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An innovative integrated solution to support digital postural assessment using the TACOs methodology

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ABSTRACT

The diversification of work as well as the challenges of modern industrial tasks make manual ergonomic assessment tools (i.e., checklist, excel-based worksheet) time consuming and strongly related to the ergonomist's experience. Recent advancements in wearable sensors technology offer new perspectives in terms of integrating human-monitoring solutions with traditional ergonomics methods by movements' digitization. Furthermore, digital posture assessment plays a critical role in the context of Industry 5.0, promoting worker well-being and productivity by identifying ergonomic risks and optimizing work environments. Also, leveraging advanced technologies for posture assessment enables proactive intervention strategies to mitigate musculoskeletal disorders and enhance overall workplace safety and efficiency. The present study proposes an innovative hardware and software solution which allows even non-expert designers or ergonomists to carry out a reliable postural ergonomic assessment according to well-known ergonomic methods, speeding up the analysis and providing accurate information. The setup consists of a wearable suit and its proprietary software tool specifically programmed to carry out the ergonomic assessment according to the Time-Based Assessment COmputerized Strategy (TACOs) method. The setup has been preliminarily tested in a controlled environment simulating a real industrial scenario and a comparison with standard ergonomic practices has been performed. The Mann-Whitney U test returned a p-value of [2.198e-11] < α [0.05] demonstrating how the solution proposes results which are numerically and qualitatively enhanced while showing the practical utility of the suggested technical setup and the validity of the suggested digital technique in retrieving and recognizing the workers' posture.

1. Introduction

The Industry 5.0 is characterized by the integration of advanced technologies and human–machine collaboration, to enhance human's physical, sensitive and cognitive capabilities, and improve the overall system performances (Valette et al., 2023). In this context, digital posture assessment is an interesting tool supporting worker health and productivity, as it is able to process huge amount of data, reaching and even surpassing performances of human experts as ergonomists and industrial safety practitioners. By utilizing state-of-the-art sensors and data analytics, digital posture assessment systems can accurately monitor and analyse workers' body postures and motions in real time. This ability supports the identification of ergonomic issues that may be present in the workplace and the early detection of possible circumstances that may develop into musculoskeletal and cumulative trauma disorders. Also, digital posture assessment facilitates the optimization of workplace design by providing useful insights into workspace layout, equipment design, and task allocation. Organizations that proactively address ergonomic concerns can minimize the risk of workplace injuries, occupational diseases, and enhance overall employee health, well-being and performance (Resnick, 1996).

According to the recent data released by the European Commission

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concerning the condition of European workers (Eurofound, 2021), the need to address the problem of ergonomics (both physical and cognitive) within the industrial context on a structural level has clearly emerged. From the telephone survey conducted on a sample of approximately 72 thousand interviewees in 36 countries in the European area (the 27 member countries including Albania, the United Kingdom, North Macedonia, Norway, Serbia, Montenegro, Kosovo, Bosnia Herzegovina and Switzerland) it clearly emerged that more than half of workers reported work-related disorders which heavily affect people's quality of life but which also translate into a cost for the European community of as much as 240 billion euros considering only the effects of musculoskeletal diseases. This problem is attributable to a lack of consideration of human factors in the design process of industrial systems (machinery, workstations, interfaces) which are usually machine-centered while neglecting interaction with users. This generates accessibility problems, inadequate workloads or complicated interactions on a cognitive level. All this contributes to amplifying job dissatisfaction and absenteeism with the consequent worsening of the quality of work and at the same time the well-being of the operator. These issues are of strategic importance today and will be increasingly so in the coming years as they are included in the concept of human-centricity of the new Industry 5.0 paradigm, which places the well-being of workers as the basis for sustainable production processes. An intense application of ergonomic principles in the layout design of workstations, machinery and their interfaces would not only synergistically increase the well-being of workers and productivity, but at the same time it would increase safety at work, considerably decreasing the burden for both the economic and social costs of preventable disabilities and deaths. In fact, according to data reported by Eurostat (Eurostat, 2020), there are 1446 workplace accidents per 100,000 workers, with percentages of fatal accidents which on average stand at 2.1 per 100,000 workers in 2020.

Recent studies have investigated the digitization of ergonomic assessment methodologies to support the postural risk assessment of manual work activities (Martins et al., 2024). This growing area of research focuses on technological advancements, such as wearable sensors, computer vision, and machine learning algorithms, to improve the accuracy of ergonomic assessment and the efficiency of ergonomists and industrial safety practitioners. In 2012, Rajabalipour Cheshmehgaz et al. proposed a model of assembly line balancing problem that incorporates assembly worker postures into the balancing algorithm, suggesting configurations of assembly lines that provide workers with opportunities for changing their body postures (Rajabalipour Cheshmehgaz et al., 2012). Fığlalı et al. proposed a prototype of integrated software based on image processing techniques for postural assessment of manual workers that eliminates the need for an expert analyst (Fığlalı et al., 2015). More recently, Battini et al. developed a real-time full-body ergonomic platform that evaluates a set of ergonomic indexes and provides visual feedback in real-time (Battini et al., 2022). These contributions offer interesting and promising applications of digital postural assessment to the literature on ergonomics in Industry 5.0. The main limitations of these applications are in the accuracy and reliability of the postural assessment methodologies adopted. Moreover, time-based ergonomic score indices are still scarcely implemented thus making modern Digital Human Simulation (DHM) tools less prone to consider time-related ergonomic factor (Berlin & Kajaks, 2010).However, the transition from traditional, subjective assessment methods to digital solutions allows to achieve a more objective and comprehensive evaluation of ergonomic issues that may lead to occupational diseases in the workplace. Moreover, digitalization enables the continuous monitoring of workers' motions and postures, providing real-time feedback and insights into potential for developing WMSDs. Data could then feed the overall industrial infrastructure to effectively implement the human-in-the loop concept and to potentially dictate an on time factory redesign. Nonetheless, privacy and data security must be tackled too, while offering effective In conclusion, the shift towards digital ergonomic assessment methodologies supports the improvement of occupational safety and health outcomes by enabling the timely implementation of ergonomic interventions and enabling the adoption of proactive risk management strategies.

This paper proposes an innovative technological and methodological approach for digital postural assessment that integrates a wearable motion capture system with a methodology of postural workload, i.e. the Colombini's Time-Based Assessment COmputerized Strategy (TACOs) (2018). The validation of the integrated system is described in this paper by means of ad hoc Key Performance Indicators (KPIs) to understand potentials and limitations of the proposed setup.

2. Literature review

This section introduces describes the state of the art in the scientific literature and current practice about the methodologies and the approaches adopted for postural assessment, supporting the reduction of Work-related Musculo-Skeletal Disorders (WMSDs). WMSDs are a leading cause of disability, impairment and lost productivity in the workplace (Eerd & Smith, 2020). Adopting uncomfortable postures at work, which causes excessive strain on the body's musculoskeletal system, is one of the primary risk factors for these occupational disorders (Anita et al., 2014). In the last years, there has been a growing awareness of the importance of ergonomics in the workplace, which aims to optimize the design of work environments to reduce the risk of developing WMSDs. Ergonomic interventions typically involve identifying and addressing the specific risk factors associated with a particular job, such as repetitive motions, heavy lifting, or awkward postures. By modifying the work environment and task design to reduce these risk factors, employers can help prevent the development of WMSDs and promote the overall health and well-being of their employees. Several studies have consistently shown a strong association between awkward postures at work and the development of WMSDs. For example, research has shown that workers who frequently bend, twist, or reach for objects are at increased risk of developing low back pain (Feng et al., 2016; Mayton et al., 2008; Pintakham & Siriwong, 2016), while those who perform overhead work are more likely to develop shoulder and neck pain (Barthelme et al., 2021; Sakakibara et al., 1995). Similarly, workers who maintain awkward postures for prolonged periods are at increased risk of developing repetitive strain injuries, such as carpal tunnel syndrome (Jackson et al., 2018; Sitompul, 2022). Given the significant impact of WMSDs on worker health and productivity, it is important for employers to take proactive steps to reduce the risk of these disorders in their workplaces. Assessing postures at work is crucial to prevent WMSDs and to promote the health and well-being of workers. The assessment of postures involves the analysis of the body position and motions required to perform a specific task, such as lifting, pushing, or typing. The assessment should consider not only the physical characteristics of the task, but also the individual characteristics of the worker, such as age, sex, and physical condition. Assessing postures can help identify ergonomic risk factors that may contribute to the development of WMSDs, such as awkward postures, and static postures. In addition to preventing WMSDs, assessing postures can also improve productivity and job satisfaction. Workers who experience less discomfort and pain are more likely to be able to perform their tasks efficiently and effectively, leading to higher levels of job satisfaction and motivation (Atmaja & Puspitawati, 2018; Atyah, 2020; Groen et al., 2019; Ikonne & Yacob, 2014; Lee & Cho, 2022).

