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A Structural Relative Motion Modeling Approach for Vision-Based CPR Performance Evaluation

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ABSTRACT

This paper presents a comprehensive structural relative motion modeling framework designed to enhance the accuracy and reliability of vision-based Cardiopulmonary Resuscitation (CPR) training systems. While conventional computer vision approaches have shown potential in monitoring CPR maneuvers, they frequently suffer from significant measurement distortions—such as cosine loss—caused by camera viewpoint dependency and the lack of physical sensors. To address these critical limitations, we introduce a novel normalization technique that utilizes a relative motion vector, c(t), defined within a body-centered reference frame to ensure viewpoint-invariant performance evaluation. The technical feasibility and robust performance of the proposed framework were rigorously validated through a series of comparative simulations. Our findings demonstrate that while conventional absolute coordinate-based methods exhibit a precision drop of up to 30% when the camera angle shifts to 45°, the proposed normalized relative depth indicator (d(t)) maintains high measurement consistency regardless of the filming perspective. Furthermore, this study introduces a directional stability assessment through vector distribution analysis. By defining a 'Stability Zone' around the mean compression vector, the system can quantitatively evaluate the structural integrity of a trainee's posture, offering sophisticated qualitative feedback that goes beyond simple depth metrics. The results of this study indicate that the proposed modeling approach can effectively substitute for expensive, sensor-integrated manikins, providing a scalable and high-fidelity solution for public health education. By enabling precise, sensor-free analysis from a single camera stream, this framework establishes a solid theoretical and practical foundation for democratizing high-quality CPR training in unconstrained and remote learning environments.

KEYWORDS: CPR education, Vision-based CPR evaluation, Relative motion modelling, Compression depth analysis, Emergency medical education.

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INTRODUCTION

Cardiovascular diseases remain a leading cause of mortality worldwide, with out-of-hospital cardiac arrest (OHCA) being a critical public health challenge [1]. Immediate and high-quality Cardiopulmonary Resuscitation (CPR) is the most decisive factor in increasing the survival rate of victims. However, the quality of CPR performed by bystanders often falls short of the recommended guidelines, emphasizing the need for continuous and accessible training. Traditionally, CPR education has relied on expensive, sensor-integrated manikins that provide real-time feedback [2]. While effective, the high cost and lack of portability of these systems limit their scalability for large-scale public health education, particularly in home-based or remote learning environments.

To overcome these barriers, vision-based motion analysis systems have emerged as a promising alternative [3]. By utilizing the cameras embedded in smartphones or tablets, these systems aim to provide feedback on compression depth and rhythm without the need for specialized hardware. Despite their potential, conventional vision-based approaches face a critical technical challenge: viewpoint dependency. Most existing algorithms rely on absolute coordinate systems to measure hand displacement. This results in significant projection errors, such as cosine loss, where the measured compression depth is underestimated as the camera angle deviates from a direct frontal view. Such inaccuracies can lead to incorrect feedback, potentially reinforcing improper CPR techniques during self-training.

Furthermore, most vision-based systems focus primarily on quantitative metrics like depth and frequency, often neglecting the structural stability of the compression motion. High-quality CPR requires not only sufficient depth but also consistent vertical force application. A lack of directional stability can reduce the efficiency of chest compressions and increase the risk of injury to the victim. Therefore, there is a pressing need for a robust modeling approach that remains invariant to environmental changes while providing qualitative insights into the trainee's postural stability.

In this paper, we propose a structural relative motion modeling framework designed to ensure viewpoint-invariant CPR performance evaluation. The core of our approach lies in shifting the analytical reference from an absolute global coordinate system to a relative, body-centered reference frame. By introducing a normalized relative depth indicator ($d(t)$), we aim to eliminate the distortions caused by camera positioning.

The primary contribution of this research is the analytical validation of the proposed framework through rigorous simulation. Unlike previous conceptual proposals, this study demonstrates the technical feasibility of the model by comparing its performance against conventional methods under varying camera angles ($0° \ to \ 45°$). Additionally, we introduce a novel method for evaluating postural integrity through vector distribution analysis, defining a 'Stability Zone' to provide structural feedback. Through this comprehensive modeling approach, we provide a solid theoretical and empirical foundation for a high-fidelity, sensor-less CPR training system that can be deployed across diverse real-world scenarios.

RELATED WORK

A. Sensor-Based CPR Training and Assessment Systems

Sensor-based CPR training and assessment systems have long been regarded as the standard approach for objectively evaluating compression depth, rate, and recoil during cardiopulmonary resuscitation. Commercial CPR mannequins equipped with pressure sensors, force transducers, or embedded accelerometers can provide precise numerical measurements and real-time feedback to trainees. Such systems are widely adopted in formal CPR certification programs and clinical training environments due to their measurement accuracy and alignment with international resuscitation guidelines [4][5].

Despite their technical reliability, sensor-based approaches present several limitations when applied to practical educational settings. First, they require specialized equipment, including sensor-embedded mannequins or wearable sensing devices, which significantly increases cost and limits scalability. Second, the setup and maintenance of these systems impose operational complexity, making them less suitable for repeated practice sessions, large-scale training programs, or resource-limited environments. Third, sensor-based feedback is often presented as absolute numerical values, which can be difficult for novice learners to interpret in terms of posture control, movement stability, or body mechanics during CPR performance.

