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3D standard motion time-based ergonomic risk analysis for workplace design in modular construction

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ABSTRACT

As construction workers are frequently exposed to ergonomic risks, accurate ergonomic risk analysis for workplace design is needed in order to mitigate risk and, consequently, improve productivity. Researchers have sought to identify ergonomic risks of continuous motions in 3D visualizations to achieve proactive workplace designs. However, the motion time is subjectively determined by designers, leading to variable risk ratings and making it difficult to make decisions on design alternatives. This paper proposes an automated 3D standard motion time-based ergonomic risk analysis method that systematically determines motion times and accurately quantifies ergonomic risks of continuous motions for workplace design. The ergonomic risk of continuous motion is assessed using existing tools such as REBA and RULA by incorporating standard motion times determined by a predetermined motion time system. The effectiveness of the proposed method is validated in a case study of two workplace designs for manual assembly tasks in modular construction.

1. Introduction

Although advanced machinery has been used to automate some aspects of production, manual operations are still essential in modular construction facilities. In this regard, due to the physically demanding nature of manual operations, work-related musculoskeletal disorders (WMSDs) are the leading cause of nonfatal occupational injuries, accounting for approximately 33% of all occupational injuries and illnesses in the United States [1], and approximately 44% of such injuries in Alberta, Canada [2]. In current practice, workplace design that does not give adequate consideration to ergonomics increases the probability of injury rates and work absenteeism, leading to schedule overruns and production loss [1,3–4]. Compared to other industries, construction workers are at an approximately 50% higher risk of developing WMSDs [5], largely due to the reliance on manual operations involving awkward body postures, forceful exertion, and repetitive motions [3]. In this context, designing ergonomically safe workplaces is essential to mitigating the risk of WMSDs arising from the physically challenging manual operations involved in modular construction.

Ergonomic risk analysis for assessing operational tasks and the associated workplace design can be implemented using various techniques, such as rapid entire body assessment (REBA) [6–7], rapid upper limb assessment (RULA) [8], Ovako working posture analysis system (OWAS) [9–10], Quick exposure check (QEC) [11], JACK [12], 3D static strength prediction program (3D SSPP) [13], and post-3D ErgoSystem [14]. REBA, RULA, OWAS and QEC are observation-based methods that generally provide quantitative frameworks of ergonomic risks in accordance with body postures. These methods aim to identify the most problematic postures and modify the workplace design accordingly to mitigate the risk of workers developing WMSDs. Instead of assessing the body postures, the ergonomic risks of continuous motions involved in these tasks are evaluated using computer technology. Examples include JACK, post-3D ErgoSystem, and 3D SSPP, which are computer-based methods focusing on human–machine interface analysis, ergonomic job analysis, and biomechanical analysis, respectively. In the present study, it should be noted, "motion" or "continuous motion" refers to any purposeful movement consisting of a series of body postures over a period of time, and it can be described in terms of displacement, distance, velocity, speed, and time. Thus, the time feature of continuous motions is essential for the computer-based analysis.

In modular construction, observation-based methods have been implemented in conjunction with 3D visualization to assess continuous

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motions for workplace design [14–16]. The post-3D ErgoSystem is a 3D-based ergonomic risk assessment method developed based on 3D visualization to evaluate ergonomic risks using REBA and RULA [14,17] in order to support ergonomic workplace design. The body joint angles describing working postures, including joint angles of neck, trunk, legs, upper arms, lower arms, and wrists, are the main inputs in ergonomic posture assessments [6–8]. The main output is the identification of high-risk postures that warrant work modification in order to mitigate the ergonomic risk. In practice, ergonomic interventions are required in order to address high-risk postures in manual operations. However, the risks associated with continuous motions are not only a function of the postures assumed by the subject at a given time frame (animation time unit) in the 3D visualization, but also the time duration of these postures (i.e., the motion time feature of the continuous motion). For example, a worker handling materials overhead with the same posture for one second versus one minute may result in different risks, and this aspect may lead to unreliable ergonomic workplace designs. In previous studies related to 3D-based ergonomic risk assessment, information pertaining to the time durations of high-risk postures has tended to be overlooked in favor of the body postures themselves, leading to inaccurate risk ratings of continuous motions. Particularly when comparing workplace design alternatives, the risk ratings of the same continuous motions may differ if the motion times are overlooked in the ergonomic risk analysis, and this can lead to unreliable decision making with respect to workplace design. To achieve reliable workplace designs and ensure accurate ergonomic risk analysis of continuous motions, the time feature of manual operations as the motion time (i.e., the time spent in each of the different motions during the continuous movement) must be accurately captured and implemented in the 3D visualization.

Standard movements in the 3D visualization, it should be noted, are generally built using 24 to 30 frames per second (fps) for normal motions [18]. Although designers use this standard when developing 3D visualizations, the animated motion time (i.e., the time spent in a given motion in the 3D visualization) may not be the same as the standard motion time (i.e., the standard time spent by a worker completing that motion). In this regard, time study at the motion level may help to improve the accuracy of 3D visualizations. However, this approach is time-consuming, error-prone, and inconsistent, given the complexity of working environments [19]. Additionally, a time study cannot be performed at the design stage (i.e., when the workplace has not yet been built in reality). Thus, this research proposes an automated 3D standard motion time-based ergonomic risk analysis method for workplace design in 3D visualization. The main objective is to systematically determine standard motion times and accurately quantify ergonomic risks of continuous motions in order to improve the accuracy and reliability of 3D-based ergonomic risk analysis for workplace design. The ergonomic risk of continuous motion is assessed using existing tools such as REBA and RULA by incorporating standard motion times determined by the motion time standard—i.e., predetermined motion time system (PMTS)—in order to accurately mimic a task and generate the output information in terms of the standard motion time. The proposed method can accurately determine the standard motion times, thereby improving the accuracy and reliability of ergonomic risk assessments for continuous motions, in turn resulting in a more accurate, reliable, and consistent workplace design.

To accomplish the proposed objective successfully, several challenges need to be overcome. (1) Standard motion time is not considered in existing 3D-based ergonomic posture assessment methods, whereas, in reality, manual construction operations are complex and dynamic, necessitating that the motion time feature be considered. By integrating 3D-based ergonomic posture assessment with standard motion time, design alternatives can be evaluated based on continuous motions from the perspective of body postures and the associated motion times. (2) A time-consuming process of 3D visualization development is required in order to accurately imitate complex and dynamic manual operations with respect to both postures and motion time. This is due to the fact that the motion time obtained during the time study and employed throughout the 3D visualization development process is subjective and error-prone. (3) The automated extraction of the motion data (i.e., motion type and corresponding motion parameters such as motion length, motion case, etc.) in the 3D visualization is required for the purpose of providing inputs of PMTS by which to automatically compute the standard motion times of the extracted motions. Due to the complex forms and procedures in PMTS, the manual implementation is complex, error-prone, and time-consuming, necessitating specialized training [19]. For these reasons, it is difficult to develop a system within the context of 3D visualization that accurately and efficiently captures motions and estimates motion times. Additionally, the lack of definitions by which to identify the start and end of each basic motion in PMTS leads to inaccurate motion capture and standard time estimations, constituting another notable challenge with respect to estimating standard motion times in 3D visualization. Thus, an interpretation algorithm must be established that is capable of translating the textual information from the PMTS to the tabulated database in order to automatically extract the standard motion time of each identified motion.

Previous research efforts have sought to address the first challenge noted above by developing automated assessment methods capable of evaluating continuous motions in 3D visualization [14,16–17]. However, these studies have not given consideration to using standard motion time to match the animated time in the 3D visualization with the actual time. As such, the present research builds on the 3D-based ergonomic posture assessment method previously developed by Li et al. [14,17] and Wang et al. [16] in seeking to fill these gaps. In this regard, this paper proposes an integrated framework using 3D-based ergonomic risk assessment methods with the PMTS approach to improve the accuracy of ergonomic risk analysis for continuous motions in order to support workplace design. The objectives of this study are to: (1) automatically identify the motions in the continuous motions in 3D visualization, (2) systematically determine the standard motion times of identified motions based on the PMTS approach, (3) incorporate standard motion times into risk ratings for the assessment of continuous motion. One of the aims of the proposed method is to address the standard motion time of continuous motions for ergonomic risk analysis. In this respect it can aid designers in improving the efficiency of design and the reliability of decision making with respect to workplace design alternatives in modular construction.

2. Background

2.1. Ergonomic risk assessment in 3D visualization

Ergonomic risk assessment for workplace design is mainly conducted by assessing the ergonomic risks based on the working postures and motions corresponding to manual operations in the workplace. REBA and RULA are commonly used risk assessment methods that have been used for more than 20 years in practice and academia. These methods are capable of providing accurate results based on simple input information (i.e., mainly joint angles), and, as observation-based methods, their implementation is practical and affordable compared with other techniques (e.g., computer vision-based methods, direct measurement-based methods, etc.) [20]. Recognized for their utility in evaluating workplace design, ergonomic posture assessment methods have been implemented in conjunction with 3D modeling technology for the assessment of continuous motions in modular construction. For example, Golabchi et al. [15,21] integrated biomechanical analysis and simulation modeling with ergonomic risk analysis in a 3D modeling approach for workplace design improvement; Li et al. [14,17] introduced a 3D-based approach to obtain construction workers' body joint angles from a 3D model and identify unsafe postures, and further developed a post-3D ErgoSystem for rapid workplace design to prevent ergonomically unsafe postures at the design stage; and Wang et al. [16] incorporated fuzzy logic into 3D-based method to accurately detect unsafe postures by eliminating human perception errors and measurement errors when identifying body joint angles in the working posture. A specialized rule-based fuzzy inference algorithm is integrated with 3D-based method to better capture the gradual transitions characteristic of continuous human motion without abrupt changes in risk ratings. These 3D-based methods typically consist of two main processes: (1) on-site measurement of workers' anthropometric data and workplace design parameters, such as dimensions of the workstation, tools, and work modules (e.g., panels), as well as video collection of the motions in the manual operation, and (2) 3D visualization and associated ergonomic risk assessment at each time frame in the 3D visualization according to the working postures defined in terms of body joint angles.