However, postural assessment is a complex and time-consuming task that requires expertise and knowledge in ergonomics, biomechanics, and occupational health. The lack of competence and knowledge on this topic can lead to inaccurate assessments, which can result in ineffective prevention strategies and an increased risk of developing WMSDs. Data inputs for postural assessment can be collected through different methods, such as observation, self-reporting, and wearable sensors. These data include body positioning, motions, and forces applied during work tasks. The selection of the most appropriate method depends on several factors, including the type of work task, the worker's characteristics, and the research questions. Furthermore, analyzing and interpreting the collected data requires specific knowledge and skills in ergonomics and, specifically, in occupational biomechanics. Inaccurate interpretations of data can lead to incorrect conclusions and, eventually, ineffective prevention strategies. Hence, it is important to ensure that the assessors have the necessary competence and qualifications to conduct accurate assessments and provide effective prevention strategies. Professionals who conduct postural assessments, i.e. ergonomists and industrial safety practitioners, should possess a multidisciplinary set of skills, including knowledge of human anatomy, biomechanics, ergonomics, and occupational biomechanics. Without a solid foundation in these areas, it can be challenging to correctly identify and analyse the risk factors associated with the adoption of poor postures at work. Despite the importance of assessing working postures and the efforts made to develop assessment methodologies, no research has yet established a clear correlation between posture assessment results and the appearance of WMSDs. Therefore, it is important to continue investigating this research area and to develop reliable and standardized methods for assessing working postures that can be used to prevent WMSDs, work-related injuries, and improve the health and well-being of workers.

2.1. Modern approaches to postural assessment

The postural evaluation in current industrial settings is interlacing with the evolving scenario brought by the emerging 5.0 technologies, which are dramatically revolutionizing ergonomics assessment. Tools such as exoskeletons, wearable sensors, artificial intelligence, computer vision, virtual and augmented reality, are being progressively integrated into the workplace adding complexity from the users' perspective (Botti et al., 2023; Grandi et al., 2019). On the other hand, modern workplaces introduce interesting challenges for ergonomics practitioners: industrial tasks are becoming more and more cognitively demanding, while maintaining a strong postural accent and inputs of diverse nature need to be considered (Kong, 2019). In this context, it is worth investigating the overall User eXperience (UX) at multiple levels, from conceptual design stage up to training, to properly understand the impact on the workers' daily life and to design usable workstations and human-centric processes. The training phase becomes fundamental for approaching the task in the best way possible and with the widest range of technical knowledge and experience. Moreover, from the current deep understanding of the human psychophysical sphere methodological proposals combining several bio-parameter are growing (Charles & Nixon, 2019). At the same time, manufacturers have increased their consideration of human factors in the development of products and processes to improve the overall perceived quality. In fact, proactive ergonomic assessments can reduce development costs and, most importantly, the risk of WMSDs at the shop floor level. Modern approaches make use of classic digital human simulation softwares such as Tecnomatix Jack (Siemens) or Ramsis (Human Solutions - Products - RAMSIS General) to prototype workstations from an ergonomic perspective. Thanks to such tools, ergonomists can evaluate the job acceptability, long before the final design moves to the assembly line, or workplace. The limit of these technologies relies in the high subjectivity and inaccuracy of such analysis during the positioning of virtual manikins and the definition of working postures: often, such analysis is preceded by a more classical approach based on-site study session and video recordings, resulting in a time-consuming procedure. New and emerging technologies such as motion capture systems, Virtual Reality (VR) and Augmented Reality (AR) address these limitations. Motion capture can be achieved by different technologies, from optical systems (e.g., VICON, Optitrack, or any system using infrared cameras) to inertial (e.g., XSENS, VIVE, or any system using inertial measurement units (IMU)). A VR analysis expands the traditional ergonomic evaluation from a mere postural workload understanding to a more general user experience examination by offering relevant information on the user interaction with the product or process, on the layout design and the equipment's reachability, on the working accessibility and working sequence feasibility too. In general, using VR and AR for ergonomics benefits from decreased development time, reduced risk to employees, and decreased manufacturing and service costs to companies. In (Brunzini et al., 2021; Khamaisi et al., 2022), the authors tested a set of non-intrusive COTS (Commercial-Off-The-Shelf) sensors for industrial use, providing a sufficient level of detail by ultimately combining the use of VR technologies and wearable solutions with a motion capture suite. Postural information could be easily retrieved either combining computer vision algorithms and human body tracking modules like the open-source Open Pose library based on a convolutional neural network or the Stereolabs body tracking module of the same software development kit (Stereolabs Docs: API Reference, Tutorials, and Integration). Alternatively, Inertial or Multi-Inertial Measurement Unit systems could be a further viable solution to avoid the occlusion typical of camera tracking modules which inhibits a correct reconstruction the human manikin. In this context, (Ligorio & Bergamini et al., 2020) developed a magnetometer-free motion capture system integrated in a proper garment to decrease the magnetic disturbances implicit in the magnetometer data in the attempt to increase sensors accuracy and usability. In terms of the future potential of all these emerging technologies for ergonomics practitioners, several benefits come to mind: inherently, an improved understanding of the physical and functional demands of modern jobs which help with the final employee placement. Involving employees in piloting technological projects is a demonstration of vision and interest about operator exposures at an individual level, which helps with employee retainment. Moreover, the training phase could be beneficial for operators by showing ways to avoid job risks while optimizing performance. Boosting up data collection and predictive analytics to determine priorities for ergonomics efforts represents another important advantage. Finally, a modern ergonomic approach translates in a time reduction needed for a first level evaluation and in improved accuracy of job assessments, with minimal training or expertise required. The use of such technologies will encourage the development of predictive multi-factorial injury risk models and cumulative exposures to ultimately improve controls and solutions for such risks. However, no studies have proposed a reliable application of these emerging technologies for postural assessment, in the context of the ergonomics approach to the design and the evaluation of manual handling activities performed at work.

2.2. Methodologies for postural assessment

Postural assessment involves both different approaches and various technologies aimed at identifying potential risks related with the work environment. A widely used approach is electromyography (EMG), which involves placing ad hoc sensors on the muscles to measure their electrical activity. EMG is a reliable technique for assessing muscle activity during various postures and movements, providing information on muscle fatigue and injury risk (Pigini et al., 2006). Another technique is the measurement of the pressure on the intervertebral disks, which can provide valuable information on spinal load and help identify potentially hazardous postures. This method involves the use of sensors that are placed on the spine to measure the pressure exerted on the disks during different postures and movements (Jensen, 1997). Biomechanics study of postures is another approach to assess the impact of working postures on the body. Biomechanics combines the principles of mechanics and biology to understand the forces and stresses acting on the body during various tasks. This method provides a detailed analysis of the musculoskeletal system and helps identify the potential risks associated with different postures and movements (Antwi-Afari et al., 2017).

International standards and regulations suggest the methodologies and the tools available for the assessment of the body postures adopted at work. Table 1 shows a list of the most well-known methods for evaluating work postures present in the literature (Colombini &

Table 1

Methodologies for evaluating work postures present in the literature.

Methodology	Reference	Investigated postures	Investigated risk factors
OWAS	Karhu et al., 1977	Trunk, arm, lower limbs	Force, duration
RULA	McAtamney & Nigel Corlett, 1993	Trunk, head/neck, forearm, wrist/hands	Force
REBA	Hignett & McAtamney, 2000	Trunk, head/neck, arm, shoulder, forearm, wrist/hands, coupling, lower limbs	Force
OREGE	Inrs, 2000	Head/neck, shoulder, wrist/hands, elbow	Force, duration
SUVA	2016	Trunk, shoulder, standing/sitting	Force, duration
QEC	David et al., 2008	Trunk, head/neck, wrist/hands, standing/sitting	Force, duration
OCRA	Occhipinti & Colombini, 1996	Arm, shoulder, forearm, wrist/hands, elbow, coupling	Force, duration, frequency, static actions, stereotypy, lack of recovery, additional risk factors, clinical data database on the predictive ability of the method regarding the probability of becoming ill
Strain Index	Moore & Garg, 1995	Wrist/hands, coupling	Force, duration, frequency, static actions, stereotypy, lack of recovery, clinical data database on the predictive ability of the method regarding the probability of becoming ill
NIOSH MMH	Waters, 1993	Trunk, coupling	Frequency, static actions, stereotypy, lack of recovery, clinical data database on the predictive ability of the method regarding the probability of becoming ill
TACOs	Colombini & Occhipinti, 2017	Trunk, head/neck, arm, shoulder, forearm, wrist/hands, elbow, coupling, standing/sitting, lower limbs	Force, duration, frequency, static actions, stereotypy, lack of recovery, additional risk factors, clinical data database on the predictive ability of the method regarding the probability of becoming ill
ISO 11,226	International Standard Organization, 2000	Trunk, head/neck, arm, shoulder, forearm, wrist/hands, lower limbs	Static working postures
EN-ISO 1005–4	European Committee for Standardization, 2008	Trunk, upper limbs, neck, other body parts	Working postures and movements

