Ergonomic Risk Assessment Technology for Scaffolding Workers Using Real-Time Monocular 3D Pose Estimation

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Abstract -

Work-related musculoskeletal disorders (WMSDs) remain a major safety issue in construction, particularly for scaffolding workers who are repeatedly exposed to awkward and constrained postures. Conventional ergonomic assessment methods such as REBA and RULA rely on manual observation and static posture sampling, which limits their applicability for continuous monitoring in dynamic job sites. This study presents a vision-based ergonomic risk assessment framework using monocular RGB camera-based 3D pose estimation. The proposed approach automatically estimates three-dimensional joint angles, classifies construction-specific hazardous postures, and computes time-weighted cumulative REBA scores in real time. Experimental validation demonstrates strong agreement with expert assessments, confirming the feasibility of low-cost, non-contact ergonomic risk monitoring for proactive WMSDs prevention.

Keywords -

3D pose estimation; Ergonomic risk assessment; REBA; Construction safety; Scaffolding work

1 Introduction

Work-related musculoskeletal disorders (WMSDs) are widely reported as one of the most prevalent occupational health problems in the construction industry, according to recent occupational injury statistics and industry reports [1, 2]. Unlike acute injuries, WMSDs develop progressively due to cumulative biomechanical loading caused by repetitive motions, sustained non-neutral postures, and excessive joint loading. Scaffolding work has been identified as a high-risk activity for WMSDs due to frequent overhead operations, squatting, and trunk rotation, as highlighted in national and international occupational safety guidelines [3, 4]..

To identify and mitigate such risks, observational ergonomic assessment tools such as the Ovako Working Posture Analysis System (OWAS), Rapid Upper Limb Assessment (RULA), and Rapid Entire Body Assessment (REBA) have been widely applied in industrial and construction settings [5, 6, 7]. Although these methods provide structured scoring schemes for posture-related risk, their practical use on construction sites remains limited. Conventional assessments are typically based on snapshot observations and rely heavily on expert judgment, making them insufficient for capturing cumulative exposure and repetitive task characteristics while also limiting scalability for continuous monitoring [8].

Recent advances in computer vision have enabled automated posture analysis using camera-based systems, offering non-contact alternatives to both manual observation and wearable sensor approaches [9, 10]. Vision-based methods allow continuous monitoring without interfering with task execution, which is advantageous in dynamic construction environments. However, early studies predominantly relied on two-dimensional 2D pose estimation, where the absence of depth information leads to inaccurate joint angle estimation, particularly for tasks involving trunk bending, rotation, and overhead reach [11].

Three-dimensional 3D pose estimation techniques have been introduced to address these limitations by providing more accurate representations of human joint kinematics. While multi-view camera systems can achieve high accuracy, their deployment on construction sites is often impractical due to complex calibration requirements, high installation costs, and sensitivity to environmental changes [12]. Recent monocular 3D pose estimation approaches enable reconstruction of 3D human motion from a single RGB camera, significantly reducing system complexity [13, 14]. Despite this progress, most existing studies focus primarily on pose estimation accuracy, with limited integration into standardized ergonomic risk assessment frameworks or consideration of temporal exposure effects.