The abovementioned studies have provided valuable insights into the use of ergonomic posture assessment for workplace design. The 3D-based method has the following benefits: (1) it assesses all the postures at each time frame in the continuous motion, in contrast to conventional methods, which assess risk only for static postures assumed during the continuous motion (thereby eliminating the variance in risk ratings caused by human perception errors and subjectivity of primary posture selection); and (2) it automates an otherwise manual, tedious, and time-consuming assessment process, making it more efficient and cost-effective for assessment of design alternatives (i.e., all drawings and editing of the imitated tasks is executed in the 3D model on the computer, thereby eliminating the need for physical imitation and costly equipment for motion data collection). In the field of construction in particular, research efforts have been made to devise a method of retrieving body joint angles from the 3D model for ergonomic posture assessment in rapid workplace design [14,16–17]. However, the accuracy of these imitations of manual operations (i.e., the motion time in the 3D visualization) has not been fully addressed in previous studies.

2.2. Standard motion times for ergonomic risk assessment

The motion time for completing the task is essential for reliable planning and scheduling process in construction. Moreover, the ergonomic risk assessment of continuous motions requires motion times since the WMSDs occur through the accumulation of ergonomic risks over time. Specifically with regard to the 3D-based ergonomic risk assessment method, a 3D model is a modeling tool that is capable of imitating real operational tasks as an alternative to videos and images, which are commonly used in the conventional ergonomic risk assessment process. Although a 3D model is essentially a stack of images of body postures, the information delivered in the 3D model format is different from static images of postures since it contains motion time information. 3D human body motion imitation is created by controlling footsteps, primary postures, and the speed of movement in the 3D model [14]. In current practice, primary postures are determined based on the recorded videos, while the corresponding keyframes are determined based on a time study [14]. This means that subjectivity and human perception errors with respect to primary postures and the motion times may result in a variance in ergonomic risk ratings.

Generally, the average risk of continuous motions over time is utilized as an indicator for comparing workplace design alternatives in 3D visualization [14,16]. As a result, the motion times must be accurately estimated in order to obtain the average risk that successfully represents design alternatives. Specifically with regard to the 3D-based method, different estimations of motion times in 3D visualization can lead to variations in the average risk of continuous motions. For example, a 24-frame reaching movement obtains an average risk of 4 (i.e., medium risk level) in RULA, as shown in Fig. 1. If the movement is short-animated in just 11 frames, it will obtain an average risk of 2 (i.e., low risk level). However, the same movement animated with 35 frames will result in an average risk of 5, which corresponds to the high risk level. It should be noted that the time durations of each risk rating can highly affect the average risk. Thus, a standard motion time determination method is needed in order to accurately determine the keyframes of primary postures and the associated ergonomic risks for workplace design.

Predetermined motion time system (PMTS) is a systematic approach that uses rules and tables to output the standard motion time as an alternative to time study. PMTS has recently received attention due to the following benefits: (1) it systematically obtains standard motion times based on motion parameters, such as the distance traveled, the motion type, and the motion condition; (2) it effectively provides the objective results of standard motion times while significantly reducing subjectivity; and (3) it allows for hypothetical scenarios to be effectively modeled and explored without the implementation of body motions in the real world. However, because PMTS is outputted in the form of procedures and tabulated data, the manual implementation process is time-consuming, error-prone, and difficult to apply, necessitating specialized training [19].

The most widely used PMTSs include methods-time measurement (MTM) [22], the Maynard operation sequence technique (MOST) [23], and the modular arrangement of predetermined time standards (MODAPTS) technique [24]. These methods can be distinguished from one another in terms of the scope of data application, the level of precision, the classification of motion and corresponding conditions, and the unit of time used [19]. Among them, the first generation of MTM (MTM-1) is the fundamental method, as it contains all the basic motions (e.g., reach, grasp, move, release, etc.) with the most detailed motion conditions to quantify the amount of time required to perform a task [25]. Thus, MTM-1 is applied in the proposed method. In the area of construction, research efforts have been made in terms of retrieving the time data from a PMTS for simulation modeling to measure productivity [15]. However, relatively little attention has been given to retrieving the standard motion time data from a PMTS and integrating that information into ergonomic risk analysis for workplace design, which is essential in the context of automating and simplifying the process of standard motion time determination. Thus, the present research focuses on filling

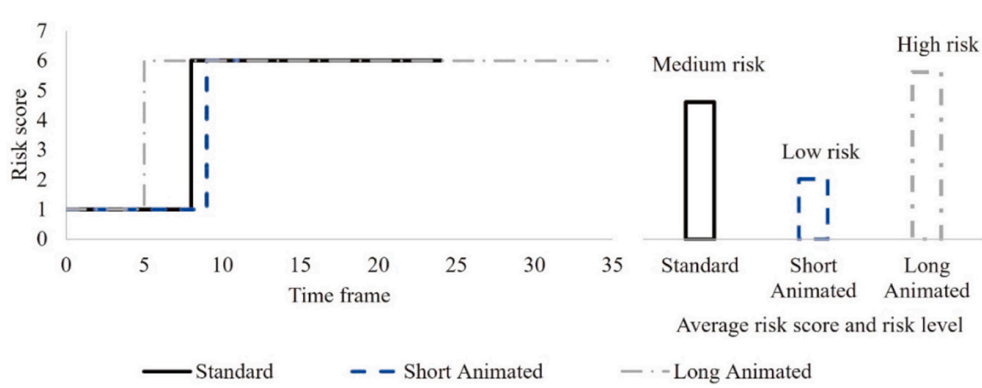


Fig. 1. Risk ratings for the same movement of different animated times.

this research gap—taking the automation of the 3D-based ergonomic posture assessment a step further by integrating the PMTS-based standard motion time determination method and compiling the output information in terms of time feature to evaluate the workplace design alternatives.

3. Methodology

The present research proposes a 3D standard motion time-based ergonomic risk analysis method for construction workers (herein referred to as "3D-MEC") to provide an automatic and detailed ergonomic risk analysis of dynamic and continuous motions for workplace design and modification in modular construction. An overview of the proposed methodology is presented in Fig. 2. The inputs are the 3D visualization developed based on the standard operating procedure, measurements of workers (i.e., anthropometry) and the workstation (i.e., dimensions), and the recorded images and videos of the body motions (if any), shown as Part (a) of Fig. 2. The outputs include the standard cycle time of the operational task, standard motion time-based ergonomic risk ratings of continuous motions, and modified work facilitation and workstation design evaluation, shown as Part (k) in Fig. 2. It should be noted that the lab experiment and video recordings provide the ground truth measurement of the motions and motion times for the proposed method. The motion times from 3D visualization and those from the experiment are comparable for the basic motions [26].

The objectives of the proposed method are to: (1) obtain standard motion time data—in a Microsoft Excel format in this case, as shown in Part (e) of Fig. 2—that records the standard cycle time of the manual operation in detail, and (2) generate standard motion time-based ergonomic risk ratings for continuous motions (i.e., average risk ratings and proportions of motions at different risk levels, as shown in Part (i) of Fig. 2) to support the design of work modifications. For this purpose, several operations related to determining standard motion time and assessing posture risk—i.e., Part (b) to Part (h) of Fig. 2—need to be conducted simultaneously. The 3D visualization must be decomposed frame by frame, as shown in Part (b) of Fig. 2, in order to extract the 3D coordinates of body joints and objects that appear at each frame of the 3D visualization. As shown in Part (j) of Fig. 2, the risks identified for a given continuous motion are checked to ensure that the workplace design satisfies the risk requirements. If the risk requirements are found to be satisfied, then the design information is outputted. Otherwise, modified work is proposed to adjust the workplace design in the 3D visualization. In the present research, MTM-1 is used as the criterion in the proposed rule-based motion recognition and PMTS interpretation algorithms, while REBA and RULA are applied as the main criteria in the frame-based ergonomic risk assessment process.

MTM-1 is a detailed PMTS method containing most of the basic motions seen in other PMTSs [19]. The main input requirements of MTM-1 are motion types, influencing factors, and working conditions. For example, the standard motion time of the arm and hand motion "move" is determined based on the distance traveled by the hand or fingers, the weight of the object moved, and the working conditions (i.e., moving object to the other hand, to the approximate location, and to an exact location). The standard cycle times of basic motions, including arm and hand motions (e.g., reach, move, grasp, release, and turn, etc.), leg and foot motions, eye motions, and body motions (e.g., walk, bend, and sidesteps, etc.), are provided as the outputs of MTM-1, as summarized in Table 1 [22,25,27]. In MTM-1, all the basic motion times are tabulated in the time measurement unit (TMU), which is a base unit of measurement for precise and convenient calculations defined as 0.036 s [22]. It should be noted that is mainly the arm and hand motions that are of interest in this work, since most manual operational tasks in modular construction involve principally the arms and hands. Thus, in this paper, the proposed rule-based motion recognition algorithm and PMTS interpretation algorithm are developed with a focus on arm and hand motions. (Full body motions will be further investigated in future research in order to mimic real-world construction operations in a more detailed and comprehensive manner.)