Occhipinti, 2017). According to the indication provided in the ISO 11226 (International Standard Organization, 2000) and in the EN ISO 1005–4 (European Committee for Standardization, 2008), the Ovako Working posture Analysing System (OWAS) (Karhu et al., 1981, 1977), the Rapid Upper Limb Assessment (RULA) (McAtamney & Nigel Corlett, 1993) and the Rapid Entire Body Assessment (REBA) (Hignett & McAtamney, 2000) are reliable indicators of postural workload following biomechanical models. While each methodology has its strengths and limitations, it is essential to consider them all to determine the most appropriate method for a specific workplace. The creators of the OWAS, RULA and REBA conceived these methodologies to describe work postures. Later, they included additional risk factors, such as force and duration. OREGE (INRS, 2000), SUVA (SUVA, 2016) and QEC (David et al., 2008) were born as rapid checklists for the investigation of the biomechanical overload including multiple risk factors. OCRA (Occhipinti & Colombini, 1996) and Strain Index (Moore & Garg, 1995) include a multi-factor study of the biomechanical overload of the upper limbs. The ISO 11226 (International Standard Organization, 2000) and the EN ISO 1005–4 (European Committee for Standardization, 2008) are international standards that provide guidelines for assessing the risk of WMSDs associated with the adoption of working postures. ISO 11226 specifies a method for the evaluation of static working postures, while EN ISO 1005–4 provides guidelines for the evaluation of working postures and movements in relation to machinery. RULA, REBA, and OWAS are widely used methodologies that have been developed to provide a rapid assessment of postures in the workplace (Kee, 2022). However, these methods have limitations in terms of their accuracy, reliability, and the amount of data that can be collected. For instance, RULA and REBA both rely on subjective judgments of body posture, which can be subject to interpretation and lead to errors in the assessment. On the other hand, the OWAS is a widely used observational method for assessing working postures. It provides a qualitative evaluation of the postures adopted by workers during work activities, taking into account the posture of the trunk, arms, and legs. It then assigns a score based on the degree of deviation from a neutral posture, which can be used to identify high-risk postures. However, the OWAS has some limitations. Firstly, it is a qualitative time-consuming method, which means that the assessments may be subjective and dependent on the assessor's interpretation. Secondly, it does not provide a quantitative assessment of the risk of WMSDs.

Lastly, it does not consider the duration of sequential postures and repetition, which is an important factor in the development of WMSDs. In contrast, the Time-Based Assessment COmputerized Strategy (TACOs) method (Colombini, 2018) is a quantitative method that combines the assessment of working postures with the analysis of the tasks performed by workers. It provides a detailed analysis of the tasks and working postures. Additionally, it considers the duration of the postures and the frequency of the tasks, which are important factors in the development of WMSDs. Therefore, the TACOs method is a more comprehensive and accurate method for assessing the risk of WMSDs associated with work operations. Finally, it is essential to consider the acceptance of the work environment from the psycho-social perspective. This approach involves assessing workers' perceptions of their work environment, including the physical and psychosocial aspects of the job. By considering workers' subjective experiences, this method provides a comprehensive understanding of the work environment's impact on the workers' health and wellbeing (Franco, 2011; Khudhir & Azuhairi, 2015; Sirzai & Dundar, 2022). No study or research has investigated yet the design and the application of an integrated solution combining the benefits of the emerging technologies introduced earlier in this section and the TACOs method for postural assessment. This paper addresses this gap in the literature contributing to the research on digital postural assessment methods and proposing an innovative technological and methodological approach which is able to speed up ergonomic evaluations without losing reliability. The proposed approach includes an innovative hardware and software solution which allows even non-expert designers or ergonomists to carry out a reliable postural ergonomic assessment according to well-known ergonomic methods, speeding up the analysis and providing accurate information. The setup consists of a wearable suit and its proprietary software tool specifically programmed to carry out the ergonomic assessment according to the TACOs method. In particular, a novel garment solution designed by TuringSense EU ("Turingsense EU LAB | wearable,") for pose estimation is presented in this paper and tested simulating a manual handling task. Then, TACOs scores provided by the garment software tool are compared with the postural assessment performed manually by ergonomists. A set of KPIs is proposed to validate the integrated solution and to understand its potentials and limitations.

The remainder of this paper is structured as follows: Section 3 will explain the adopted approach both from a theoretical point of view and a technological one, by analysing the reasons behind each research choice and the ergonomic background. Section 4 and Section 5 will go through the chosen use case and discuss limits and potentialities of the proposal, both on an ergonomic and technical side to offer a complete overview of the benefits for ergonomic practitioners derived from its use. Finally, Section 6 concludes the paper introducing the future developments of the proposed study.

3. Materials and methods

This study provides a comprehensive overview of the potentials and limitations of a commercial wearable technology meant for movement analysis in sport and rehabilitation as an innovative integrated tool for digital ergonomic postural assessment of industrial tasks. Since the overall accuracy of the setup has already been extensively investigated in (Ligorio et al., 2020, 2018), the present paper focuses on the validation of the system as a support tool for ergonomists during the postural assessment of industrial tasks by mean of the TACOs methodology. The TACOs methodology is adopted to assess the risk of biomechanical overload due to the adoption of awkward postures of the spine and lower limbs. The methodology requires to identify the number of employees and the duration of the single task within the job. Typically, an ergonomist performs the ergonomic risk assessment following the TACOs methodology by observing the postures assumed by the workers during the task: then, each posture is allocated a designated maintenance duration from a selection of proposed time intervals. Each specific time interval corresponds to a score that is contingent upon the posture's associated severity. Upon the completion of timing for all postures, the system computes a cumulative score, which is categorized into distinct attention bands. These attention bands are represented by a colour scale spanning from green to purple, as shown in Fig. 1.

3.1. *Technological set-up*

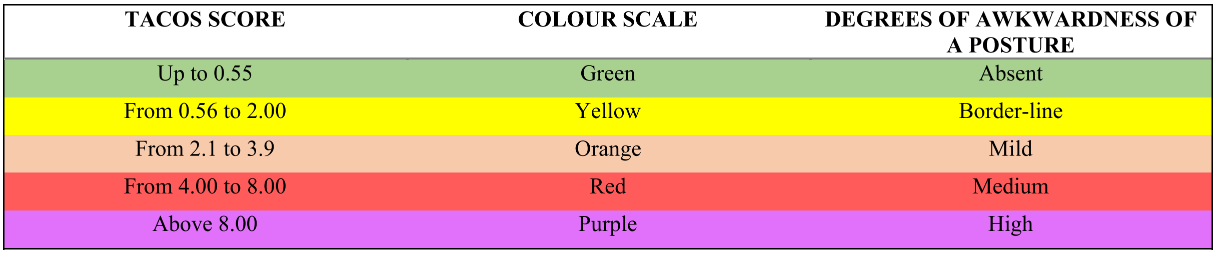
The proposed integrated solution for digital postural assessment includes the second generation of the Pivot Yoga suit ("Turingsense EU LAB | wearable,"): it is a sensorized garment (i.e., long-sleeved shirt and pants) providing a full-body, real-time 3D joint kinematics, developed for being used in heavily magnetically disturbed environments (Fig. 2).

The proprietary biomechanical protocol processes the inertial data (i.e., accelerations and angular rates) obtained from 14 garment embedded IMUs and provides as output the 3D kinematics of human joints (respectively left and right wrists, elbows, humeral thoracic joints, ankles, knees, hips). The orientation of the pelvis segment with respect to its initial pose and the thoracic girdle (chest with respect to pelvis) are also provided. The entire system is based on (Ligorio & Bergamini et al., 2020), where a novel magnetometer-free motion capture is presented in the attempt to increase sensors accuracy and usability by means of a cutting-edge algorithm to compensate for the lack of the magnetometer. Being IMUs attached to body segments, it is necessary to compensate for the misalignment between their reference frame and the body segments anatomically based one: to do so, an initialization step is foreseen before the actual motion capture begins to record. The number, location and orientation of each inertial sensor has been designed so that the suite can be manufactured for different body size: the configuration is itself customizable, to allow tracking of exclusively the upper or the lower body part. The garment communicates through the Wi-Fi protocol to a desktop-based garment software tool named Gemma (Fig. 2). Gemma manages the communication and calibration processes and serves as a graphical user interface where to visualize the reconstructed manikin, as depicted in Fig. 3: it then allows to export the entire set of recorded joint angles in a.csv file.

According to the objective of the study, seeing that the TuringSense system implements just a pose estimation, an ad hoc Matlab script computing the TACOs score has been appositely developed. A testing session was developed to map the TACOs postures with the TuringSense reconstructed human manikin by means of joint angles thresholds. The testing session involved 5 users who performed the final task. A series of static and dynamic postures assumed by the operators in the chosen use case has been analyzed and object of angular fine-tuning. Fig. 4 shows a user performing the fine-tuning calibration for each posture of the task. In particular, being consistent with the definitions given by TACOs, the working posture identified during the preliminary tests coincided with: fully flexed lumbar tract or trunk twisted (Posture A); lumbar tract semi flexed (Posture B); standing with upright back (Posture D), crouching or sitting on the heels (Posture G). The posture adopted during transport operations was considered equal to standing with upright back (Posture D). The definition of the adopted ranges was performed conjunctively by the ergonomists and the TuringSense engineers and was iterated several times by simulating the task and the operators' postures up to the achievement of coherent results with the ergonomist evaluation. Fig. 5 shows the results provided by the Matlab script after importing the joint angles file of a single recording from the Gemma software: for each posture, name, number of frames, posture maintenance time in seconds, percentage of time on the total execution time of the task and the associated TACOs score are provided. For the sake of brevity, authors will use the terms "Gemma software tool" throughout the article to point out the integration of the Gemma software with the TACOs Matlab script's computation.

