Human Stress Investigation in Manufacturing Contexts

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Stress is a critical concern in manufacturing environments, as it impacts the well-being and performance of workers. Accurate measurement of stress is essential for effective intervention and mitigation strategies.

stress measurement | Industry 5.0 | experimental protocol | human factors | human-centered

1. Introduction

The well-being of workers is a central pillar of Industry 5.0 [1]. When introducing new technologies into the manufacturing industry, it is crucial for developers to assess the extent to which the proposed system satisfies individual, collective, and production needs [2]. Technological advancements have predominantly driven industrial transitions [3], resulting in economic growth as well as increased social and environmental challenges [1]. Concerns regarding the health and safety of workers have intensified [4], particularly due to the introduction of new stressors, such as worker displacement or complete replacement by emerging technologies [5].

Peruzzini et al. [6] revealed that a range of incorrect movements during task execution directly increases a worker's exposure to risk. These movements include the manual handling of heavy loads, improper postures between different tasks, a high mental workload, and stressful conditions induced by time pressure or unexpected events. Effective control and management of these risk factors, including uncomfortable body positions, repetitive tasks, and elevated stress levels, provide companies with the ability to avert accidents, enhance production efficiency, promote the psychosocial well-being of employees, and ultimately realize substantial cost savings by minimizing rejection rates and associated costs [6]. In addition, excessive stress from work may cause mental or physical ailments, such as anxiety, depression, heart disease, and gastrointestinal disorders. These conditions can cause employees to take more sick days, leave their jobs at a higher rate, and experience decreased productivity and job satisfaction [7][8][9][10][11].

Consequently, the analysis of workers' stress has gained significant importance due to its profound impact on employee well-being, productivity, and organizational effectiveness [12]. Such analysis is crucial to the development of solutions that effectively mitigate stress and concurrently enhance a company's productivity and efficiency.

Perceived work stress, as defined by the World Health Organization (WHO), pertains to the array of responses individuals experience when confronted with job limitations and pressures that are incongruent with their skills and capabilities [13]. Seyle [14] classified stress into two distinct categories: positive stress and negative stress. Positive stress, often referred to as eustress or beneficial stress, is typically experienced briefly and serves as a motivational force, enhancing concentration, bolstering employees' coping mechanisms, generating enthusiasm, and ultimately fostering improved performance. In contrast, negative stress—also termed distress or unfavorable stress—can result in feelings of anxiety, a sense of ineffectiveness, and mental or physical issues. This type of stress has the potential to diminish performance in both the short and long term [15].

The discourse on stress extends beyond individual attributes. Organizational and environmental factors also impact work-related stress and have implications for health and productivity. In this regard, an exploration of stress's intricate manifestations, which encompass physiological, psychological, and behavioral dimensions, can provide crucial insights into its effects in the workplace [15]. Chronic stress has significant repercussions, manifesting as adverse physiological and cognitive changes, which underscore the necessity of comprehensive strategies to mitigate stress-related health and productivity challenges [15].

2. Human-Centered Manufacturing Industry

The emergence of Industry 5.0 signifies a milestone in the industrial revolution, bringing about transformative changes to the manufacturing sector. As technology continues to advance, adopting a human-centered approach becomes imperative to effectively address the challenges and opportunities presented in this new era [16]. Industry 5.0 places human needs, preferences, and experiences at the forefront of industrial design and production. Unlike previous revolutions, this paradigm acknowledges the crucial integration of technology with human factors to achieve sustainable and inclusive industrial systems [1][2]. Prioritizing a human-centered approach allows us to tackle the negative environmental and social impacts associated with traditional industrial systems and foster the development of equitable and sustainable practices [17].

Industry 5.0 brings forth a new wave of digital transformation, revolutionizing manufacturing processes and operations. However, it also reveals the existence of a digital divide characterized by differences in access, generational gaps, cognitive disparities, and gender imbalances. Addressing this digital divide becomes essential to ensure that all workers can effectively navigate and leverage the technological advancements associated with Industry 5.0. Enhancing technological familiarization among workers is crucial to harness the full potential of digital tools and technologies in the manufacturing environment and maximize their benefits [18].

In this sense, design plays a pivotal role in shaping the future manufacturing industry, where products are seen as platforms for service experiences and functionalities. Designing for human factors and user experiences becomes paramount for creating an environment that promotes worker well-being, productivity, and job satisfaction. Employing design thinking methodologies and tools allows for addressing the diverse needs and preferences of workers and improving the overall industrial experience [19].

Achieving a comprehensive understanding of workers is fundamental to promoting their well-being and optimizing their performance. This understanding encompasses cognitive processes, ergonomic requirements, and emotional well-being. Stress-related indicators, such as workers' thoughts, actions, and emotions, provide valuable insights into their experiences. By identifying and addressing these indicators, manufacturers can create a safe and supportive work environment that enhances worker satisfaction, motivation, and engagement. Understanding and mitigating work-related stress is essential for fostering a positive work environment and improving overall productivity [20].