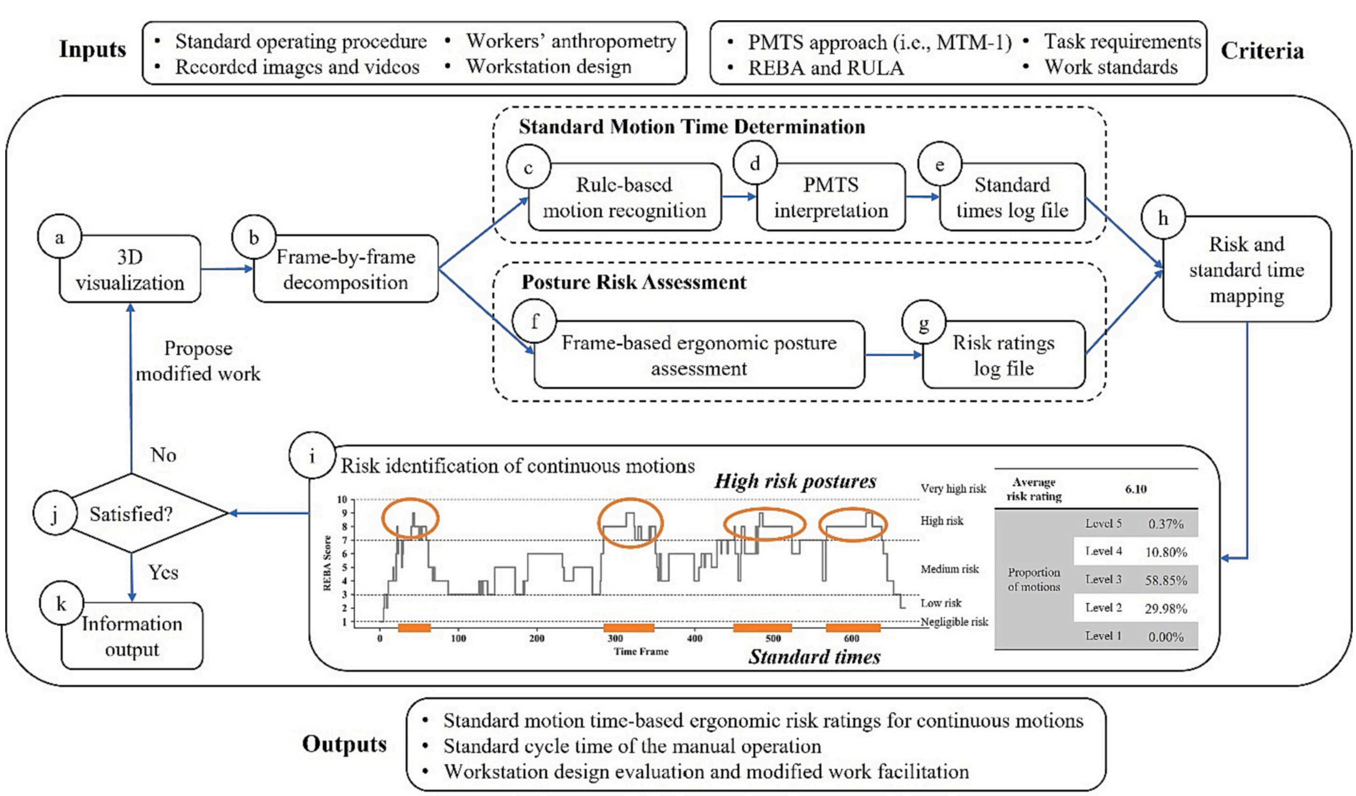


Fig. 2. Overview of proposed methodology.

Table 1
Summary of 25 basic motions represented in MTM-1.

MTM motions (Symbol)		Description	Factor	Standard time (TMU)	Animation time (Frame)
Arm and hand motions	Reach (R)	Movement of the hand or fingers	Motion length Motion case	1.6–26.7	2–29
	Move (M)	Relocating an object	Motion length Motion case Object weight	1.7–62.05	2–67
	Grasp (G)	Grasping an object	Motion case	0–12.9	0–14
	Position (P)	Align, orient, or engage an object to another	Class of fit Symmetry case Ease of handling	5.6–53.4	6–58
	Release (RL)	Surrendering control of an object	Motion case	0–2.0	0–2
	Turn (T)	Rotation of the hand and wrist	Degree of turn Object weight	2.8–28.2	3–30
	Apply pressure (AP)	Application of force	Motion case	10.6 / 16.2	11 / 17
	Disengage (D)	Separating two objects	Class of fit Ease of handling	4.0–34.7	4–37
Leg-foot motions	Leg motion (LM–)	Movement of leg	Motion length	7.1 + 1.2 × (length – 6 in) (TMU)	
	Foot motion (FM)	Movement of foot	Motion case	8.5 / 19.1	9 / 21
Eye motions	Eye focus (EF)	Visual attention on an object	–	7.3	8
	Eye travel (ET)	Eye movement with line-of-sight change	Motion length	15.2 × motion length / perpendicular distance (TMU)	
Body motions	Sit (SIT)	Act of sitting	–	34.7	37
	Stand (STD)	Act of standing	–	43.4	47
	Bend (B)	Act of bending	–	29.0	31
	Arise from bend (AB)	Act of arising from bent position	–	31.9	34
	Stoop (S)	Act of stooping	–	29.0	31
	Arise from stoop (AS)	Act of arising from stooped position	–	31.9	34
	Kneel on one knee (KOK)	Act of kneeling on one knee	–	29.0	31
	Arise from kneel on one knee (AKOK)	Act of arising from kneeling position on one knee	–	31.9	34
	Kneel on both knees (KBK)	Act of kneeling on both knees	–	69.4	75
	Arise from kneel on both knees (AKBK)	Act of arising from kneeling position on both knees	–	76.7	83
	Walk (W-FT/ W—P)	Act of walking	Number of feet/ Number of paces	5.3 × number of feet 15.0 × number of paces (TMU)	
	Sidestep (SS)	Act of sidestepping	Motion case	17.0 + 0.6 × (length – 12 in) / 34.1 + 1.1 × (length – 12 in) (TMU)	
	Turn body (TB)	Act of body turning 45° to 90°	Motion case	18.6–37.2	20–40

3.1. Standard motion time determination

The purpose of the standard motion time determination is to automatically identify the basic motions and assign the standard motion times of continuous motions. It is composed of the rule-based motion recognition algorithm, PMTS interpretation, and standard motion time logging process, as shown in Part (c) to Part (e) of Fig. 2. The main process underlying the determination of standard motion time, meanwhile, is shown in Fig. 3. After being processed in the frame-by-frame decomposition of the 3D visualization, the body postures within continuous motions are saved at each frame. Moreover, the dimensions of the biped bones are collected as the length, width, and height of cuboids, while the body joint data are extracted as the 3D coordinates of the pivot point of each bone at each frame [14,16]. A total of 51 bones are used in the data processing; these include the head, clavicle, neck, spine, pelvis, thighs, calves, feet, toes, upper arms, forearms, hands, and finger bones. It should be noted that five fingers for each side of the body are set up in the 3D human model for precise animations and standard motion time determination. However, only one finger is required for the ergonomic risk assessment, since fingers are not considered in REBA and RULA. The dimensions and 3D coordinates of objects (i.e., work-related elements and tools) are exported from the 3D visualization at each frame. All these time-sequential data derived from the 3D visualization are stored for data processing in the subsequent phases of the rule-based motion recognition process in the formats expressed in Eq. (1) (representing the 3D human model) and Eq. (2) (representing the work-related elements and tools).

$$B_t = \begin{bmatrix} b_{1x} & b_{1y} & b_{1z} \\ b_{2x} & b_{2y} & b_{2z} \\ \vdots & \vdots & \vdots \\ b_{jx} & b_{jy} & b_{jz} \end{bmatrix}_t \tag{1}$$

$$O_t = \begin{bmatrix} o_{1x} & o_{1y} & o_{1z} \\ o_{2x} & o_{2y} & o_{2z} \\ \vdots & \vdots & \vdots \\ o_{ix} & o_{iy} & o_{iz} \end{bmatrix}_t \tag{2}$$

where, B_t and O_t are 3D coordinates of the biped bones and objects, respectively, at time frame t; b_{jx}, b_{jy}, and b_{jz} are the j^{th} bone's position at the x-, y-, and z-axes, respectively; and o_{ix}, o_{iy}, and o_{iz} are the i^{th} object's position at the x-, y-, and z-axes, respectively.

3.1.1. Rule-based motion recognition algorithm

The proposed rule-based motion recognition algorithm detects all the basic arm and hand motions in continuous motion. Following the frame-by-frame decomposition of the 3D visualization, the distance traveled by each body joint and object is computed between two adjacent frames based on their 3D coordinates and the Euclidean distance using Eq. (3). As the smallest parts (in the case of arm and hand motions), fingers are used for rule-based motion recognition. At this juncture, it should be noted that the design tolerance is the acceptable

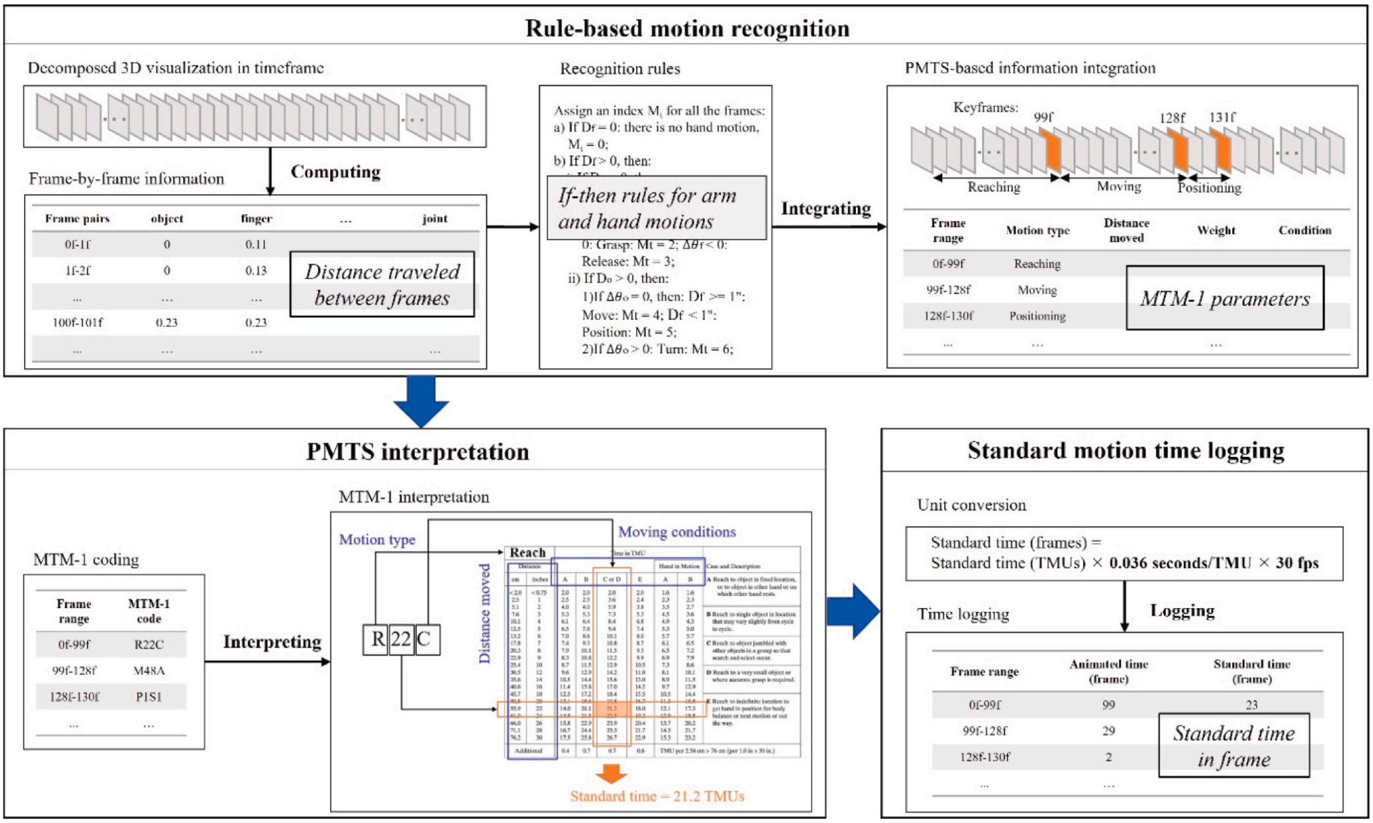


Fig. 3. Processes underlying the determination of standard motion time.