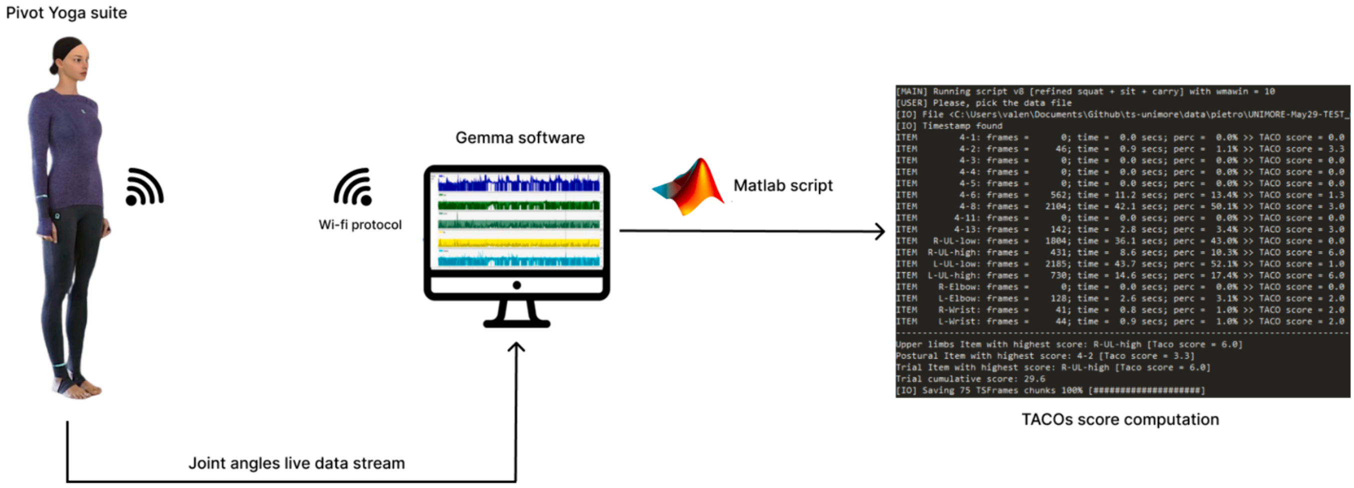
3.2. *Experimental protocol*

The study involved 27 users (16 males and 11 females) who voluntarily participated in the experiment: no reward was given. The subjects



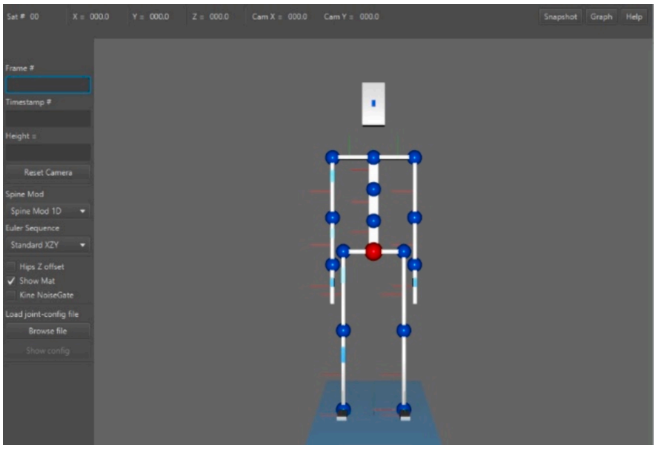
TACOS SCORE	COLOUR SCALE	DEGREES OF AWKWARDNESS OF A POSTURE
Up to 0.55	Green	Absent
From 0.56 to 2.00	Yellow	Border-line
From 2.1 to 3.9	Orange	Mild
From 4.00 to 8.00	Red	Medium
Above 8.00	Purple	High

Fig. 1. Colours defining the exposure bands for the postures of the spine and lower limbs in the TACOs method.



```
[MAIN] Running script v8 [refined squat + sit + carry] with wmawin = 10
[USER] Please, pick the data file
[IO] File <C:\Users\valen\Documents\Github\ts-unimore\data\pietro\UNIMORE-May29-TEST_
[IO] Timestamp found
ITEM        4-1: frames =     0; time =  0.0 secs; perc =  0.0% >> TACO score = 0.0
ITEM        4-2: frames =    46; time =  0.9 secs; perc =  1.1% >> TACO score = 3.3
ITEM        4-3: frames =     0; time =  0.0 secs; perc =  0.0% >> TACO score = 0.0
ITEM        4-4: frames =     0; time =  0.0 secs; perc =  0.0% >> TACO score = 0.0
ITEM        4-5: frames =     0; time =  0.0 secs; perc =  0.0% >> TACO score = 0.0
ITEM        4-6: frames =   562; time = 11.2 secs; perc = 13.4% >> TACO score = 1.3
ITEM        4-8: frames =  2104; time = 42.1 secs; perc = 50.1% >> TACO score = 3.0
ITEM       4-11: frames =     0; time =  0.0 secs; perc =  0.0% >> TACO score = 0.0
ITEM       4-13: frames =   142; time =  2.8 secs; perc =  3.4% >> TACO score = 3.0
ITEM   R-UL-low: frames =  1804; time = 36.1 secs; perc = 43.0% >> TACO score = 0.0
ITEM  R-UL-high: frames =   431; time =  8.6 secs; perc = 10.3% >> TACO score = 6.0
ITEM   L-UL-low: frames =  2185; time = 43.7 secs; perc = 52.1% >> TACO score = 1.0
ITEM  L-UL-high: frames =   730; time = 14.6 secs; perc = 17.4% >> TACO score = 6.0
ITEM    R-Elbow: frames =     0; time =  0.0 secs; perc =  0.0% >> TACO score = 0.0
ITEM    L-Elbow: frames =   128; time =  2.6 secs; perc =  3.1% >> TACO score = 2.0
ITEM    R-Wrist: frames =    41; time =  0.8 secs; perc =  1.0% >> TACO score = 2.0
ITEM    L-Wrist: frames =    44; time =  0.9 secs; perc =  1.0% >> TACO score = 2.0
-----------------------------------------------------------------------------------
Upper limbs Item with highest score: R-UL-high [Taco score = 6.0]
Postural Item with highest score: 4-2 [Taco score = 3.3]
Trial Item with highest score: R-UL-high [Taco score = 6.0]
Trial cumulative score: 29.6
[IO] Saving 75 TSFrames chunks 100% [####################]
```

Fig. 2. The overall system architecture.



Sat # 00 X = 000.0 Y = 000.0 Z = 000.0 Cam X = 000.0 Cam Y = 000.0

Frame #

Timestamp #

Height =

Spine Mod: Spine Mod 1D

Euler Sequence: Standard XZY

☐ Hips Z offset

☑ Show Mat

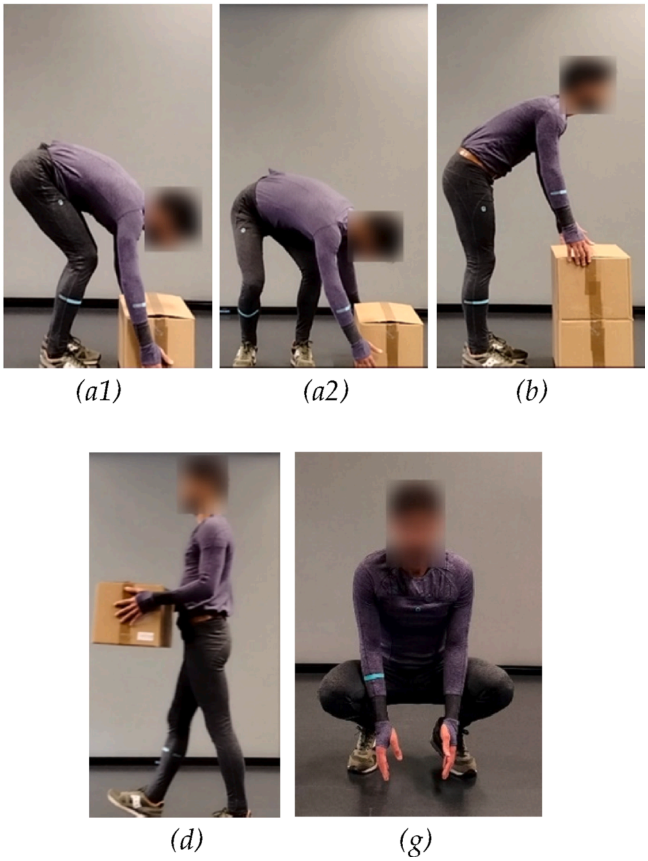
☐ Kine NoiseGate

Load joint-config file

Fig. 3. The graphical user interface showing the real-time human posture reconstruction.

are mainly university students, PhD students, full time researchers and professors with no previous experience on the task. Fig. 6 shows the experimental protocol adopted throughout tests with the subjects, which were conducted at the XiLab laboratories of the Department of Engineering "Enzo Ferrari" at the University of Modena and Reggio Emilia (Xilab). Prior to starting the study, it is ensured that the subjects involved are in good health at the time of the study and do not present or have a history of WMSDs or issues affecting their upper limbs, lower limbs, or spine. Furthermore, the risk associated with the manual material handling task performed during the study is evaluated using the NIOSH method (Waters, 1993) in order to exclude the presence of the related ergonomic risks. After an initial explanatory session aimed at providing the instructions to perform the task (Phase 1 in Fig. 6) and ask the consent to collect personal data, subjects wear the garment (Phase 2 in Fig. 6), and the suite calibration starts (Phase 3 in Fig. 6).