To address these gaps, this study proposes an auto-

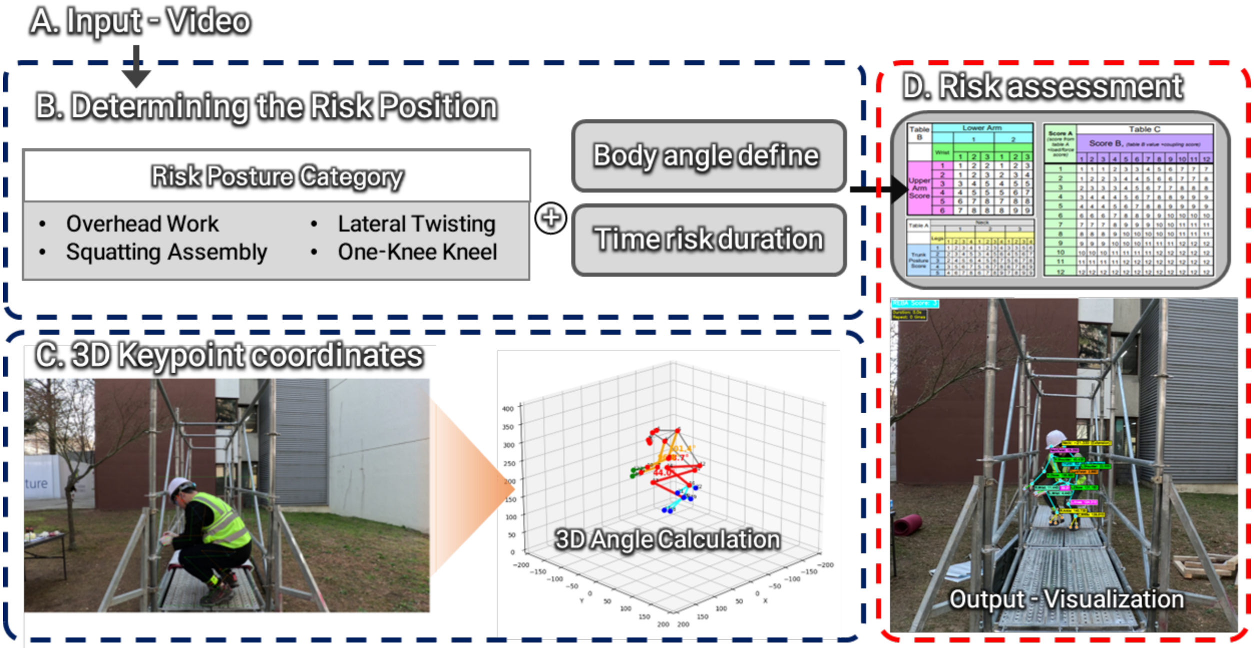

Figure 1. Workflow of the proposed postural risk assessment framework

mated ergonomic risk assessment framework for scaffolding workers based on monocular 3D pose estimation. The proposed approach integrates construction-specific risk posture definitions with REBA-based scoring and time-weighted cumulative risk evaluation, enabling continuous and objective assessment of WMSDs risk. By leveraging a single RGB camera, the framework minimizes deployment cost and operational complexity while supporting real-time monitoring in realistic construction environments. The overall workflow of the proposed system is illustrated in Fig. 1.

2 Related Work

Ergonomic risk assessment has traditionally relied on observational methods such as the OWAS, RULA, and REBA to identify hazardous work postures and prioritize intervention strategies [5, 6, 7]. These tools have been widely applied in industrial and construction contexts due to their simplicity and standardized scoring schemes. However, their effectiveness in dynamic construction environments is constrained by reliance on manual observation, evaluator subjectivity, and snapshot-based posture sampling, which limits their ability to represent cumulative exposure and repetitive task characteristics [8].

To overcome these limitations, vision-based ergonomic assessment approaches have been increasingly explored. Early studies primarily employed two-dimensional 2D pose estimation techniques to automate posture analysis using RGB cameras [9, 10]. While such approaches enable continuous, non-contact monitoring, the absence of depth information in 2D representations leads to significant inaccuracies in joint angle estimation, particularly for tasks involving trunk bending, rotation, and overhead work [11]. Consequently, the applicability of 2D based methods for construction ergonomics remains limited.

Recent advances in three-dimensional 3D human pose estimation have enabled more accurate reconstruction of joint kinematics. Multi-view camera systems have demonstrated high estimation accuracy but require complex calibration procedures and substantial installation effort, making them impractical for most construction sites [12]. In contrast, monocular 3D pose estimation methods can infer 3D joint positions from a single RGB camera, significantly reducing system complexity while maintaining acceptable accuracy [13, 14]. Despite these advances, existing studies have largely focused on pose estimation performance, with limited integration of monocular 3D pose data into standardized ergonomic risk assessment frameworks or explicit consideration of temporal exposure effects. This gap motivates the development of an automated, time-aware ergonomic assessment approach tailored to construction work environments.

