rover context.
		Level 2	NASA-TLX	Jaguar Land Rover expects around 10 min for this level of review and NASA-TLX takes approximately 1–2 h. Implementing, scoring, and conducting pairwise comparison to arrive at a final workload score is more time-consuming than anticipated by Jaguar Land Rover.	OK	OK	OK
		Level 3	Physiological measures	OK	OK	OK	Detailed review of acceptability range should be in place before this technique. Knowledge of physiological measurement tools should be in place.
		Level 3	Primary/secondary	OK	OK	OK	Appropriate acceptability range of primary performance and relevant selection of secondary tasks should be in place before implementation of this technique.

Note: Methods in bold are those recommended for short-term deployment.

potentially suitable to represent mental efforts as the brain is metabolically demanding. In a study conducted by Fairclough and Houston (2004), heart rate variability (0.1 Hz,) as well as a metabolic measure (blood glucose) of 29 participants, confirmed the sensitivity of using metabolic analysis to detect highly demanding tasks.

Approaches for evaluating workload commonly follow one of two key theories: Limited resource theory (Kahneman, 1973) and multiple resources model (Wickens, 2008). Limited resource theory focusses on the fact that the capacity of attention is limited and deals with three key questions: (1) What makes an activity more or less demanding? (2) What factors control the total amount of capacity at any given time? and (3) What is the basis for resource allocation policy? (Kahneman, 1973). Wickens (2008) proposes that there are four distinctive dimensions that are competing with each other for attention and resources, these include visual, auditory, spatial, and verbal. The three components associated with multiple resources including demand, resource overlap and allocation policy should be explored to facilitate a comprehensive understanding of MWL.

To develop an in-depth understanding of user MWL and to consequently informing the use of automation within complex work environments, Di Flumeir et al. (2019) conducted a study to evaluate mental demand of car drivers through their EEG measurements. This was accompanied with eye tracking data and the algorithm developed for the study (despite the low number of participants) and it showcased an effective mechanism to evaluate MWL in real-life situations (Di Flumeir et al., 2019). Relatedly, Marinescu et al. (2018) confirmed the suitability of noninvasive monitoring of physiological responses (i.e., facial thermography and pupil diameter) for measuring MWL. Subjective measures (e.g., NASA-TLX, questionnaires, interviews) are minimally intrusive and can provide a good overall indication of user perceived workload (Maior et al., 2015). SWAT (Subjective workload assessment technique) is a multidimensional technique with three levels: Time load, mental effort load, and stress load. This technique is quick and cost efficient but has low sensitivity to MWL (Stanton et al., 2005). Simplified variations of SWAT presented in Luximon and Goonetilleke (2001) eliminate the need for pretask procedures followed by scoring and analysis and, therefore, reduce the time required for conducting this assessment. “ASWAT” is a variation of SWAT that allows for continuous SWAT with equal weights where there is no need for pretask procedures and, therefore, it is less time-consuming and, according to Luximon and Goonetilleke (2001), reliable in determining cognitive workload.

Another example of subjective workload assessment is NASA-TLX which is a multidimensional rating scale by Hart and Staveland (1988). It is designed to be used immediately following performance of a task (Vidullch et al., 1991). It provides information about six workload-related factors: Three of the factors reflect the demands the task put on the operator (mental, physical, and temporal) and the other three focus on the interaction experience (performance, effort, and frustration).

Subjective workload assessments are particularly useful due to their ease of implementation and optimized use of resources. In addition, these techniques can be adopted with little intrusion on primary task.

6 | DECISION MATRIX

The systematic review and ongoing conversations with the project team around the criteria, applicability and implementation requirements for different workload assessment tools led to the development of a decision matrix (Table 4) that could potentially guide a participatory ergonomics approach towards workload evaluation. The review of available workload assessment techniques, and correspondence with Jaguar Land Rover to understand their requirements and resources as informed by the interview studies and project discussions, allowed for the selection of applicable and feasible workload assessment techniques suitable for different levels of application (Figure 1). In addition, discussions with project team informed the practicality of implementing those techniques within the automotive manufacturing context. Table 4 also shows a summary of the resources and requirements for the proposed cognitive and metabolic assessment techniques against the Jaguar Land Rover ideal resources at each level (Figure 1). Gaps and aspects that need to be developed (mostly data that should be in place before workload assessment) are noted and further described. For example, to facilitate metabolic workload assessment during the design phase (virtual), job workload classification could be utilized where different activities categories are assigned “standard” metabolic demands. The “time” requirement includes reviewing the appropriate scenarios which would take approximately 30 min, without requiring specialized equipment or HF expertise. However, this approach would require classification of job categories and describing what may be low, medium, and high workload. It must be noted that this is an oversimplification and is aimed to guide prioritization of next steps at Jaguar Land Rover to facilitate effective and validated ergonomics workload review and assessment.