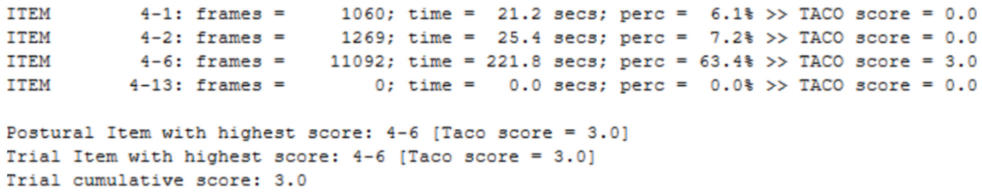
At the beginning of the test, a gyroscopic calibration in sitting position is performed. A gyroscope calibration is strongly recommended before each recording to assess the bias values of the IMU sensors. The bias estimation requires the garment to be as still as possible (being theoretically motionless). Subsequently, a full body calibration in standing position is performed (Phase 3 in Fig. 6). At the end of the calibration process, the user starts the task (Phase 4 in Fig. 6). It consists in picking 24 cardboard boxes from a fixed height of 75 cm and place them on a pallet (type Epal Europallet EUR, dimensions 800 x 1200 mm). The boxes are arranged across four levels, with six boxes on each


(a1) (a2) (b)

(d) (g)

Fig. 4. The figures show the selected TACOs postures for which a joint-angle software fine-tuning operation has been performed. Respectively, (a1) and (a2) refer to Posture A, (b) refers to Posture B, (d) to Posture D and (g) to Posture G.

level, for a total of 24 boxes. Each box is 44 x 31.5 x 28.5 cm, has no handles and weighs 13 kg. The users are instructed to grab the boxes from the lower edge, keeping the grip as close as possible to the body. At the beginning of the lifting task, the boxes are placed side by side on the pallet in such a way that the shortest side of each box faces the operator, who can then grasp the box from the bottom, rotate it before lifting, and carry it with the long side resting against the chest. The pick-up and deposit points, i.e. the distance between the starting and the ending



```
ITEM        4-1: frames =     1060; time =  21.2 secs; perc =  6.1% >> TACO score = 0.0
ITEM        4-2: frames =     1269; time =  25.4 secs; perc =  7.2% >> TACO score = 0.0
ITEM        4-6: frames =    11092; time = 221.8 secs; perc = 63.4% >> TACO score = 3.0
ITEM       4-13: frames =        0; time =   0.0 secs; perc =  0.0% >> TACO score = 0.0

Postural Item with highest score: 4-6 [Taco score = 3.0]
Trial Item with highest score: 4-6 [Taco score = 3.0]
Trial cumulative score: 3.0
```

Fig. 5. Extract of the output generated from the Matlab script developed by Turingsense, analysing a single recording.

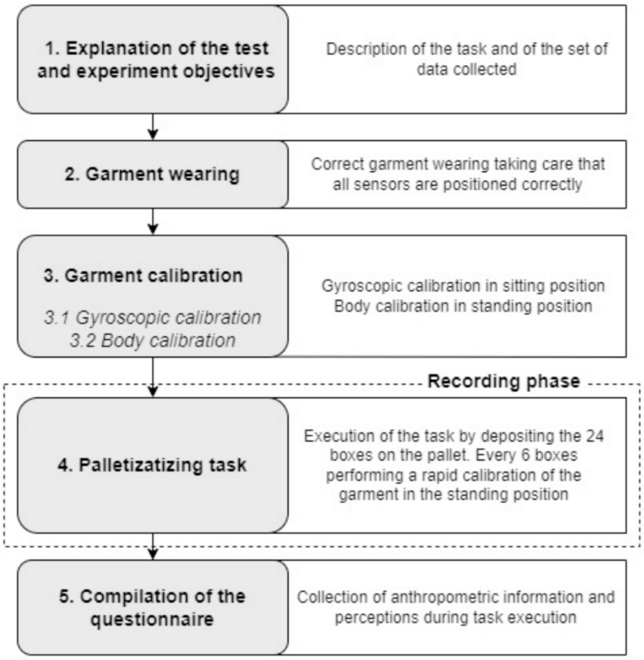


Fig. 6. The experimental approach adopted throughout the test.

position, which are positioned facing each other with the same orientation, are set at a distance of 2 m. This ensures that the sub-task, consisting of retrieving the cardboard box, translating it towards the deposit location, depositing the box on the pallet and returning to the pick-up point, involves a sufficient number of movements to perform a proper posture assessment test. At the end of the lifitng task, the subjects deposit the boxes on the pallet following a precise alternating arrangement to ensure uniform manual handling conditions and the stability of the four levels of boxes on the pallet (Fig. 7).

A rapid body calibration is carried out to compensate for gyroscope drifting (Fig. 7) every time a level is completed. Each participant is required to perform a single trial. Tests are recorded by a Stereolabs Zed 2i stereo camera (ZED 2 – AI Stereo Camera | Stereolabs) to provide high resolution stereo video recordings on which to perform the traditional postural assessment. After the test, each participant was asked to fill in a questionnaire to collect demographic data and subjective impressions (Phase 6 in Fig. 6). The aim of this questionnaire is to investigate the technological acceptance related to the proposed solution in a working environment. The first part of the questionnaire collects the demographic information of the subject, the potential knowledge and familiarity with the use of technological devices. Then, the questionnaire proposes a set of statements adopting an approach inspired by the System Usability Scale (Brooke, 1996). For the purposes of the study, the statements are defined with the objective of evaluating the overall subjective opinions regarding the garment and the task as a whole. Specifically, the 5-point Likert Scale (Albert, 2023) was adopted to collect user perceptions about the overall comfort provided by the garment during the test, the wearability, the manufacturing quality, and potential limitations experienced during the movements (see the full text of the questionnaire in the Appendix).

Three ergonomists with diverse level of expertise (two apprentices and an expert) performed data analysis by means of Gemma. The same ergonomist performed a traditional ergonomic assessment with the TACOs method watching the test recordings of all the users. No limitation on the number of visualizations of the recordings was defined. Also, the garment is not able to identify the moments when the users grab and lift the boxes with the hands. Hence, the ergonomists were asked to not consider the external loads on the final TACOs computation.

4. Results

This section presents the results obtained during the study. Data from each user was linked to a numeric identification code to ensure the

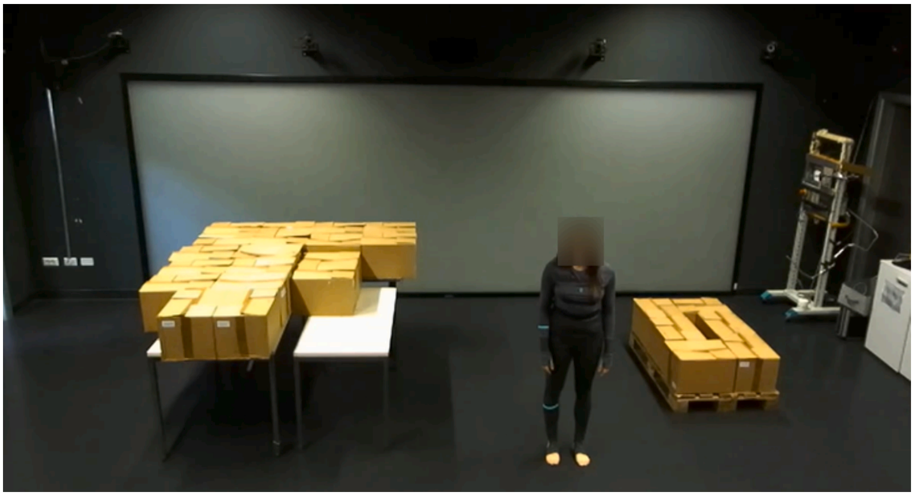


Fig. 7. Example of a body calibration at the end of the first pallet layer: the user is standing in normal pose.

anonymity of the collected information. The demographic and anthropometric data collected in the questionnaires returned an average population age of 27.8 years, an average weight of 67.2 kg and an average height of 173.8 cm. Table 2 contains mean values and Standard Deviation (SD) of age, weight and height of the user sample.

Table 3 shows mean scores and SD values for each answer in the questionnaire. From these values it emerges how users found the garment comfortable to use and easy to wear, with an average score of 3.85 and 3.41 respectively. The garment was generally appreciated as for its quality (average score of 3.74). Also, the users revealed that the garment did not restrict the movements during the task (average score of 1.52).