According to Romero et al. [21], Operator 4.0 refers to the development of future factory work toward knowledge work, which is more demanding but also more enriched and flexible. It involves the use of human cyber-physical systems and adaptive automation toward human–automation symbiosis work systems. The goal of Operator 4.0 is to increase work well-being by carefully designing future factory tools and work practices from the worker's point of view. The design of Operator 4.0 solutions should prioritize individual worker perspectives, ensuring that new work tools and practices contribute to meaningful, motivating, and engaging tasks. The approach by Kaasinen et al. [22] aims to enhance work well-being and yield company benefits. To achieve this, a comprehensive framework was developed to guide the design, evaluation, and impact assessment of these solutions. Their framework focuses on antecedents, immediate implications, and impacts. Antecedents encompass the work environment, organization, and worker characteristics. Immediate implications pertain to workers' experiences with new tools and practices. Impacts, which include work well-being and company benefits, are assessed through positive indicators like job satisfaction, work engagement, and motivation. The design and evaluation process involves gathering feedback from users during piloting and subsequently assessing company-level benefits.

While the transition from Operator 4.0 to Operator 5.0 is anticipated, it is important to acknowledge that both paradigms are currently in developmental stages [23]. On the other hand, the concept of the "Healthy Operator 4.0" category arose as part of the broader Operator 4.0 framework [21] as a direct response to growing apprehensions regarding the escalating levels of stress among the workforce and the overall state of psychological and social well-being [24][25][26] and empowerment [27]. It involves integrating data from wearable technologies, the Internet of things (IoT), ambient intelligence, and modeling techniques to create a digital twin of the operator.

In the context of assessing worker well-being, a comprehensive overview was presented by Wijngaards et al. [28] that encompassed conventional methodologies such as surveys and interviews, as well as innovative approaches like wearable sensors, for evaluating workers' well-being. The authors categorized these assessment sources into four distinct types: closed-question surveys, word-based analyses, behavioral observations, and physiological measurements. Further differentiation was made between unobtrusive, reaction-based obtrusive, and observation-based obtrusive methods.

Diener [29] articulated the constituents of subjective well-being, highlighting the inclusion of long-term levels of positive affect, absence of negative affect, and overall life satisfaction. Although self-report measures have demonstrated validity and reliability, emerging methodologies in the field point toward more advanced and diversified techniques. Drawing from advancements in psychology, a multimethod approach to appraising subjective well-being was proposed to yield a more holistic representation of this phenomenon [29].

The knowledge about users' needs and ergonomics is fundamental to optimizing workers' well-being, working conditions, and industrial results [30]. Khamaisi et al. [30] presented a strategic framework for evaluating worker experience, emphasizing a human-centric perspective within industrial settings to enhance overall sustainability. Employing wearable devices, such as eye-tracking technology, electrocardiograms, and electrodermal activity monitoring, they collected physiological data and paired it with subjective self-assessments, utilizing the NASA-TLX questionnaire. This comprehensive strategy allowed for the monitoring of human activities within virtual reality environments and facilitated a deeper understanding of worker well-being and its implications on industrial outcomes.

In light of the rapidly evolving landscape ushered in by Industry 5.0 and the growing emphasis on human-centricity, it becomes evident that a standardized protocol for measuring stress in manufacturing contexts is not just a convenience, but an imperative need. The profound integration of technology and human factors in Industry 5.0 underlines the urgency of comprehensively assessing the well-being of workers. While the transition from Operator 4.0 to Operator 5.0 holds promise, the developmental stages of both paradigms underscore the critical role of addressing stress-related challenges.

3. Work-Related Stress Measurement in the Industrial Context

The concept of work-related stress is widely researched [20]. The most commonly accepted definition for this phenomenon derives from the cognitive model and suggests that it is due to a missing balance between job demands and the ability of workers to execute them [31] and it is affected by the social and organizational context where subjects operate [32].

The effects of stress on workers' well-being are not limited in time. Indeed, this phenomenon has long-term consequences on an employee's physical health, such as heart disease and chronic pain, and on psychological health since it leads to persistent anxiety and depression [33].

As a consequence, workers' turnover and absenteeism due to stress-related disorders affect a company's productivity, increasing costs. In addition, higher stress levels increase the probability of negative stress consequences, such as accidents and errors, leading to decreased efficiency in the workplace [31]. Finally, the literature still lacks details about work-related stress; therefore, further research and new solutions have to be developed to improve the health status of workers and mitigate the impact on companies.