variance in the closeness to the measurement during design, which is predefined in such a way as to overlook minor movement and dimensional variations in the 3D visualization. The tolerance is used for determining whether the finger and the object are close enough which can be identified as they are contacting each other. In other words, as long as the distance between finger and object is less than tolerance, the status of "contacting" is satisfied.

$$d(p,q) = \sqrt{\sum_{t=1}^{n} (q_t - p_t)^2} \quad (3)$$

where p and q are two points in Euclidean n-space, p_i and q_i are Euclidean vectors, starting from the origin of the space, and n represents n-space, which is 3D space in this case.

1. Start:
   a) Predefined variables: tolerance (T)
   b) Read all the 3D coordinates of the biped bones and objects from the 3D visualization at each frame.
2. Calculate the distance traveled by each biped bone and object between tth frame and t+1th frame.
3. Assign an index M_t for all the frames:
   a) If the distance traveled by finger = 0: there is no arm or hand motion, $M_t = 0$;
   b) If the distance traveled by finger > 0, then:
      i) If the distance traveled by object = 0, then:
         1) If the distance between finger and object decrease to T, then: Reach: $M_t = 1$;
         2) If the distance between finger and object is within T, then:
         Angular change ($\Delta\theta$) of finger > 0: Grasp: $M_t = 2$; $\Delta\theta$ of finger < 0: Release: $M_t = 3$;
      ii) If the moved distance of object > 0, then:
         1) If $\Delta\theta$ of object = 0, then:
         Distance traveled by finger >= 1": Move: $M_t = 4$; Distance traveled by finger < 1": Position: $M_t = 5$;
         2) If $\Delta\theta$ of object > 0: Turn: $M_t = 6$;
4. Repeat Step 3 for all objects;
5. Repeat Step 3 and Step 4 for both hands;
6. Simultaneous motion check between the left and right hands;
7. Generate recognized motions in time series;
8. End

Fig. 4. Pseudo-code for proposed rule-based motion recognition algorithm.

In the proposed motion recognition algorithm, the if-then rules are developed and formulated based on the definitions of basic motions and procedures in the MTM-1, which include: (1) the "reach" motion, when the finger is approaching the object while the object is not moving; (2) the "move" motion, when the finger and object are close to one another and are moving at the same speed; (3) the "grasp" motion, when the fingers are closing to hold the object while the hand remains in a fixed position; (4) the "release" motion, when the fingers are opening to release the object while the hand remains in a fixed position; (5) the "position" motion, which refers to a "move" motion with a distance of less than 1 in.; and (6) the "turn" motion, when the object is turning while the positions of the hand and object remain fixed. The moving speeds of the finger and object (i.e., the distance traveled and the angular change between two adjacent frames) are used to formulate the if-then rules for the motion recognition. The if-then rules are shown in the pseudo-code for the proposed rule-based motion recognition algorithm, as presented in Fig. 4.

The algorithm starts by defining the variable of tolerance (T) and loading all the 3D coordinates of the biped bones and objects at each frame into the 3D visualization. In Step 2, the distance traveled by each biped bone and object between the t^{th} frame and the $t + 1$th frame is calculated. After Step 2, values of the index M_t are assigned for all frames based on the distance traveled by both the finger and the object as follows: $M_t = 0$ for the case of no arm or hand motion, $M_t = 1$ for "reach" motion, $M_t = 2$ for "grasp" motion, $M_t = 3$ for "release" motion, $M_t = 4$ for "move" motion, $M_t = 5$ for "position" motion, and $M_t = 6$ for "turn" motion. In Step 3, the distance traveled by the finger is first checked. If the distance traveled by the finger is 0, then it is determined that there is no arm or hand motion (i.e., $M_t = 0$). When the distance traveled by the finger is greater than 0, the distance traveled by the object is then checked. On the other hand, when the distance traveled by the object is 0, the obtaining motions (i.e., the "reach", "grasp", and "release" motions) are identified (using different rules). If the distance between finger and object decreases to within the threshold defined by the tolerance, the "reach" motion is identified for all these frames and a value of 1 is assigned to M_t. Moreover, if the distance between finger and object is within T, the angular change of the finger is then checked in order to distinguish between the "grasp" motion and the "release" motion.

In Step 3, the angular change ($\Delta\theta$) between two frames, it should be noted, is calculated based on the dot product theory [28], as in Eq. (4) and Eq. (5). If the $\Delta\theta$ of the finger is greater than 0, "grasp" motion is recognized; otherwise, if $\Delta\theta$ of the finger is less than 0, "release" motion is identified. For example, the given motion is categorized as grasping an object when $\Delta\theta$ is positive (i.e., closing fingers), while it is releasing an object if $\Delta\theta$ is negative (i.e., opening fingers). When the distance traveled by the finger and that by the object are both greater than 0, the angular change of the object is checked to distinguish the rotate action (i.e., "turn" motion) and the locate actions (i.e., "move" and "position" motions). When the $\Delta\theta$ of the object is 0, the "move" motion is identified, provided that the distance traveled by the finger and that by the object are about the same and the total distance within these frames is greater than or equal to 1 in.; otherwise, the "position" motion is detected. The "turn" motion, meanwhile, is recognized when $\Delta\theta$ of the object is greater than 0. For example, the given motion is recognized as the "move" motion when both finger and object are moved from time frame t to $t + n$ and the total distance is greater than 1 in..

$$\theta = cos^{-1}A \bullet B / |A||B| \tag{4}$$

$$\Delta\theta = \theta_t - \theta_{t+1} \tag{5}$$

where A and B are vectors representing the body segments, and θ_t and θ_{t+1} are angles between vector A and B at frame t and $t + 1$, respectively.

For all objects and for both hands, Step 3 is required to process repeatedly in Step 4 and Step 5, respectively. Then, based on the degree of handling difficulty demoted in the simultaneous motion table in MTM-1, the simultaneous motion check between the left and right hands is performed in Step 6 to generate the recognized motions for the entire body in the time series. Based on MTM-1, only a longer time duration is considered when the motions are easy to perform simultaneously, while both times are allowed when the motions are difficult to perform simultaneously [22,25].

3.1.2. PMTS interpretation

After all motions have been identified, these motions and their parameters are integrated to generate the PMTS-based information, which includes the frame range of each identified motion, motion type, and MTM-1 parameters such as distance traveled, weight of object, and working conditions. The MTM-1 codes are then automatically generated (based on the MTM-1 parameters for interpreting the MTM-1 motion timetables) in order to extract the standard motion times for the identified motion series. As shown in Fig. 5, the MTM-1 code is constructed in three parts: (1) the MTM motion symbol (e.g., R for reach, M for move, G for grasp, etc.) for motion type, (2) the distance traveled, and (3) the motion case type. For example, reaching out approximately 22 in. to retrieve screws from the box on the shelf can be coded as R22C, where C is included in the code because the screws may be jumbled together in the screw box. In the PMTS interpretation process, the MTM-1 code is used to extract the standard motion time from the MTM-1 system. As shown in the example in Fig. 5, the given motion coded as R22C is assigned 21.2 TMUs using the MTM-1 table for "reach" motion with the parameters of 22 in. as the distance traveled and motion case C. The standard motion time in TMUs is converted to 23 frames (i.e., about 0.8 s in the 30-fps model). The standard motion times are then logged in the time log file and compared with the animated time.

3.2. Posture risk assessment

Posture risk assessment is another of the main processes; it seeks to identify the ergonomic risk of each body posture at each frame in the continuous motion. The frame-based ergonomic posture assessment and risk ratings are logged as part of this process. It should be noted that the ergonomic risk ratings at each frame are still assessed based on the body posture at the discrete time point. As shown in Fig. 6, the degree of ergonomic risk depends on the posture, force load, and activity conditions. The postures are defined as joint angles of body segments, there being determined based on the positions of body segments in terms of the joint angle between the body segment and the extension of its connected body segment. The force load is considered from the perspectives of both magnitude and type of action (i.e., intermittent, static, repeated, and shocks). As with the risk rating adjustment, activity conditions are assessed based on the degree of repetitiveness (i.e., frequency per minute), corresponding to the activity score in REBA and the muscle use score in RULA. As a time-related factor, the activity score is mainly used to describe the dynamic feature and continuity of continuous motions. The outputs is presented in terms of the five risk levels in REBA and the four risk levels in RULA, as shown in Fig. 6.