Fig. 8 shows the comparison of the TACOs scores between the Gemma software and three ergonomists, (from here on denominated as Erg1, Erg2, Erg3) for all the 27 users and for the four different postures identified during the task. In each graph, the scores assigned to each posture are represented by circles: if the circle is present, the posture is detected and considered relevant for the TACOs method. The absence of the circle means that the analyzed posture was not maintained for a significant amount of time, as required in the TACOs method. The size of the circles represents the posture score, i.e., the bigger the size of the circle, the higher the posture score. The posture score is proportional to postural holding time, as described in Colombini (2018). Furthermore, Fig. 8 shows that the Gemma software returns less scores than the ergonomists (note that fewer circles are present in the Gemma line): this is due to the garment software tool time's thresholds defined for each posture, according to the TACOs method. The garment software tool automatically neglects the postures that do not reach the established threshold, i.e., the software tool considers such posture as not relevant for the TACOs method. Posture A was detected in 44 % of cases by all three ergonomists and it was found with the same score (i.e., TACOs score = 3) in 41 % of the tests, while the garment software tool recognized a significant presence in four trials (Fig. 8). Similarly, posture B has been identified by at least one ergonomist in 81 % of the cases and only in four cases by the Gemma software. Ergonomists' assessments coincide with regard to the score (TACOs score = 3.3), however, there is no test in which the three ergonomists agree on the presence of posture B. Posture D was the most present in the task, including the transport phase and the walking back to the picking area. Such posture was detected in all the tests by all three ergonomists and in 93 % of the cases by the Gemma software. Posture G was detected by one of the ergonomists in 33 % of the tests. Finally, Fig. 8 shows a comparison between the TACOs cumulative score assessed by each ergonomist and by the Gemma software, computed according to previous assumptions.

The score provided by the Gemma software is equal to or lower than the score provided by the ergonomists, except for users 16 and 15 (Fig. 9). In case of user 16, Erg3 associated a score of 6, while the Gemma software returned a score 6.3. For user 15, Erg1 associated a score of 3, while the Gemma software returned a score of 4.6. In addition, the three ergonomists assigned the same TACOs score in 3 out of 27 cases, i.e. for users 17, 18 and 20.

5. Discussion

The results in Section 4 show that the Gemma software can recognize the postures adopted by the users during the study. High consistency between the results of the postural assessments provided by the ergonomists and the Gemma software is found for the recognition of the posture D (standing with upright back). Also, the results reveal some discrepancies in the recognition of posture G (crouching or sitting on the heels) and posture A (fully flexed lumbar tract or trunk twisted): the detection of posture G is limited to one ergonomist; posture A is evaluated quite similarly by the three ergonomists, while the Gemma software identifies it as relevant for a limited number of users (4 out of 27). These recognition discrepancies may be due to the subjective judgments of the ergonomists, which could be more significantly influenced by the severity of the posture itself rather than its actual duration. Consequently, the TACOs scores show significant discrepancies between the results provided by the ergonomists and the results obtained with the Gemma software. The software consistently returns scores equal to or lower than those assigned by the ergonomists, except in case of users 15 and 16, where the assessments of Erg1 and Erg3 reveal a higher score (Fig. 11). Also, according to the very nature of the setup, the garment is not able to automatically detect the presence of loads during the task. A future garment software tool release will allow the ergonomist to point out which postures are characterized by handling loads, thus enriching the computation of the TACOs postures score with further information.

Finally, the traditional procedure adopted by the ergonomists to perform the postural assessment with the TACOs method is time consuming, i.e. the assessor is required to observe the task multiple times on site and/or using video recordings. Observation time increases with the task complexity. Tasks that require the adoption of multiple postures may require the assessor to watch them several times. The integrated solution introduced in this paper collects and analyses the body postures in fractions of seconds, offering an interesting opportunity to simplify and speed up the TACOs analysis. Hence, two Key Performance Indicators (KPI) are introduced, i.e. X_p and Y, to investigate the effectiveness of the proposed set-up to support the TACOs analysis during the postural assessment of industrial tasks. X_p investigates the discrepancy between the results of the postural assessment following the TACOs methodology performed by three ergonomists and the results obtained adopting the proposed wearable technology and the Gemma software, for each posture p. X_p is based on the score S defined as a value ranging from 0 to 4, where 0 refers to a posture that is not identified throughout the task and 4 is assigned when a posture is present for about the whole time of execution, according to the TACOs methodology. Then, X_p is the difference between the posture score obtained with the Gemma software, $S_{Gemma,p}$, and the mean value of the posture scores provided by the ergonomists, $s_{erg,p}$ (Equation (1). This index represents the ability to identify the duration of maintenance of a posture p over time.

$$X_p = S_{Gemma,p} - S_{erg,p} \quad (1)$$

Equation (2) shows Y, which quantifies the difference between the digital postural assessment with the Gemma software and the traditional assessment performed by an ergonomist.

$$Y = \sum_{u=1}^{U} \sum_{p=1}^{P} |X_p| \quad (2)$$

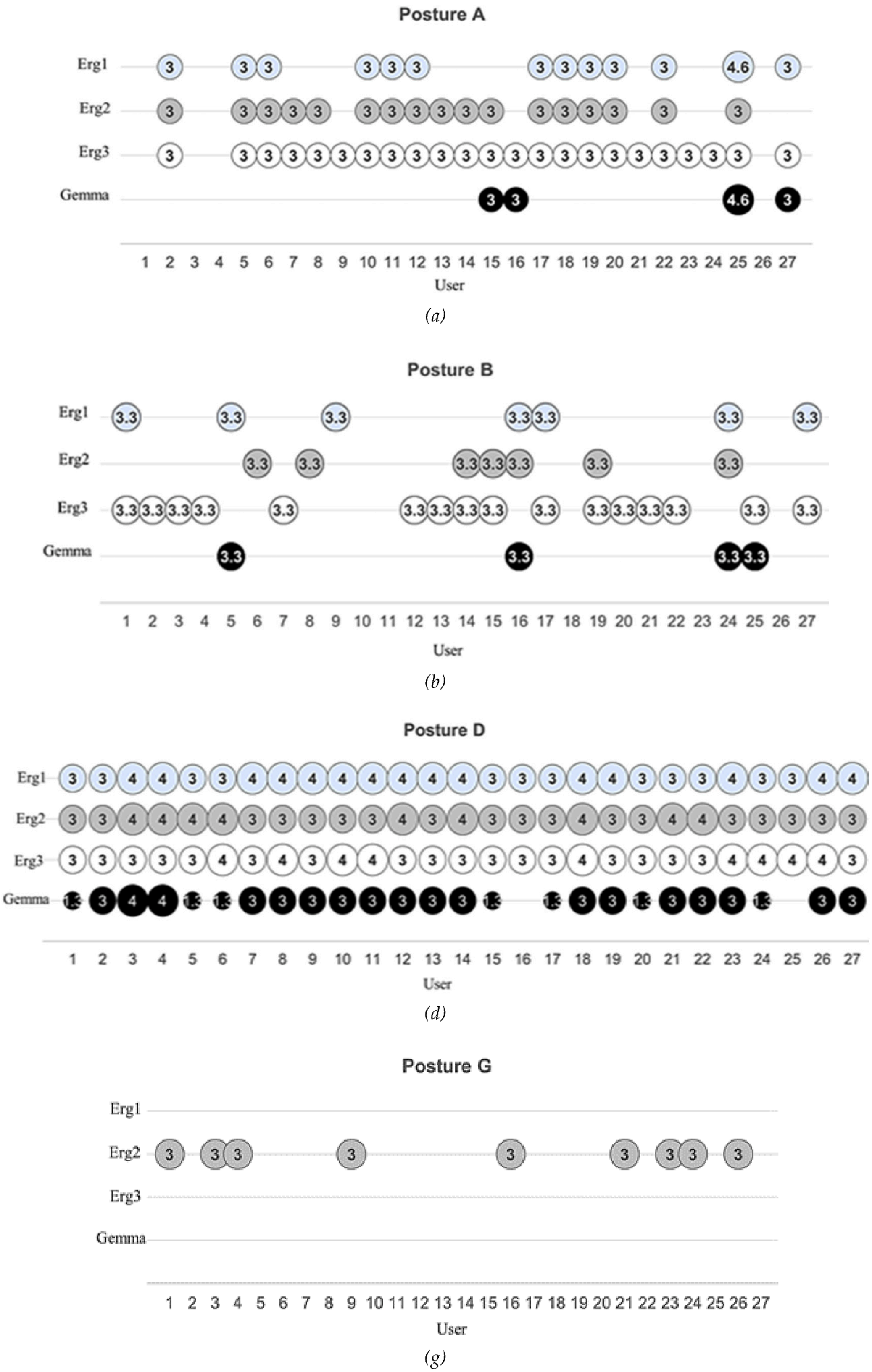
Particularly, Y sums the absolute values of X_p of each posture p, where p goes from 1 to P (with P corresponding to the total number of

Table 2
Anthropometric characteristics of the analysed sample of users.

	Males and females	Males	Females
Number of users	27	16	11
	Mean (SD)	**Mean (SD)**	**Mean (SD)**
Age [years]	27.8 (3.7)	27.6 (2.8)	28.2 (4.9)
Weight [kg]	67.2 (10.2)	73.7 (7.9)	57.8 (3.1)
Height [cm]	173.8 (7.4)	177.9 (6.3)	167.7 (4.0)

Table 3
Results from the questionnaire regarding the garment wearability and usability.