3 Methodology

This study proposes a Risk-Posture-Defined 3D Pose (RPD-Pose3D) framework for automated ergonomic risk assessment of scaffolding workers using monocular RGB video. The proposed framework aims to provide an objective and reproducible evaluation of work-related musculoskeletal disorder (WMSDs) risk by explicitly formalizing construction-specific hazardous postures using joint-angle criteria, temporal exposure thresholds, and REBA-based risk levels. Figure 1 illustrates the overall workflow of the proposed system, while Table 1 defines the core posture-risk criteria adopted in this study.

3.1 System Overview and Monocular 3D Pose Estimation

The RPD-Pose3D framework consists of four sequential processing stages: monocular video acquisition, three-dimensional skeletal reconstruction, risk posture identification, and time-weighted ergonomic risk aggregation. A single RGB camera is used to capture full-body motion of scaffolding workers, which significantly reduces installation complexity and improves deployability in real construction environments compared with multi-camera or wearable sensor-based systems.

Each video frame is processed using monocular 3D human pose estimation to reconstruct three-dimensional joint coordinates. Compared with two-dimensional pose estimation, monocular 3D approaches provide depth-aware posture representations that are essential for accurately analyzing trunk flexion, shoulder elevation, and rotational movements frequently observed in scaffolding tasks [13, 12]. Although monocular 3D pose estimation is inherently ill-posed, recent learning-based methods have demonstrated sufficient accuracy for ergonomic analysis when combined with geometric constraints and temporal consistency.

To ensure robustness against camera viewpoint variations and worker orientation changes, a worker-centric coordinate system is adopted. The pelvis joint is defined as the origin, and body-aligned coordinate axes are constructed using hip and shoulder joints. This transformation enables consistent joint angle computation regardless of camera placement, viewing direction, or moderate self-occlusion, thereby improving the generalizability of the proposed framework across different scaffolding layouts and site conditions [14].

3.2 Risk Posture Definition Based on Joint-Angle Criteria

Scaffolding work is characterized by a limited set of postures that are repeatedly associated with elevated WMSDs risk. Based on international ergonomic guidelines and construction safety standards from KOSHA, OSHA, and EU-OSHA, four representative risk posture categories were identified: overhead work, squatting work, lateral twisting, and one-knee kneeling [3, 15, 4]. These postures are commonly sustained or repeatedly performed during scaffolding installation, inspection, and material handling tasks.

Each risk posture category is explicitly defined using joint-angle criteria rather than subjective visual descriptions. As summarized in Table 1, specific angular ranges are assigned to key joints such as the trunk, shoulder, knee, and ankle. For instance, overhead work is characterized by sustained shoulder elevation exceeding 90° combined with neck extension, whereas squatting work involves excessive knee flexion accompanied by trunk bending. By formalizing posture definitions in terms of joint kinematics, the proposed framework enables objective posture classification and reduces evaluator-dependent variability.

Rather than exhaustively modeling all possible body configurations, the proposed approach focuses on a limited number of representative high-risk postures. This design choice improves classification robustness and minimizes false detections caused by transient or non-risk-related movements, which are common in dynamic construction activities.

3.3 Temporal Exposure Criteria and REBA Risk Mapping

In addition to instantaneous joint configuration, WMSDs risk is strongly influenced by posture duration and repetition. To account for these temporal factors, both short-term posture duration thresholds and cumulative daily exposure limits are incorporated into the posture definition process. As shown in Table 1, each risk posture is associated with a short-term duration criterion (e.g., 30 s or 1 min) and a cumulative exposure limit (e.g., minutes or hours per day), reflecting established ergonomic recommendations.