In the present research, 3D coordinates of body joints are used to compute the required joint angle data in REBA and RULA at each frame. A total of 41 body joint angle data points covering the sagittal plane, frontal plane, transverse plane, and axial rotation are obtained from the 3D model, these being defined in terms of the required angles of each body segment in the biomechanical analysis software, 3D Static Strength Prediction Program (3D SSPP) [13]. The joint angle conversion of the 41 joint angles computed among different frames in the 3D visualization must accommodate the REBA/RULA requirements, which is described in detail in a prior study co-authored by the author of the present work [14]. In the present research, continuous motions are presented as a series of postures in a time sequence for the purpose of ergonomic risk assessment. Each posture obtains risk scores from both REBA and RULA. The output of the posture risk assessment process is the risk ratings log

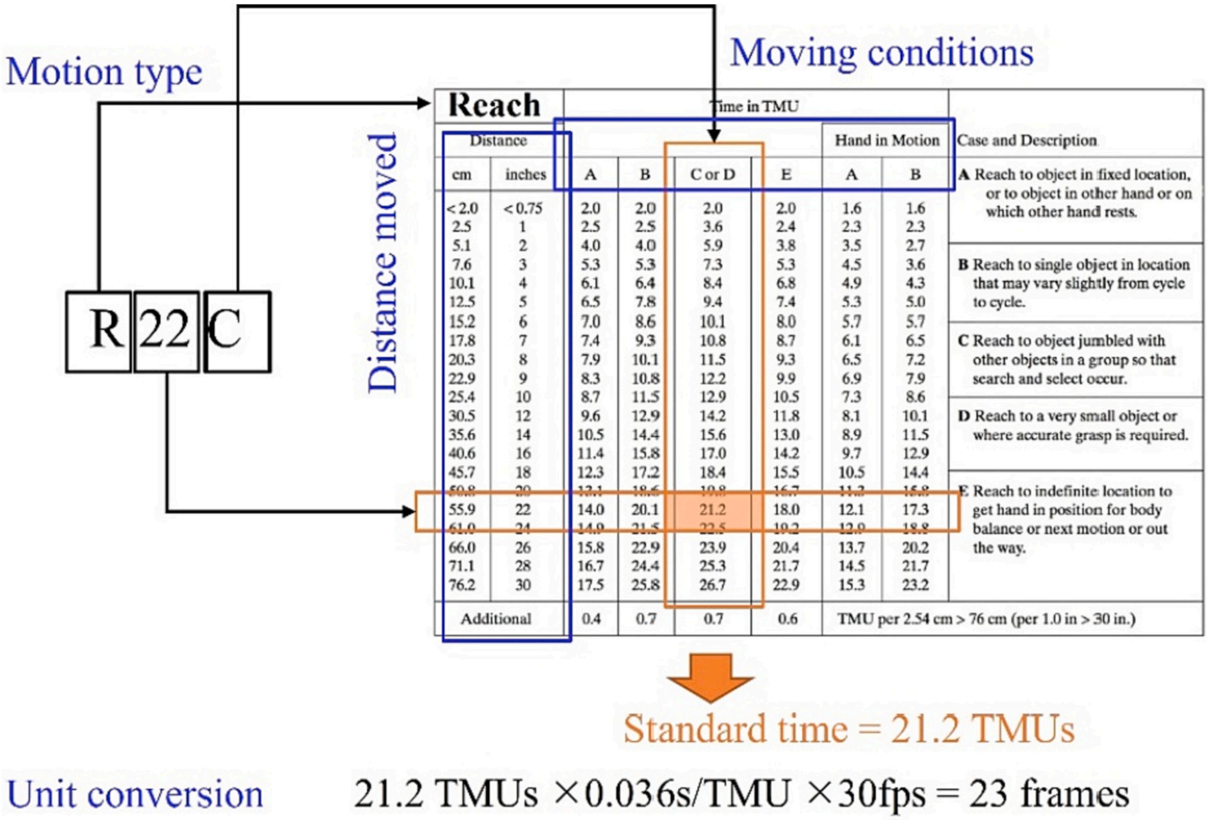


Fig. 5. Example of MTM-1 Codes, interpretation, and unit conversion.

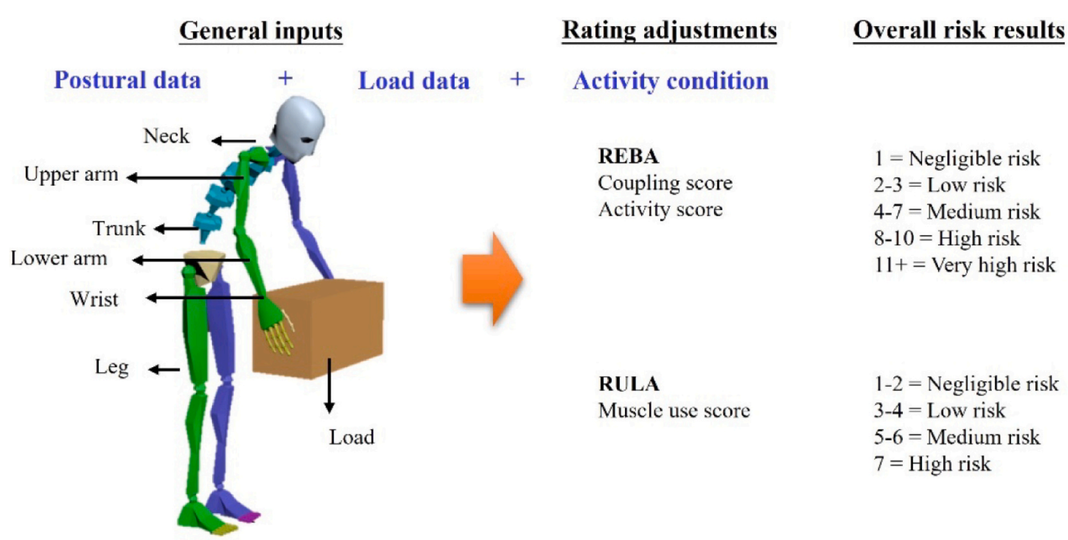


Fig. 6. Inputs and outputs of REBA and RULA.

file for all the postures at each time frame in time series; this is subsequently used in the risk and standard time mapping process.

3.3. Risk and standard time mapping

The ergonomic risks and standard times of the analyzed postures are mapped in order to generate accurate risk ratings for continuous motions. According to the standard time and animated time range of the identified motion, the standard times of each time frame in the animated frame range are calculated using the linear interpolation method. As shown in Fig. 7, the identified motion spans from the 1st frame to the 31st frame in the animation, corresponding to 15 frames in the standard motion time determination algorithm. Thus, the standard time in frame is scaled down from 31 frames to 15 frames using the linear interpolation method. Since the time frames are all integers, the standard time frames are rounded up to the nearest integer. With regard to the REBA and RULA scores, the same frames are deduplicated to obtain the risk scores associated with the standard time frames. It should be noted that the highest risk score is selected to represent the risk rating of the standard time frame during the deduplication process.

Fig. 8 presents the graphic results of the risk and standard time mapping process. As can be seen, the risk ratings in REBA and RULA are

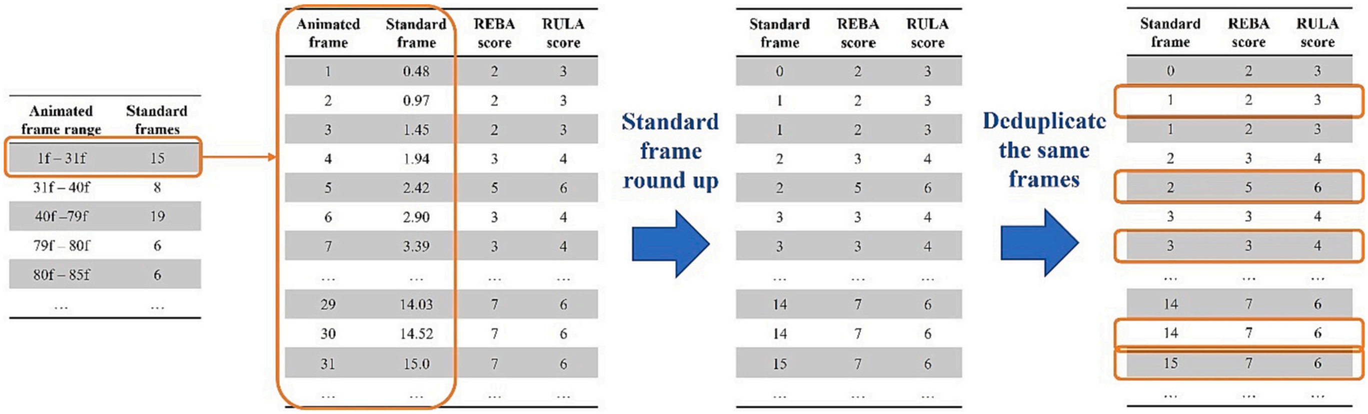


Fig. 7. Risk and standard time mapping process.

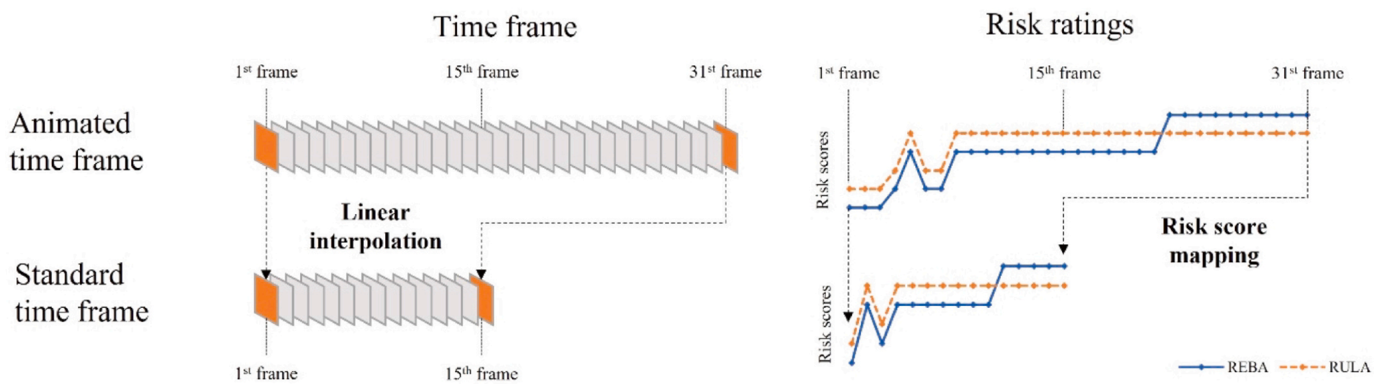


Fig. 8. Graphic results of risk and standard time mapping.

obtained at each time frame. These risk ratings still follow the same trend after being mapped with the standard motion time. After the mapping process, the average risk rating of continuous motions is calculated as the summation of risk ratings of continuous motions divided by the standard motion times, as shown in Eq. (6). The average risk rating is used as a key indicator for comparing the design alternatives. It should be noted that, with the exception of the average risk ratings, the activity condition is also time-related, meaning that standard motion time is required in order to ensure accurate ergonomic risk analysis.

$$Average\ risk\ rating = \frac{Sum\ of\ risk\ ratings}{Standard\ time} \quad (6)$$

4. Case study

The methodology developed in the present research is implemented in a case study to evaluate two proposed design alternatives for an existing workstation on a production line at a window manufacturing facility in Edmonton, Canada. In the case company's current practice, a worker operates for extended periods at a horizontal table with toolboxes placed underneath the table for easy access to screws and other hardware needed for hardware installation tasks. Back, neck, and shoulder pain have been self-reported by workers on this production line. Thus, the case company requested an on-site investigation to design a new workstation that mitigates the risk of developing WMSDs. To avoid interruptions of production and to avoid incurring costs for building prototypes, new workstation designs and the corresponding human motions are created in a 3D visualization environment in which the standard motion time-based ergonomic performance can be evaluated to support decision making with respect to the workstation design.