Questions	I found the garment comfortable to be used	I found the garment easy to wear	I think the quality of the garment is high	I think that movements are limited wearing the garment
Mean (SD)	3.85 (0.99)	3.41 (1.19)	3.74 (0.86)	1.52 (0.94)



(a)

(b)

(d)

(g)

Fig. 8. Comparison between the TACOs score assigned by the three ergonomics and by the Gemma software tool for each of the 27 users and for each of the four postures. Letters (a), (b), (d) and (g) refer to the postures in Fig. 4. Postures A1 and A2 are both identified as posture A.

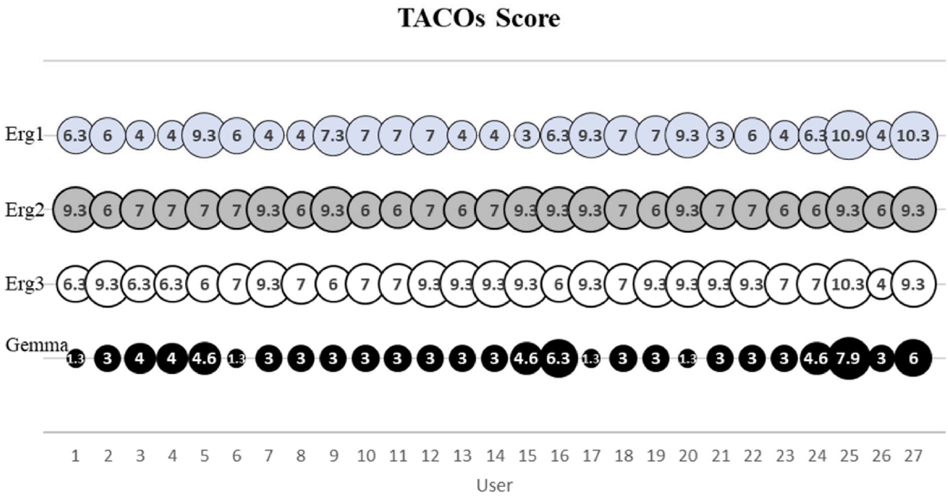


Fig. 9. Comparison between the overall TACOs score assigned by the three ergonomists and the scores assigned by the Gemma software for the 27 users, considering all the postures investigated in the study.

postures identified during the tests): then the values obtained are added together for each user *u* (where *u* goes from *1* to *U,* with *U* equals to the total number of users in the sample). Fig. 10 describes the distribution of X_p through the 27 tests for each posture: “0″ means that the Gemma software and ergonomists have recognized the single posture for the same duration. The distribution of X_p in case of posture A, i.e. X_A, presents values ranging from −1 to 0.67 with an average of −0.49 and a value of 0 reached in 5 cases out of 27 (19 %) (Fig. 10a). The distribution of X_p in case of posture B, i.e. X_B, ranges from −1 to 0.67 with an average of −0.27 and a value of 0 reached in 8 cases out of 27 (30 %) (Fig. 10b). The distribution of X_p in case of posture D, i.e. X_D, ranges from −2.33 to 0.33 with an average of −0.74 and a value of 0 reached in 1 case out of 27 (4 %) (Fig. 10d). Finally, the distribution of X_p in case of posture G, i.e. X_G, ranges from −0.33 to 0, with an average of −0.11 and the value of 0 achieved in 18 cases out of 27 (67 %) (Fig. 10g). The analysis of *Y* allows to understand the percentage error between the scores of the digital postural assessments performed with the Gemma software and the traditional assessments performed by the ergonomists. The final percentage error is attested at 14 %. Then, to further evaluate the individual postures, the sum of each absolute value of X_p of each user was calculated for the four investigates postures. The percentage error for each score compared to the maximum score obtainable for the given posture has been calculated. Posture A determined a percentage error of 15 %, while the percentage error for Posture B, D and G where 13 %, 26 % and 3 % respectively. The distribution patterns of the posture KPIs (X_A, X_B, X_D, X_G) clarify cases where both the Gemma software and ergonomists agree on a single posture (value 0), highlighting potential areas for improvement in recognition. The distribution of X_p highlights the complexity of ergonomic challenges in the monitored activities. The discussion focuses on specific indications or characteristics that may contribute to such discrepancies, with the goal of identifying areas for refinement in both assessment methodologies. Practical differences in ergonomic assessments require careful consideration of the contexts and factors specific to the tasks involved. The study also elucidates potential limitations of human-based ergonomic assessments, including subjective biases and disparities in expertise among ergonomists.

These discrepancies are not intrinsically inherent with the proposed solution. It also discusses the challenges of automatic systems in detecting subtle postural nuances. The error rates in *Y* provide a quantitative measure of disparities, contributing to a detailed understanding of specific error-related postures. This analytical approach provides a necessary foundation for developing targeted interventions or improvements in assessment protocols, ultimately increasing the effectiveness of ergonomic assessments in the workplace. The analysis of the TACOs indexes and of the first KPI shows that the three ergonomists overestimate the scores compared to that assigned by the Gemma software: this is due to the greater accuracy and objectivity of the automated system’s calculation, which has greater sensitivity to the narrower thresholds of the angles given by the ISO standards. This represents a clear benefit during the analysis of manual handling tasks.

In order to provide insights on the general correlation rate between the two approaches and anthropometric data as well as to determine whether the datasets originated from the same population, non-parametric statistical tests, specifically the Mann-Whitney *U* test and Spearman’s rank correlation coefficient (Mann & Whitney, 1947; Wilcoxon, 1945), were employed (Fig. 11). This was done to offer a wider interpretation of this study, overcoming the verticality of the use case and by highlighting benefit and limitations of the presented solution as an effective tool to assess industrial task. These specific tests were chosen due to the non-normal distribution of almost all data samples, as confirmed by the Shapiro-Wilk test (Shapiro & Wilk, 1965). Specifically, no correlation was found (p-value [2.198e-11] < α [0.05]) through the Mann-Whitney *U* test, performed with continuity correction for discrete datasets, between the TACOs scores calculated by the Gemma software (sample size (n) = 27) and those computed by ergonomists (sample size (n) = 81, considering this dataset as generated from all TACOs scores given by ergonomists). This implies that they do not belong to the same population of values, indicating that Gemma is a tool with a sensitivity that differs from the human assessment. At this point, the assumption made is that the inertial motion capture system’s sensitivity is higher than humans’ eye because it can retrieve a more precise overview compared to the visual observation. The garment accuracy and punctuality are extremely beneficial in complex and dynamic operations where traditional approaches may provide more rough ergonomics estimations. On the contrary, the garment software tool lacks the cognition of the task, context, user, and especially of the applied loads. As for the Spearman correlation test, the average score between the three ergonomists rounded to the nearest score range was considered: this conservative approximation was performed to avoiding losing of coherency with the score provided by the TACOs approach. In particular, the study employed Spearman’s correlation matrix to explore intrinsic non-linear relationships among ordinal variables, including Gemma scores, rounded ergonomists’ scores, age, height, and weight of the users.

The matrix provides values approximating + 1, indicating a strong positive correlation, or values nearing −1, indicating a significant negative correlation. A value of 0 indicates no correlation between the variables. The matrix obtained was visualised using a “heatmap”, with