When a detected posture satisfies both the joint-angle and duration criteria, a corresponding REBA risk score range is assigned. This mapping enables systematic translation of continuous posture observations into standardized ergonomic risk levels. Unlike conventional REBA assessments, which are typically conducted on isolated posture snapshots, the proposed approach integrates posture severity and temporal exposure into a unified risk evaluation framework [7, 16].

The adopted temporal thresholds are not intended to represent strict regulatory cutoffs, but rather practical reference values for continuous risk monitoring. By combining short-term posture persistence with cumulative exposure, the framework captures both acute and chronic risk characteristics, which are known to contribute differently to the development of WMSDs.

Table 1. Angle- and duration-based criteria with corresponding REBA risk levels for scaffolding work postures

Risk posture category	Joint-angle criteria	Short-term duration	Cumulative exposure limit	REBA score
Overhead work	Neck extension 20–30°, shoulder elevation > 90°, elbow flexion 90–120°	30 s	2 h/day	2–7
Squatting work	Knee flexion > 100°, trunk flexion 30–60°, ankle plantarflexion 10–35°	30 s	3 h/day	3–7
Lateral twisting	Trunk rotation > 20°, shoulder abduction 20–45°, neck lateral flexion 10–25°	1 min	15 min/day	3–7
One-knee kneeling	Knee flexion > 120°, ankle dorsiflexion 30–60°, trunk flexion 15–30°	1 min	10 min/day	3–7

3.4 Time-Weighted Cumulative Ergonomic Risk Assessment

To derive a cumulative ergonomic risk index, frame-level posture detections and associated REBA scores are aggregated over time using a time-weighted formulation. For each posture category, exposure duration is continuously accumulated and compared against the predefined limits in Table 1. Both the magnitude of the assigned REBA score and the length of exposure contribute to the cumulative risk index, enabling differentiation between short-duration high-risk postures and prolonged moderate-risk exposures.

Formally, the cumulative ergonomic risk is defined as a time-weighted average of frame-level REBA scores:

$$R = \frac{1}{\sum_{t=1}^{T} \Delta t} \sum_{t=1}^{T} s_t \cdot \Delta t \tag{1}$$

where s_t denotes the REBA score assigned at frame t, Δt represents the temporal interval between consecutive frames, and T is the total number of frames. The denominator corresponds to the total observation time, ensuring that the cumulative risk is normalized with respect to exposure duration.

This formulation integrates posture severity and temporal exposure into a unified metric, allowing the system to capture both instantaneous and accumulated ergonomic risk. As a result, it enables more accurate differentiation between transient high-risk postures and sustained risk conditions.

This time-weighted aggregation provides a more realistic representation of musculoskeletal loading compared with snapshot-based assessments and supports identification of critical task segments associated with elevated WMSDs risk. From a methodological perspective, the proposed RPD-Pose3D framework emphasizes transparency and reproducibility by explicitly defining posture criteria, temporal thresholds, and risk mapping rules. Unlike video data-driven approaches, the rule-based structure of the proposed method facilitates interpretability and enables direct validation against established ergonomic assessment principles. This characteristic is particularly important for safety-critical applications in construction, where explainable risk indicators are essential for decision-making by site managers and safety practitioners.

4 Experimental Validation

This section presents the experimental validation of the proposed RPD-Pose3D framework to evaluate its effectiveness in posture classification and ergonomic risk assessment for scaffolding work. The validation focuses on both quantitative performance metrics and qualitative visualization results to demonstrate the robustness and practical applicability of the proposed method.

4.1 Experimental Setup

To validate the proposed framework, a video dataset representing typical scaffolding work activities was collected in a controlled experimental environment designed to replicate realistic construction conditions. To minimize occlusion, a monocular RGB camera was positioned at the side to capture full-body movements of the worker during task execution.