Workload assessment techniques identified as part of this project should be modified to be practicable within the Jaguar Land Rover context. Only five of the techniques listed are currently ready (*or nearly ready*) for application, albeit not fully meeting the Jaguar Land Rover requirement for time, equipment, knowledge and data for each application and at each level, or needing validation of the acceptance criteria in the Jaguar Land Rover context: Garg, Borg RPE, IPAQ, SWAT, and NASA-TLX. The remainder of the proposed techniques require an initial phase to create customized data collection sheets and workload interpretation (i.e., acceptability range).

The methods identified in the decision matrix are aimed to facilitate exploring workload at different stages of work (from virtual design of the workplace to conducting the processes in the field). Although similar to Pickup et al. (2005) the methods proposed in the decision matrix are best used in combination to ensure higher reliability and validity (i.e., triangulation), they can be conducted on their own (for each of the levels). Once the workload assessment detected a possible high workload situation, they can be explored in further details and in combination with other techniques.

7 | DISCUSSION

The work presented in this paper provides a high-level insight to workload intervention within automotive manufacturing, at the design stage and for assessment of existing workplaces. The ideal program of intervention is shown in three levels, based on resources and expertise available at each level. A decision matrix is proposed to facilitate selection of appropriate workload evaluation technique for each of the levels. This, to our best knowledge, is the first program of research aimed to explore participatory ergonomics inspired workload evaluation within large and complex manufacturing processes.

Common workload assessment techniques applicable to analyze metabolic and cognitive workload (Research question 1) were identified and reviewed along with their benefits and limitations specifically when they are to be adopted in the automotive industry (Research question 2). In addition, exploration of the Jaguar Land Rover context provided the meanes to guide appropriate assessment techniques of relevant to analytic or empirical workload analysis (Research question 3) and, consequently, to recommend activities to fill the gap (Research question 4).

Most of the workload assessment techniques reviewed as part of this study are not ready to be used in the manufacturing sector and require modification and customization to develop a thorough and relevant understanding of validated “thresholds” for acceptable and unacceptable workload levels. Garg, Borg, IPAQ, SWAT, and NASA TLX are ready for use in some applications, but this approach still requires validation. Also, to be fully effective in industry, tools need to be developed which can be used by people other than a small specialist ergonomics teams. This way, the workload of the broader workforce can be considered and monitored, and the specialist ergonomics teams can support this process of workload management, as a “steering committee,” and spend more time on the unique cases which need their expertise. Finally, this study highlighted that in industry, the general trend is towards moving ergonomics input earlier in the process (as part of a proactive approach and greater use of virtual properties), which means that assessment tools need to be developed for use before physical properties exist (i.e., on virtual properties).

There is a particular lack of prior research in metabolic workload assessment; most previous work focuses on physical workload or cognitive workload. The Garg et al. (1978) equation is one of the most detailed and developed tools for metabolic assessment, but this did not originate in manufacturing and consequently the elements of physical movement and metabolic requirements associated with manufacturing are not included. Additional and more focused research is needed to identify and record awkward postures common in manufacturing and measure their corresponding metabolic loads to be used as part of the Garg et al. (1978) assessment approach.

This paper showcases the need for practical guidance towards implementing workload evaluation techniques in large and multilayer organizations and demonstrate the piecemeal approach in utilizing cognitive and metabolic assessment tools. Our work, in-line with Haines et al. (2002) explored where ergonomics review activities can occur at different layers of an organization. This is particularly a useful (and perhaps the only) solution to address challenges and complexities of large, multisite organizations.

8 | CONCLUSION

The present paper reports a research program to review existing literature on cognitive and metabolic workload assessment within manufacturing. This was also accompanied with industry focused interviews and discussions. The aim was to get an understanding of the landscape of workload assessment, key gaps, and potential next steps. The final output of this project was a decision matrix that could guide a participatory ergonomics approach towards workload evaluation. Further research is required to allow in-depth exploration of these techniques within specific contexts as well as to inform acceptable workload thresholds. This would also shed light on the quality and characteristics of methods to inform workload (reliability, generalizability, sensitivity validity, resources, feasibility of use, acceptance, and ethics). Currently validity, reliability and sensitivity are mostly discussed to assess the effectiveness of workload assessment methods, further work is required to explore these characteristics in more depth and to understand their weight and association.

The methodology to develop the decision matrix presented in this paper can be used to inform workload assessment techniques (i.e., participatory workload assessment) in any other industry. The process of exploration, literature review and drawing from industry expertise while exploring different phases of work structure can help better understanding of ergonomics needs in the workplace. In addition, the methods suggested in the present decision matrix can also guide relevant complex control sociotechnical systems including transport, energy, process manufacturing as well as healthcare.

DATA AVAILABILITY STATEMENT

Participants of this study did not agree for their data to be shared publicly, so supporting data is not available.

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