In the existing literature, there are only a few studies that have specifically looked into the topic of work-related stress measurement in industrial or manufacturing environments [20]. These studies often dive deep into examining a particular method or tool for assessing stress, and they suggest specific ways to design solutions in this context [20]. Rescio et al. [34] introduced a novel heterogeneous multi-sensory hardware–software architecture devised to facilitate the automated detection of stress conditions and is particularly tailored for applications within industrial environments. The authors adopted a dual-pronged approach that encompasses distinct sensor categories, namely, ambient and wearable sensors, thus orchestrating a versatile and efficient monitoring mechanism that is adaptable to diverse contextual demands. This strategic configuration ensures continued operability in instances of sensor incapacitation or malfunction. In the domain of wearable sensors, Rescio et al. [34] meticulously devised a specialized system to facilitate unobtrusive monitoring while mitigating perturbations arising from motion artifacts. On the ambient sensor facet, a judicious selection criterion centered on accessibility and affordability was employed, resulting in the choice of readily accessible and economical technology. Notably, the study undertook an evaluative consideration of cardiac activity, electrodermal activity, and RGB signals, collectively forming a robust framework for the evaluation of psychophysical conditions.

The human stress indicators most commonly adopted to study this phenomenon in manufacturing contexts can be separated into objective and subjective categories. The former includes indicators calculated on the basis of workers' physiological signals since they monitor the biological and unconscious processes of individuals, which are not influenced by personal perceptions and feelings. On the other hand, the subjective category consists of stress indicators, which refer to the psychological perception of stress and the emotional states of workers.

In literature, physiological processes, such as skin sweating, cardiac and brain activity, and respiration, are the most frequent processes observed for stress assessment. The electrodermal activity (EDA) technique is commonly adopted for evaluating stress in terms of dermal sweat levels [35], where skin conductance is the most used indicator related to this technique for measuring stress levels [36][37]. In this sense, Sriramprakash et al. [38], Anusha et al. [39], and Vila et al. [40] used the galvanic skin response (GSR) as an equivalent to EDA for stress evaluation. On the other hand, the electrocardiogram (ECG) technique allows for the monitoring of the electrical activity of the heart, where the two derived stress indicators are heart rate (HR) and heart rate variability (HRV), which depend on the time between two successive beats and the variability of this period [36][41]. The scientific validity of stress detection through HRV assessment is substantiated by neurobiological evidence [42]. Nevertheless, Tran et al. [43] suggested that HRV does not fully reflect the work-content-related stress during work, and it is problematic to measure the effect of work-content-related stress on HRV in the real manufacturing environment. Tran et al. [43] stated that since HRV strongly depends on too many factors (e.g., work context, individual physical and mental status), its real-time usage for stress monitoring can be problematic. They emphasized the need for more comprehensive studies to distinguish work-related stress from typical stress types, as existing studies lacked solid scientific conclusions about the relationship between work-related stress and HRV [43]. In the literature, authors such as Zhang et al. [44], Sriramprakash et al. [38], Anusha et al. [39], and Vila et al. [40] used ECG to measure work-related stress.

The electroencephalogram (EEG) technique monitors brain activity by tracking the electrical signals generated by neurons. The frequency range of the signal recorded through this technique is from 0.5 to 45 Hz, and specifically, the frequency band between 23 and 38 Hz is most significantly affected by stress [45]. In the end, variations in respiratory frequency are estimated as a physiological indicator of work-related stress [6].

In contrast, the psychological assessment of stress relies on the subjects' responses to questionnaires, which investigate their feelings, perceptions, and emotions related to a specific task execution. In the literature, standard questionnaires for the investigation of work-related stress can be found. The National Aeronautics Space Administration Task Load Index (NASA-TLX) is traditionally adopted and aims to investigate an individual's perception of comfort [41]. On the other hand, the Subjective Workload Assessment Technique (SWAT) investigates time and mental load in addition to the feeling of psychological stress [46], while the Perceived Stress Scale (PSS) and the Short State Questionnaire (SSSQ) investigate stress by asking individuals to express the frequency of positive and negative feelings related to the executed task [47][48]. These questionnaires are frequently filled in both during and after the conclusion of a complete task cycle in order to assess how respondents' perceptions have evolved over time.

Finally, stress monitoring is a complex practice in industrial contexts and the measurements are affected by some limitations. First of all, physiological data collection is conducted through wearable biometric devices, which could make the participant uncomfortable, negatively impacting the psychological state of the individual while performing the activity. On the other hand, individuals' feelings and emotions have impacts on human biological processes that are beyond their direct control, affecting physiological stress assessments as well. Therefore, Peruzzi et al. [41], Panchetti et al. [48], and Caterino et al. [49] combined the psychological results with physiological evaluations in order to validate the findings through cross-analysis of the different signals and data collected improving the accuracy of the estimation.

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