Two representative high-risk scenarios—squatting work and overhead work—were selected, as these postures are frequently observed in scaffolding operations and are closely associated with WMSDs. To ensure sufficient data variability and capture diverse posture variations and motion transitions, each task was performed more than 10 times by the worker.

The selected experimental scenarios inherently include variations of other defined posture categories. In particular, squatting work and overhead work were chosen as the primary evaluation scenarios because they represent the most frequently observed and ergonomically significant WMSDs-inducing postures in scaffolding operations. These two postures serve as dominant task configurations in which workers spend the majority of their operational time.

The remaining posture categories, namely lateral twisting and one-knee kneeling, are not independent task types but are typically embedded within these primary working conditions. Specifically, lateral twisting frequently occurs as a natural component of overhead work due to trunk rotation during installation tasks, while one-knee kneeling appears as a transitional or supportive posture within squatting-based assembly activities.

Therefore, rather than evaluating each posture category in isolation, the selected scenarios provide a more realistic representation of construction workflows, where multiple posture variations coexist within a single task. Based on this observation, we consider that separate evaluation of lateral twisting and one-knee kneeling is not necessary, as their effects are implicitly reflected in the performance under the primary scenarios.

This design enables comprehensive validation of the proposed framework under practical working conditions while maintaining a focused evaluation on the most representative and high-impact WMSDs-inducing postures.

For 3D pose estimation, the proposed RPD-Pose3D framework adopted a pre-trained monocular 3D human pose estimation model and fine-tuned it using the collected construction-specific dataset. This transfer learning approach enabled the model to better generalize to scaffolding work environments while leveraging the robust feature representations learned from large-scale general-purpose pose datasets.

All recorded video sequences were processed frame-by-frame using the proposed RPD-Pose3D framework to extract 3D skeletal keypoints and compute joint-angle information. The extracted joint angles included key body segments such as the trunk, neck, upper arms, lower arms, and knees, which are critical indicators for ergonomic risk assessment. These encompass all the body joint angles necessary for evaluating the ergonomic risk of scaffolding workers at construction sites.

For quantitative evaluation, ground-truth posture labels were assigned by ergonomics experts based on the joint-angle and temporal criteria defined in Table 1. The REBA scoring process involved frame-by-frame review of the video sequences, where experts evaluated each frame according to the predefined angular thresholds for each body segment. Based on the cumulative risk scores, each frame was categorized into ordinal risk levels (Stable, Risk, and High Risk), and these annotations were used as reference labels for performance evaluation.

4.2 Quantitative Performance Evaluation

The posture classification performance of the proposed framework was evaluated using normalized confusion matrices and standard classification metrics, including overall accuracy, weighted precision, weighted recall, and weighted F1-score. Figure 2 illustrates the normalized confusion matrices for squatting and overhead work scenarios.

As shown in Fig. 2(a), the proposed method achieved high classification consistency for squatting work, with most samples correctly classified and minimal confusion with other posture categories. In contrast, Fig. 2(b) indicates relatively higher misclassification rates for overhead work, which can be attributed to increased depth ambiguity and self-occlusion caused by sustained arm elevation and upper-body rotation.

Table 2 summarizes the quantitative performance metrics for both work scenarios. The proposed framework achieved an overall accuracy of 88.89% for squatting tasks and 80.87% for overhead tasks. Higher weighted precision and F1-score were observed for squatting work, indicating more stable joint-angle estimation and posture recognition under lower occlusion conditions. Despite the increased visual complexity of overhead work, the classification performance remained sufficiently robust to support automated ergonomic risk assessment.