In this case, the installation of snubbers (i.e., hardware installed on the hinged side of the window frame to prevent bowing) is modeled for the evaluation of design alternatives. The case study focuses on the awkward body posture and standard motion time analysis rather than on heavy loads on the body, since the materials handled in this task are relatively small and lightweight. Two aspects of the research are implemented in this case study: (1) comparison of the standard motion time and animated time for each of the design alternatives; and (2) comparison of the standard motion time-based ergonomic risk ratings for different design alternatives to support decision making with respect to workstation design.

4.1. Workstation design alternatives

The workstation under consideration is used for hardware installation, including the installation of hinges, snubber, tie bar, handle, and operator. A notable finding of the ergonomic risk assessment carried out as part of the on-site investigation was that the maximum risk resulted from the forward bending and twisting of the neck and trunk of the worker to fit the working surface. The issues identified that may contribute to the development of WMSDs include that: (1) the worker tends to frequently assume neck and trunk-bending postures and twisted positions to reach across the working surface at the inner side of the window frames; (2) the worker tends to bend more for the trunk to reach the objects in the toolboxes underneath the table; and (3) the worker stands close to the edge of the table in order to lean forward to support the window frame for hardware installation, and this may exert pressure on the worker's body. The workstation modifications recommended to address the abovementioned issues include: (1) tilting the table to a sufficient angle to expose the working surface, thereby reducing the degree of bending and twisting of the body required on the part of the worker; and (2) introducing a practice of fixing the window frame to the workstation (using clamps) to reduce the pressure exerted on the worker as they use their body to support the weight of the window frame. Two new workstation designs are proposed, as presented in Table 2. The Case 1 design provides a supportive table (at a height of 85 cm) to assist with the hardware installation task. The panel is tilted to 20°, and the toolbox is located on top of the table due to the limited space under the table. In the Case 2 design, the panel is tilted to 60° and the toolbox remains under the table.

The human motions involved in completing the task are imitated in the 3D visualization for both design cases. These motions include: (1) picking up hardware from the shelf; (2) placing hardware in the target position on the window frame; (3) picking up screws from the box on the shelf; and (4) attaching hardware to the window frame using screws and an impact driver. The above processes are repeated until all hardware has been installed. The 3D human model simulations of both cases are shown in Fig. 9. The default settings for sizes of body segments are used, and the height of the subject is set as 163 cm, as this aligns approximately with both the worker's height in the actual case under study as well as the 50th percentile of female height in North America. It should be noted that although the motions used in current practice are used as a reference, the magnitudes of motions are adjusted according to the specifications of the proposed modified workstation scenarios. The speeds of motions are imitated based on the designer's experience and can then be adjusted to the standard motion times based using the proposed method. The snubber, as the smallest hardware component installed at this workstation, is selected as the component whose installation is to be modeled and analyzed in this case study.

4.2. Comparison of the standard motion time and animated time for design alternatives

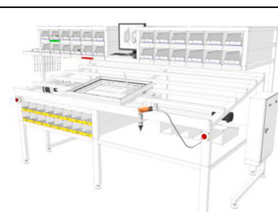
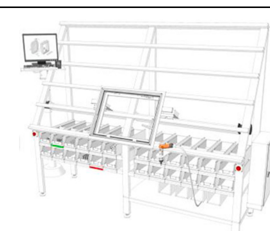
After being processed by the standard motion time determination algorithm, all the motions in the continuous movement and their standard motion times are generated and saved in a log file. In this case, there are 6 subtasks within the task of installing snubber on the window frame, which are the installation of 2 snubbers and 4 screws. As shown in Fig. 10, snubber installation includes the recognized motions of “reach”, “grasp”, “move”, “position”, and “release” using the non-dominant (in this case, left) hand and “move” with the screwdriver using the dominant (right) hand. The corresponding case types are generated based on working conditions to obtain the standard motion times. In this case, about 109 frames are animated for this subtask, corresponding to 73 frames based on the standard motion time determination algorithm. Moreover, the standard motion times of each respective motion in the subtask are generated.

In the case study, the task is animated with 575 frames and 554 frames for Case 1 and Case 2, respectively. Employing the proposed 3D-MEC method, the standard motion times are found to be 537 frames and 425 frames for Case 1 and Case 2, respectively. As shown in Table 3, reductions in standard motion times of approximately 6.6% and 23.3% are identified for Case 1 and Case 2, respectively. Here the animated times of the operation are longer than the standard motion times generated by the proposed method. Possible explanations for this include the following: (1) the detailed animations include both body postures and motion speed; (2) the recorded video reference may not be at a normal speed in the operation due to variations in the worker's real-world performance (e.g., fatigue, level of experience); and (3) the motion speed for the adjusted motion magnitude for each of the design alternatives is subject to the designer's experience and personal judgment. This example demonstrates that the proposed method can boost the reliability of workplace design by incorporating standard motion time information.

4.3. Comparison of the standard motion time-based ergonomic results for design alternatives

The ergonomic posture risk ratings for each of the design alternatives are evaluated at each frame for continuous motions and are further categorized into five risk levels for REBA and four risk levels for RULA. All the risk scores are generated and saved in the risk rating log file in the time series. As per the requirements of the proposed method, the standard motion time-based REBA and RULA risk scores are compared to risk scores from the 3D method (herein referred to as the baseline method), as presented in Fig. 11 and Fig. 12 for Case 1 and Case 2, respectively. The plotted risk rating curves, it should be noted, are moving forward along the axis of time frame, since the standard motion times are shorter than the animated times in both cases. For Case 1, the shapes of the respective risk rating curves in REBA and RULA are similar between the baseline method and the proposed method. The standard motion times are also about the same—about 19 s for the baseline method and about 18 s for the proposed method. Thus, it can be inferred that the standard motion time analysis slightly affects posture risk ratings in Case 1. However, the motion time decreases by about 4 s (from about 18 s to about 14 s) with application of the proposed method to Case 2. Since the 14-s duration of Case 2 meets the requirement of “4 times repeat per minute” in REBA and RULA, the risk rating adjustment score of the activity condition needs to be added. Thus, the shapes of the risk rating curves are altered in Case 2. The posture risk ratings and standard motion times are mapped for the same motions using linear interpolation. In this case, the risk ratings of 6 subtasks are matched between the baseline method and the proposed method, as shown in Fig. 11 and

Table 2
Summary of relevant workstation design specifications.

Workstation design	Case 1	Case 2
Shop drawing		
Table slope	20°	60°
Table dimensions	Length (x) = 2800 mm Height (y) = 850 mm Width (z) = 1500 mm	Length (x) = 2800 mm Height (y) = 850 mm Width (z) = 800 mm
Shelf dimensions	Length (x) = 3000 mm Height (y) = 1800 mm Width (z) = 1000 mm	Length (x) = 2800 mm Height (y) = 1000 mm Width (z) = 800 mm

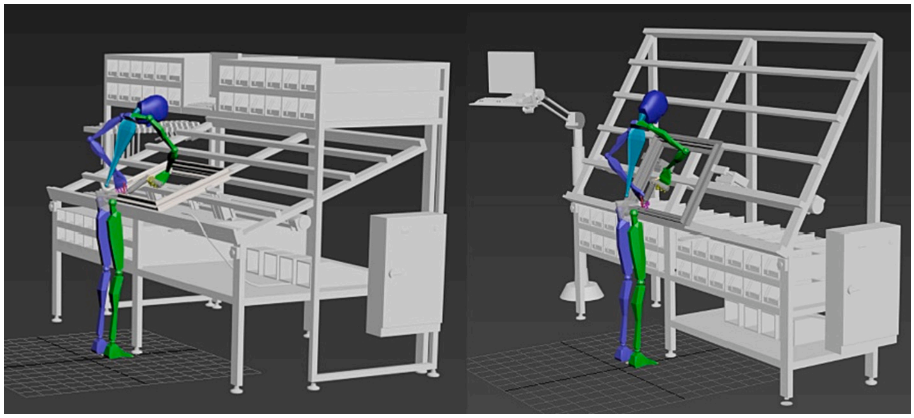
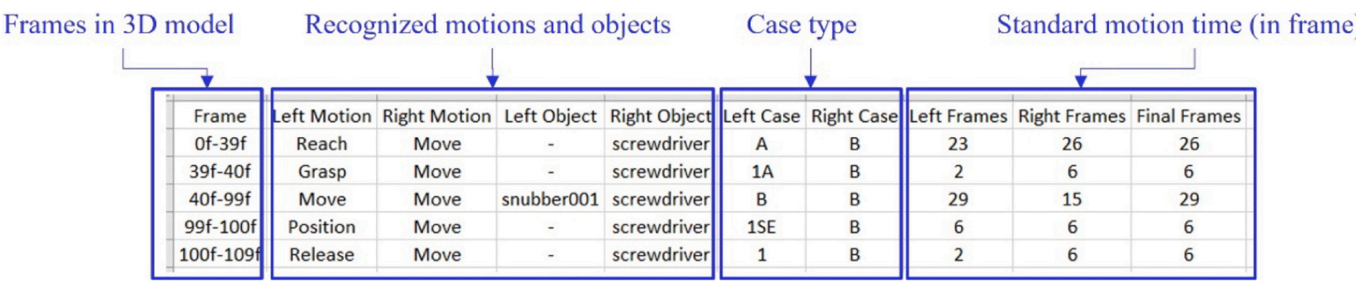


Fig. 9. 3D human model simulations of Case 1 and Case 2 designs.