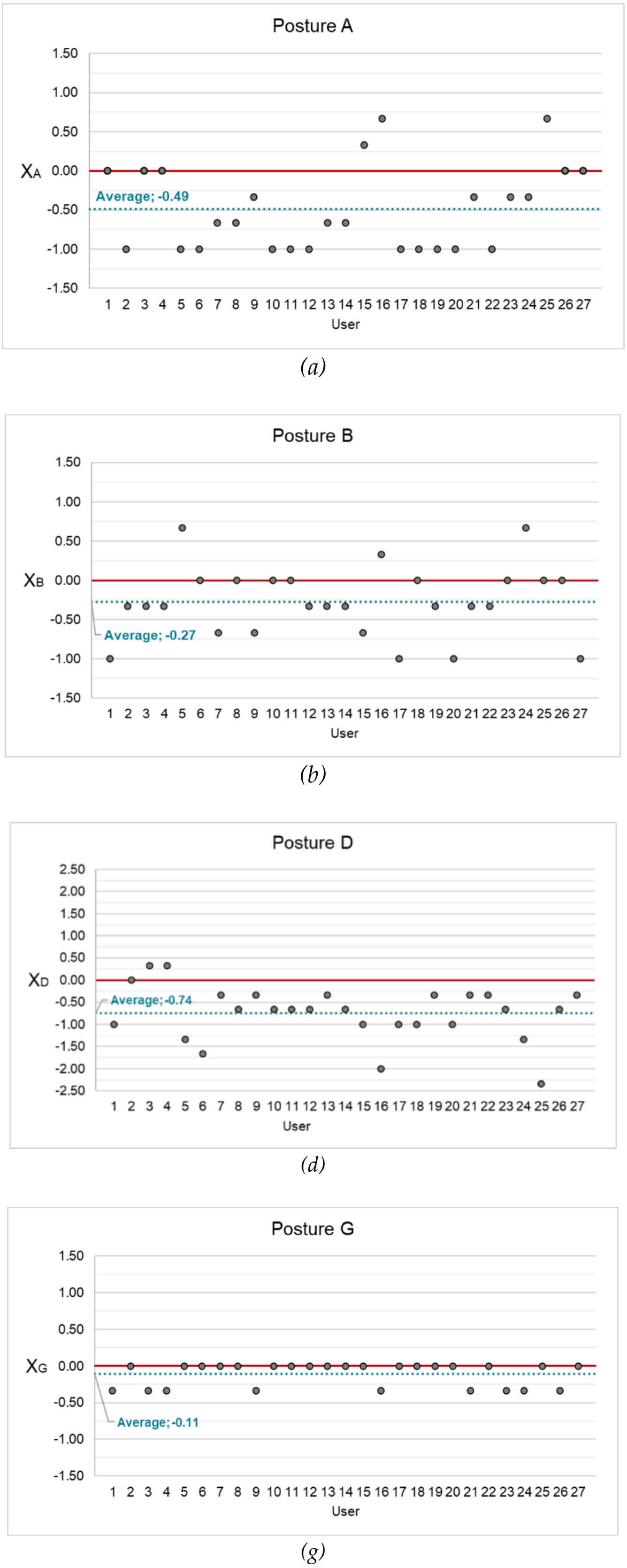


Fig. 10. Distribution of Xp for each of the 27 users and for each posture. Letters match the distinction presented above in Fig. 3: postures A1 and A2 are both included in posture A.

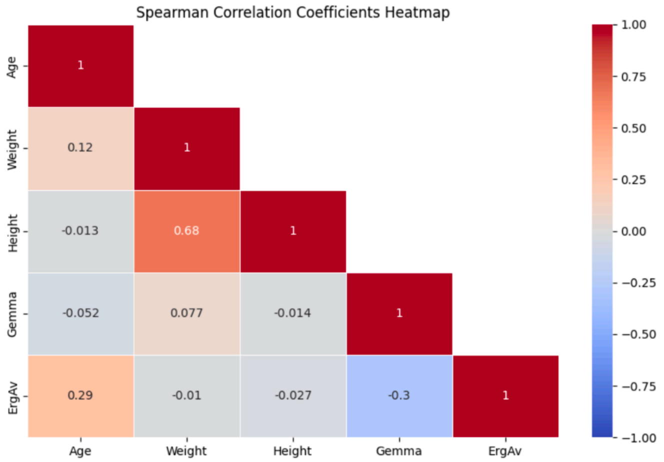


Fig. 11. Spearman correlation coefficient matrix.

intense colours representing stronger correlations. This graphical representation provides an immediate interpretation of the strengths and directions of associations among ordinal variables, contributing to a deeper understanding of the analysed data structure, as shown in Fig. 11.

A medium-level inverse correlation is highlighted between Gemma's TACOs scores and those of the ergonomists, indicating a different evaluation approach between the digital approach and the human-based approach, particularly emphasizing an antithetical assessment. Furthermore, a medium-level direct correlation is found between age and ergonomists' scores, suggesting that the human eye has an age-related bias, indirectly considered despite the narrow age range of users. In general, the variability in height and weight does not imply different postural behaviours, meaning that users do not exhibit differences in posture due to physical characteristics, as the described angles remain the same. As a final analysis, no significant correlation was found between the scores of the three ergonomists (Spearman correlation coefficient $r_{s,\ 3ErgAverage} = 0.173$), indicating different evaluations for each (except for those made by Erg1 and Erg2). Regarding the acceptance of the garment, according to the questionnaire users reported a general comfort, without being perceived as intrusive and limiting for laboratory activities: it must be anyway considered that the solution could be affected by extreme and harsh industrial environments, thus reducing its effective application for specific tasks.

The study also acknowledges inherent limitations, such as sample size and contextual factors while the integration with the Gemma software revealed technological deficiency. The sample size in this study was chosen to estimate an effect size rather than to test for statistical significance. Effect size, in this context, represents the magnitude of the phenomenon or relationship being investigated, allowing for a reliable measurement (Baguley, 2004). Future research will focus on statistical significance testing. Also, a continuous and demanding calibration has been encountered due to gyroscope drifting, especially with abrupt movements: considering an industrial application, a frequent recalibration would mean loss time on the shop floor. Additionally, the tool does not provide an on-time TACOs monitoring feedback being limited to a task redesign phase: such functionality will allow engineers and ergonomist to instantaneously retrieve the overall postural condition of industrial operators and to accordingly adapt productive systems. This will in turn emphasize human-centricity at design stage as promoted by the Industry 5.0 paradigm (Industry 5.0 - European Commission) while reducing the appearance of Musculo-skeletal disorders. Considering the TACOs method, the system is not able to recognise load handling: as aforementioned, future developments of this study, e.g., a new software release and its adjustment to collect data regarding body postures assumed during different manual handling task, will introduce a user input to overcome this limitation and to provide a more realistic TACOs score. In the future, the possibility of conducting a technological and numerical comparison with other hardware solutions will be considered. This includes the marker-less optical motion capture system by mean of stereoscopic cameras such as the Zed 2i released by StereoLabs ("ZED 2 – AI Stereo Camera | Stereolabs," n.d.). Specifically, the ZED Software Development Kit (SDK) allow developers to implement custom object and body tracking software.

6. Conclusions

The current study aims at highlighting the potentials and limitations of a digital setup as an effective and reliable support tool to perform ergonomic analysis when adopting the TACOs methodology. A manual handling task has been replicated by non-experienced operators in a controlled environment. The results of the postural assessment with the TACOs method performed by three ergonomists were compared with the results obtained from the Gemma software, i.e. the garment software tool described in this paper. The analysis showed that the postures detected through the Gemma software are more accurate compared to the subjective assessments made visually by ergonomists during task observation. Also, the software can speed up the ergonomic evaluation at the expense of a frequent calibration of the inertial sensors: in fact, dynamic tasks are more prone to gyroscopic drifting due to frequent contact with working tools or manipulated objects. A specific feature on the Gemma software has been appositely developed to tackle this issue: the setup validation on a real industrial environment will provide information on the effective recalibration requirement according to the analysed task and the operator interactions. Anyway, the traditional manual assessment overestimates the TACOs results compared to the Gemma software ones of almost 12 % as emerged from the analysis, probably due to the very nature of the proposed solution and to its exact identification of postures and postural holding time during the task. Joint angles thresholds biases and the absence of load in the evaluation of the TACOs score represents the first limitations to be tackled in future studies. Each posture is characterized by a sequence of predefined joint angles thresholds whose combination highly affects the recognition pattern of the automatic system: distinct ranges lead to a diverse sensibility of the software in identifying the analysed posture. This requirement should be object of further fine-tuning operations. An on-time TACOs computation represents another important step for an effective industrialization of the setup.

The proposed integrated solution for the prevention of ergonomic risk factors from awkward postures adopted by workers allows preventive interventions to mitigate biomechanical overload and the potential appearance of work-related musculoskeletal disorders. Integration of this digital solution into workplace safety management systems facilitates proactive risk mitigation strategies and enhances regulatory compliance for safety practitioners and occupational ergonomics. Periodic ergonomic assessments utilizing this method can provide employers with objective data to prioritize workstation redesigns and administrative controls optimizing worker safety and productivity. Furthermore, the digitization streamlines the assessment process, reducing evaluation time and costs, while enabling data-driven decision-making for an effective allocation of the resources for ergonomics interventions. Finally, the implementation of the solution proposed in this paper encourages the adoption of participatory ergonomics, by actively involving workers in hazard identification and control measure development, and fostering a positive safety culture (Botti et al., 2022). Ergonomic interventions guided by these findings can decrease work-related musculoskeletal disorder rates, absenteeism, and the associated workers' compensation costs.

Future research will investigate the reliability of the proposed setup in a real industrial scenario being tested on several industrial tasks, contributing to suggest peculiar interventions and data interpretations. Harmonizing the postural workload data together with psychophysical parameters and subjective questionnaires while proposing practical and adequate technological solutions to meet reliable results will guarantee designers and ergonomist to effectively implement the human-center design approach at multiple levels and with a fine-grained resolution. Although the garment software tool has some limitations, this study represents an initial step toward the development of a fully digital automated system capable of accurately recognizing postures assumed during both static and dynamic tasks performed at work, along with their exact duration. With this development, the risk of biomechanical overload resulting from both static and dynamic postures will be precisely assessed. Additionally, the tool is a great help to both ergonomists and industrial practitioners since it allows to quickly and accurately evaluate these risks when work activities and workstations are being designed.

CRediT authorship contribution statement

Riccardo Karim Khamaisi: Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matteo Perini:** Writing – original draft, Formal analysis, Data curation. **Alessio Morganti:** Writing – original draft, Validation, Formal analysis, Data curation. **Marco Placci:** Validation, Conceptualization. **Fabio Grandi:** Supervision. **Margherita Peruzzini:** Visualization, Validation, Supervision, Investigation, Conceptualization. **Lucia Botti:** Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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