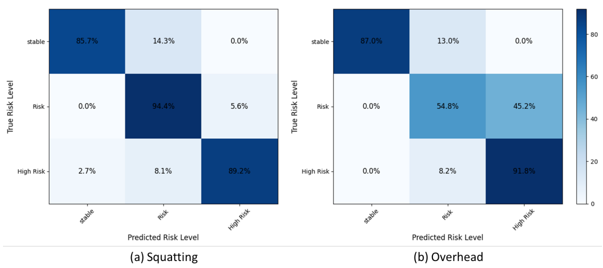

Figure 2. Normalized confusion matrices for RPD-Pose3D performance evaluation: (a) squatting work, (b) overhead work

4.3 Qualitative Visualization Results

To further examine the practical behavior of the proposed framework, qualitative visualization results were analyzed. Figures 3 and 4 present representative examples of squatting and overhead work scenarios, respectively. In each visualization, the estimated 3D skeleton, joint-angle configuration, and detected risk posture are overlaid on the original video frames.

For squatting work (Fig. 3), the proposed method successfully captured excessive knee and hip flexion accompanied by trunk bending, resulting in stable posture classification and consistent risk detection. For overhead work (Fig. 4), the framework accurately identified sustained shoulder elevation and neck extension, even under partial self-occlusion. These results demonstrate that the proposed monocular 3D pose-based approach can effectively interpret complex scaffolding postures without requiring multi-view camera setups or wearable sensors.

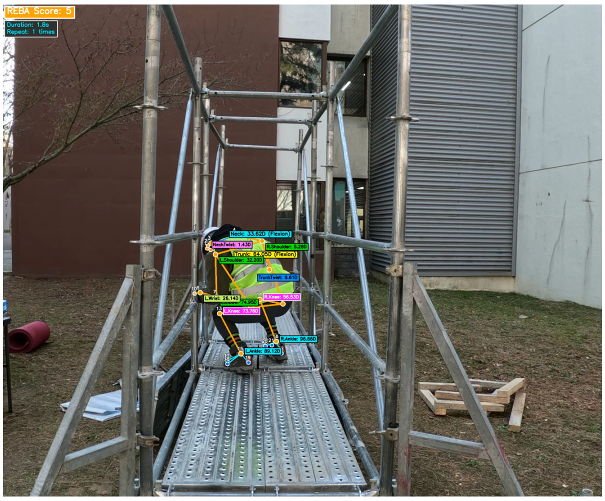

Figure 3. Squatting

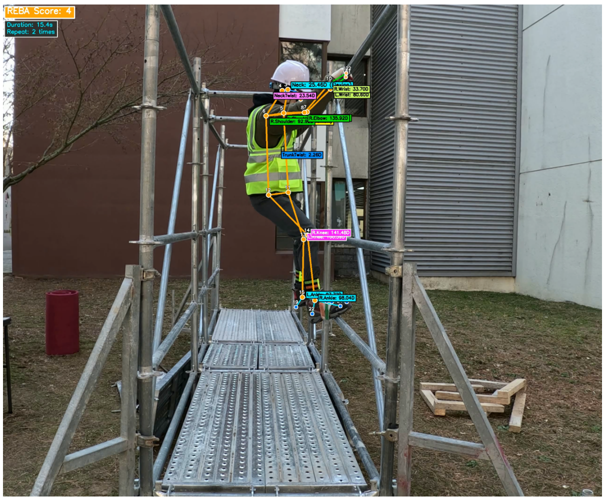

Figure 4. Overhead

4.4 Discussion of Validation Results

The experimental results confirm that the proposed RPD-Pose3D framework can reliably classify high-risk scaffolding postures and support time-weighted ergonomic risk assessment using a single RGB camera. While overhead work exhibited relatively lower classification performance compared with squatting work, this limitation reflects inherent visual challenges rather than methodological instability. Importantly, the observed performance remains sufficient for practical risk monitoring, particularly when combined with the cumulative exposure criteria defined in Table 1.

Overall, the experimental validation demonstrates that the proposed framework effectively bridges the gap between monocular 3D pose estimation and standardized ergonomic assessment, providing a scalable and explainable solution for WMSDs risk monitoring in scaffolding work environments.