Frame	Left Motion	Right Motion	Left Object	Right Object	Left Case	Right Case	Left Frames	Right Frames	Final Frames
0f-39f	Reach	Move	-	screwdriver	A	B	23	26	26
39f-40f	Grasp	Move	-	screwdriver	1A	B	2	6	6
40f-99f	Move	Move	snubber001	screwdriver	B	B	29	15	29
99f-100f	Position	Move	-	screwdriver	1SE	B	6	6	6
100f-109f	Release	Move	-	screwdriver	1	B	2	6	6

Fig. 10. Example of log file with recognized motions and standard motion time information.

Table 3
Comparison of standard time and animated time for design alternatives.

	Case 1	Case 2
Animated time (frame)	575	554
Standard time (frame)	537	425
Difference (%)	6.6%	23.3%

Fig. 12. However, the proportions of each posture in the continuous motion vary, and this could lead to variations in the shapes of the risk rating curves.

The results obtained from the posture risk assessment show that the average risks of the two cases in REBA are 5.77 and 5.30, respectively, meaning that both are at a “medium” risk level. As for RULA, the average risks of the two cases are 5.21 and 4.60, respectively, with workers being exposed to a “medium” risk level for Case 1 and a “low” risk level for Case 2. However, the posture risk ratings are mapped with the standard motion time in the proposed method, resulting in average risk ratings of 6.10 and 6.64 in REBA and 5.43 and 6.10 in RULA for Case 1 and Case 2, respectively. These average risk levels all correspond to a “medium” risk level. In comparing the average risk ratings between the two design alternatives, Case 2 yields the lower risk in the case of the baseline method, suggesting that this design alternative should be adopted for the workstation design, whereas Case 1 yields the lower risk in the proposed method. This example demonstrates that the incorporation of standard motion time, which is the critical difference between the baseline and the proposed method can affect decision making in workplace design.

In Case 1, the average risks in the case of the proposed method increase approximately 5.59% (REBA) and 4.22% (RULA). These slight increases in the average risks are a result of the minor decrease in the standard motion times in the case of the proposed method. In Case 2, the average risks increase by approximately 25.38% (REBA) and 32.50% (RULA). The possible reasons for the greater increases in average risks in the latter case include: (1) the 23.3% decrease in motion times in the case of the proposed method; and (2) the increases in the risk ratings of the adjusted activity scores caused by the high degree of repetitiveness for the motions in Case 2. As mentioned above, the activity condition is evaluated by the degree of repetitiveness, which corresponds to the motion time. Thus, the average risk ratings for Case 2 increase more rapidly following the incorporation of standard motion time. Table 4 summarizes the REBA and RULA risk ratings and risk levels with average, maximum, and minimum factors for the two cases.

As for the maximum and minimum risk ratings, they remain the same since the postures are the same in both methods, as indicated in Case 1. However, if the integration of standard motion time affects the activity condition, the increase in the degree of repetitiveness may in turn increase the maximum and minimum risk scores, and vice versa [29]. In addition, the detailed risk rating results of each body segment are found to be comparable between the baseline method and the proposed method with respect to both cases, as summarized in Table 5. The risk ratings of the upper arms and wrists are slightly higher in the proposed method than in the baseline, while the risk ratings for the neck see a slight decrease in the case of the proposed method. It can thus be inferred that the average risk ratings of each body segment are slightly affected by the integration of standard motion time when the motion times are comparable.

The proportion of motions at each risk level for the two cases varies between the baseline method and the proposed method, as shown in Table 6. Throughout the collective motions, no motion attains a risk level of 5 in REBA (or, correspondingly, the risk level of 1 in RULA) for either of the two cases in either of the two methods. In the baseline method, Case 1 is found to expose workers to the higher risk of the two cases considered (approximately 22.09% and 11.13% in REBA and RULA, respectively, compared to approximately 11.55% and 4.69%, respectively, for Case 2). Thus, according to the baseline method, the optimum choice for the task under investigation in the case study is Case 2. On the other hand, in the proposed method, the proportion of motions that are exposed to the risk level of 4 increases slightly when

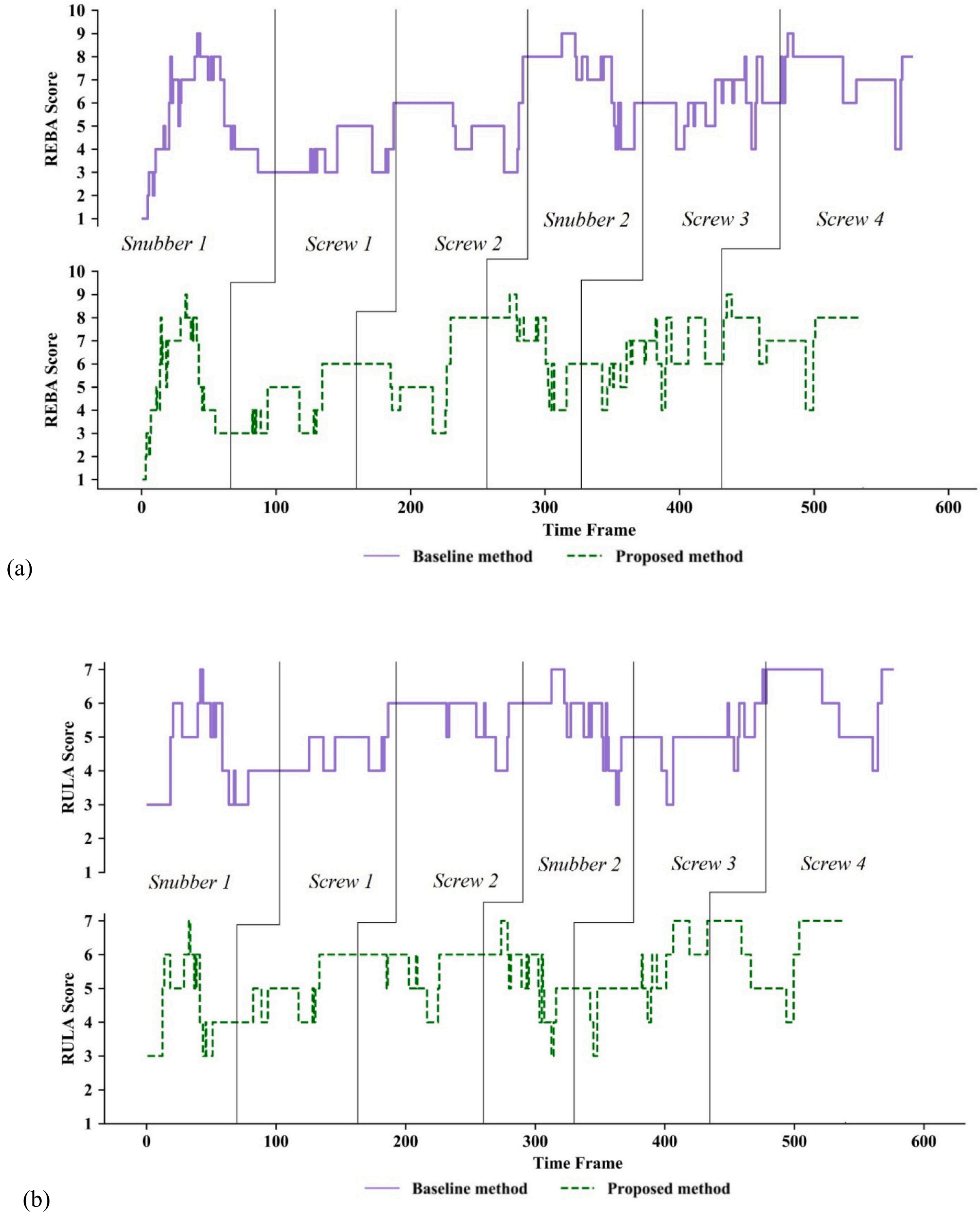


Fig. 11. REBA/RULA total risk rating comparison for Case 1: (a) REBA score; (b) RULA score.

implementing Case 1 (approximately 7.89% and 5.82% in REBA and RULA, respectively), whereas, when implementing Case 2, the proportion of motions at the risk level of 4 increases considerably (by 14.57% and 41.66% in REBA and RULA, respectively). Thus, with the integration of standard motion time in the proposed method, Case 1 is found to be the optimum choice for completing this task.

5. Discussion

Based on the task movement analysis results, the case study underscores the importance of integrating standard motion time into the framework for evaluating design alternatives and comparing ergonomic risk ratings to support decision making prior to the workstation design implementation. Based on the case study, it is recommended to have the working table tilted to 20° for the task of hardware installation as a design modification, as presented in Case 1. The worker in the Case 1

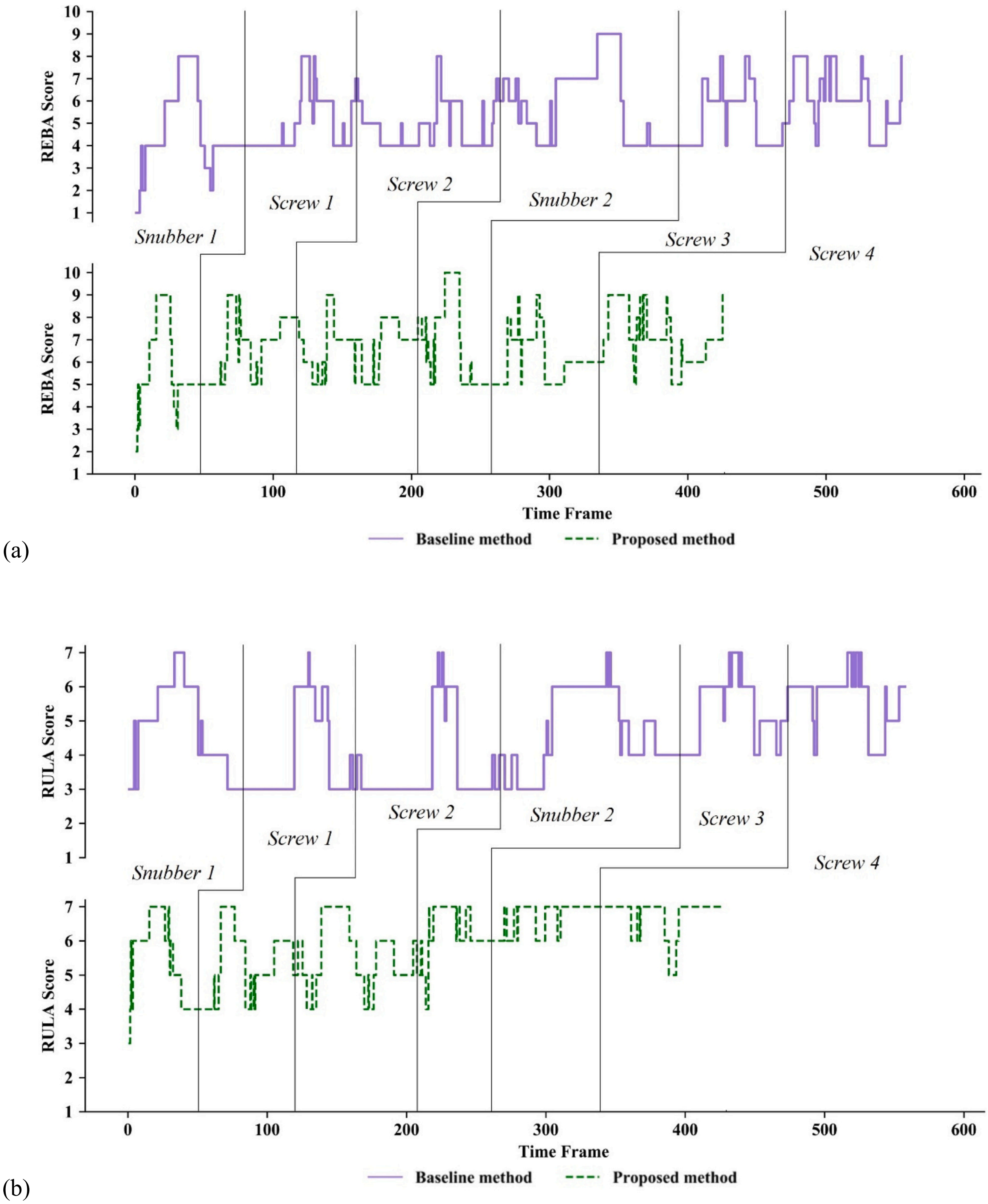


Fig. 12. REBA/RULA total risk rating comparison for Case 2: (a) REBA score; (b) RULA score.

design scenario is exposed to a lower risk rating compared to the worker in Case 2, meaning that Case 1 is the optimum choice for completing this task. In contrast, when applying the previously developed 3D method (i.e., baseline method), the optimum choice is Case 2. Thus, integrating the standard motion time into the 3D visualization can highly influence the ergonomic risk results and decision making with respect to selecting the optimum workplace design alternative. In other words, the incorporation of standard motion time is essential for 3D-based ergonomic analysis of continuous motions for workplace design.

The results also indicate that the proposed 3D-MEC method can consistently generate the standard motion time for ergonomic risk ratings of continuous motions, even though the detailed animations may obtain more time frames, or the rapid animation may contain fewer time frames in the 3D visualization. The proposed method is found to successfully achieve accurate motion capture, precise measurement of the required parameters, and reliable estimations of standard motion times. Moreover, the proposed method ensures consistency by providing standard motion times and objective and reliable risk ratings of continuous motions for the purpose of evaluating workplace design alternatives. The existing 3D method mainly relies on manual observation

Table 4
REBA and RULA results from two cases for baseline method and proposed method.

	Design	Case 1		Case 2	
	Factors	REBA	RULA	REBA	RULA
3D	Mean	5.77	5.21	5.30	4.60
	Max	9	7	9	7
	Min	1	3	1	3
	Risk level	3.07	2.86	3.09	2.54
3D-MEC	Mean	6.10	5.43	6.64	6.10
	Max	9	7	10	7
	Min	1	3	2	3
	Risk level	3.18	2.98	3.26	3.36

Table 5
REBA and RULA risk ratings of each body segment.

	Case 1				Case 2			
	REBA		RULA		REBA		RULA	
	3D	3D-MEC	3D	3D-MEC	3D	3D-MEC	3D	3D-MEC
Neck	1.05	1.03	1.19	1.13	1.38	1.33	2.17	2.02
Trunk	4.08	4.19	4.08	4.19	3.66	3.64	3.66	3.64
Legs	1.65	1.67	1.00	1.00	1.90	1.93	1.00	1.00
Upper Arm	3.05	3.15	3.05	3.15	2.28	2.55	2.28	2.55
Lower Arm	1.88	1.87	1.88	1.87	1.84	1.90	1.84	1.90
Wrist	2.62	2.68	3.62	3.68	2.50	2.64	3.50	3.64

and user experience for the collection of motion time data, meaning that the accuracy is generally low. Moreover, the traditional method fails to capture standard motion time, which defines the speed of motion and the degree of repetitiveness in continuous motions; this deficiency of the traditional 3D method also hampers the accuracy and utility of the resulting ergonomic risk ratings. By improving the accuracy of the ergonomic risks, standard motion time information greatly improves decision making with respect to workplace design in modular construction. In addition, the proposed method eliminates the reliance on time studies and on the designer's experience, thereby expediting the workplace design process.

To summarize, the contributions of this study include: (1) improving the level of automation and accuracy of risk rating results in 3D-based ergonomic risk assessment by integrating the standard motion time determination algorithm; (2) proposing a systematic method to obtain motion times of identified motions in a standard manner by implementing PMTS, which eliminates the human perception errors and subjectivity characteristic of traditional time studies; (3) providing objective standard motion times and the associated ergonomic risks of continuous motions, thereby leading to more accurate, reliable, and consistent workplace design; (4) achieving proactive workplace design in an efficient and cost-effective manner at the design stage without having to physically imitate the tasks or construct design prototypes; and (5) proposing a highly efficient method that reduces the time required for motion data collection (i.e., compared to real-world observation) and circumvents the interruptions to production for data collection or workplace reconstruction that would normally be associated with implementing ergonomic improvements to the existing workplace.

The research has some limitations that need to be resolved in future research. In the present research, the arm and hand motions are automatically identified and analyzed as part of the standard motion time determination, and this information is integrated with the ergonomic risk assessment to evaluate design alternatives. However, these arm and hand motions are not sufficient to represent 100% of all manual construction operations (e.g., walking between workstations, lifting objects from the floor to the working surface, etc.). Nevertheless, arm and hand motions are the primary motions in manual assembly tasks at workstations in modular construction, and these motions are characterized in detail in MTM-1, whereas full body motions, such as walking, bending, and stooping, are not described in detail in MTM-1. Moreover, eye motions and force-related motions (i.e., apply pressure and disengage) are excluded due to the limitations of 3D modeling. The proposed method applies MTM-1 for the integration of standard motion time with ergonomic risk assessment since it is the most detailed PMTS approach currently available. Other PMTSs, such as MOST and MODAPTS, can also be implemented to investigate they might achieve better performance with respect to integrating standard motion time with ergonomic risk assessment. In addition, due to the lack of real motion time data, statistical analyses are not applicable in this study. With enough real time data of each motion, additional statistical analyses could be applied to achieve more accurate results. Other promising avenues of future research include: (1) developing a standard motion time determination algorithm for full body motions to supplement the MTM-1 body motion categorization; and (2) incorporating full body motion assessment into the evaluation of workplace design, and considering multiple workstations rather than limiting the scope of the evaluation to single workstations.

6. Conclusions

Ergonomic risk assessment is the foundation on which an efficient and ergonomically sound workplace design is developed, since the occupational health condition of the workers is assessed and analyzed as the basis for decision making in this process. In order to improve the reliability and level of automation of ergonomic risk assessment of continuous motions, this research integrated predetermined motion time system with ergonomic posture assessments to automatically determine the motion time and compile the ergonomic risk results in terms of the standard motion time feature for workplace design. The main processes include rule-based motion recognition, the determination of standard motion time, and the integration of REBA and RULA-based ergonomic risk assessment. Integrating the standard motion time analysis into the proposed method ensures that the ergonomic risk

Table 6
REBA and RULA risk level comparison for the baseline method and proposed method.

	Design	Case 1			Case 2		
Method	Risk level	3D	3D-MEC	Difference	3D	3D-MEC	Difference
REBA	1	0.70%	0.37%	−0.32%	0.54%	0.00%	−0.54%
	2	13.57%	10.80%	−2.76%	1.62%	0.47%	−1.15%
	3	63.65%	58.85%	−4.81%	86.28%	73.41%	−12.87%
	4	22.09%	29.98%	7.89%	11.55%	26.12%	14.57%
	5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
RULA	1	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	2	24.70%	19.37%	−5.33%	50.54%	10.35%	−40.19%
	3	64.17%	63.69%	−0.49%	44.77%	43.29%	−1.47%
	4	11.13%	16.95%	5.82%	4.69%	46.35%	41.66%

assessment is efficient and reliable due to the fact that (1) the average risk ratings of the design alternatives are corrected and improved with the standard motion times of the working postures; and (2) the degree of repetitiveness of continuous motions is determined objectively based on the standard motion times.

A case study evaluating workstation design alternatives in an actual modular construction facility was performed based on the proposed method in order to validate its effectiveness and applicability. The findings indicate that the proposed 3D-MEC method can provide the standard motion time of hypothetical manual operations and can also be implemented to evaluate ergonomic risk ratings of continuous motions. The results also show that the integration of standard motion time allows for the standard motion time in MTM-1 to be associated with the animated motions, thereby improving the accuracy and reliability of the ergonomic risk results (i.e., the standard cycle times, average ergonomic risk ratings, and proportion of motions at each risk level for the associated design alternatives). This method identifies the optimum workstation design alternative so that in can be introduced in the existing workplace in the form of modified work. Furthermore, the proposed method provides a more reliable, less time-consuming, easy to apply, and cost-effective method to assess multiple design alternatives, since no physical imitation of tasks or motion data collection for design alternatives in the real-world implementation is required.

Declaration of Competing Interest

The authors declare there are no competing interests.

Data availability

All data generated or analyzed during the study are available from the corresponding author by request.

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