Table 2. Classification performance metrics for different work scenarios

Performance Metric	Squatting Task	Overhead Task
Overall accuracy	88.89%	80.87%
Weighted precision	91.14%	80.77%
Weighted recall	88.89%	80.87%
Weighted F1-score	89.38%	80.32%

5 Discussion

The experimental validation results demonstrate that the proposed RPD-Pose3D framework can effectively classify high-risk scaffolding postures and support automated ergonomic risk assessment using a single RGB camera. The achieved classification performance indicates that monocular 3D pose estimation, when combined with explicitly defined posture and temporal criteria, provides sufficient accuracy for practical WMSDs risk monitoring in construction environments.

The relatively higher classification performance observed for squatting work compared with overhead work can be attributed to differences in visual complexity and joint visibility. Squatting postures primarily involve lower-body joint flexion with relatively stable body orientation, resulting in more reliable joint-angle estimation. In contrast, overhead work often induces upper-body self-occlusion, extreme shoulder elevation, and trunk rotation, which are well-known challenges in monocular 3D pose estimation [12, 14]. Despite these challenges, the proposed framework maintained robust performance for overhead tasks, indicating that the integration of 3D joint information and temporal exposure criteria mitigates transient estimation errors.

An important contribution of this study lies in the explicit formalization of ergonomic assessment criteria. Unlike black-box data-driven approaches, the proposed method defines risk postures using interpretable joint-angle thresholds, exposure durations, and REBA-based risk levels. This rule-based structure enhances transparency and facilitates validation against established ergonomic principles, which is particularly important for safety-critical applications where explainable risk indicators are required for decision-making by site managers and safety practitioners.

The incorporation of time-weighted cumulative risk assessment further distinguishes the proposed framework from conventional snapshot-based ergonomic evaluations. The emphasis on cumulative exposure and posture duration is consistent with ergonomic studies reporting that WMSDs risk is strongly associated with prolonged and repetitive postural loading rather than isolated peak events [16]. By jointly considering posture severity and exposure duration, the framework provides a more realistic representation of musculoskeletal loading and supports identification of prolonged moderate-risk exposures that may be overlooked by instantaneous assessments.

Several limitations should be acknowledged. First, the experimental validation was conducted in a controlled environment with a limited number of task scenarios, which may not fully capture the variability present in real construction sites. Second, monocular 3D pose estimation remains sensitive to severe occlusion and extreme camera viewpoints, which can affect joint-angle accuracy in complex work conditions. Future work will focus on large-scale field deployment, adaptive threshold calibration, and integration with real-time feedback mechanisms to further enhance robustness and practical applicability.

6 Conclusion

This study presented an automated ergonomic risk assessment framework, termed RPD-Pose3D, for scaffolding workers based on monocular 3D human pose estimation. The proposed framework integrates construction-specific risk posture definitions, joint-angle-based posture interpretation, temporal exposure criteria, and REBA-based risk mapping to enable continuous and objective evaluation of work-related musculoskeletal disorder (WMSDs) risk using a single RGB camera.

By explicitly formalizing hazardous scaffolding postures and incorporating time-weighted cumulative risk assessment, the proposed approach addresses key limitations of conventional snapshot-based ergonomic evaluations. Experimental validation demonstrated that the framework can reliably classify high-risk postures and provide meaningful ergonomic risk indicators under realistic work scenarios, even in the presence of partial occlusion and viewpoint variability.

A key strength of the proposed RPD-Pose3D framework lies in its transparency and interpretability. Unlike black-box data-driven approaches, the rule-based structure allows direct validation against established ergonomic principles and facilitates practical adoption by safety managers and practitioners. By leveraging monocular 3D pose estimation, the proposed framework aligns with recent research trends toward low-cost and scalable vision-based ergonomic assessment systems for real-world work environments [13, 11].

Future work will focus on large-scale field deployment to further validate robustness under diverse site conditions, adaptive calibration of posture and duration thresholds, and integration with real-time feedback or digital twin-based safety management systems. Overall, the proposed framework provides a practical and scalable solution for proactive WMSDs risk monitoring and prevention in scaffolding work environments.

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