Previous studies have shown that although accurate depth estimation is achievable using accelerometer-based signal processing or pressure sensor fusion, such approaches are inherently constrained by device placement, calibration requirements, and sensitivity to sensor drift or misalignment [4]. As a result, sensor-based systems, while effective for quantitative evaluation, exhibit limited flexibility and educational interpretability in real-world CPR training contexts.

B. Non-Contact CPR Motion Analysis

To overcome the physical and logistical constraints of sensor-based systems, recent research has increasingly explored non-contact CPR analysis methods based on computer vision and motion recognition techniques. These approaches typically employ RGB cameras, depth sensors, or pose estimation algorithms to capture upper-body movements during CPR performance, enabling compression analysis without requiring physical contact or wearable devices [6][7].

Vision-based CPR analysis methods offer notable advantages in terms of accessibility and learner comfort. By eliminating wearable sensors, these systems reduce physical burden and allow more natural CPR practice. Several studies have demonstrated the feasibility of estimating compression rhythm, posture consistency, and approximate compression depth using joint trajectories or vertical displacement of the upper body [2][3].

However, many existing non-contact approaches rely heavily on absolute coordinate systems or fixed camera viewpoints. For instance, compression depth is often estimated by measuring vertical displacement along a predefined axis relative to the camera frame. Such assumptions introduce vulnerability to changes in camera placement, viewing angle, and rescuer orientation. In realistic training environments, where camera positions cannot be strictly controlled and rescuers may shift their stance during CPR, these methods may suffer from degraded accuracy and inconsistent analysis results [7][8].

Furthermore, some vision-based systems implicitly assume that CPR motions are observed from a frontal or lateral perspective, which limits their applicability in omnidirectional or unconstrained training scenarios. Consequently, while non-contact CPR analysis has demonstrated promising potential, robustness against viewpoint variation and rescuer positional changes remains a critical challenge.

C. Limitations of Absolute-Coordinate-Based Motion Analysis

Both sensor-based and vision-based CPR analysis methods commonly rely on absolute measurements, whether in physical space (e.g., displacement in centimeters) or camera-centered coordinate systems. Although absolute metrics are useful for standardized evaluation, they do not adequately account for individual differences in body size, posture, or movement style. As a result, absolute-coordinate-based analysis may conflate meaningful compression characteristics with inter-individual physical variability.

Moreover, absolute-coordinate approaches are inherently sensitive to external factors such as camera orientation, sensor alignment, and environmental setup. In educational contexts, where training conditions vary widely across classrooms, simulation labs, and informal learning spaces, such sensitivity limits the generalizability and scalability of CPR assessment systems.

Several prior studies have acknowledged these issues and suggested the need for more robust representations of CPR motion that emphasize relational or structural characteristics rather than absolute positions [9]. However, systematic frameworks that explicitly model CPR compression actions using relative body movement relationships remain limited

D. Research Gap and Distinction of This Study

In contrast to prior work, this study focuses on modeling CPR compression actions through relative body movement relationships among the rescuer's upper-body segments. Rather than relying on absolute coordinates or fixed reference frames, the proposed framework defines CPR compression depth and stability using relative vectors between an upper-body reference point and the hand position.

This relative representation offers several key advantages. First, it inherently reduces sensitivity to camera viewpoint and rescuer orientation, enabling omnidirectional analysis under unconstrained training conditions. Second, by normalizing relative displacement, the framework mitigates inter-individual physical differences, allowing consistent comparison of compression quality across learners. Third, relative vector modeling facilitates interpretation of directional stability and movement consistency, which are critical but often overlooked aspects of CPR education.

Unlike existing approaches that prioritize numerical precision alone, the proposed framework emphasizes educational interpretability and structural understanding of CPR motions. By translating relative motion characteristics into intuitive feedback indicators, the framework bridges the gap between motion analysis and practical CPR training needs.

Accordingly, this study contributes a design-oriented, non-contact, and direction-independent CPR compression analysis framework that complements existing sensor-based and vision-based approaches while addressing their key limitations in educational scalability and robustness.

E. Viewpoint Robustness in Vision-Based Human Motion Analysis

In vision-based human motion analysis, dependence on absolute or camera-centered coordinate systems has been widely recognized as a fundamental limitation, particularly in unconstrained environments. When motion descriptors are defined with respect to a fixed global axis, variations in camera viewpoint, orientation, and subject positioning can introduce substantial distortion in motion interpretation. Such sensitivity poses a critical challenge for real-world training scenarios, where strict control of recording conditions is often impractical.

To address this issue, prior research has explored motion representations that emphasize relational or body-centered characteristics rather than absolute spatial positions. Studies in skeletal motion analysis demonstrate that relative relationships between body joints provide more stable descriptors under viewpoint variation, as they preserve intrinsic motion structure regardless of observation direction [10]. By modeling motion through joint-to-joint relationships, these approaches reduce dependency on camera alignment and global coordinate definitions.

Subsequent work has further shown that relative skeletal representations remain robust even when camera placement varies across sessions or environments [11]. These findings suggest that relational motion descriptors are particularly suitable for applications deployed in heterogeneous physical settings, such as classrooms or training facilities, where camera viewpoints cannot be standardized.

Although these studies were not conducted in CPR-specific contexts, they provide an important theoretical foundation for designing motion analysis frameworks that must operate reliably under changing viewpoints and subject orientations.

F. Relative Motion Modeling for Repetitive and Cyclic Skill Assessment

Beyond robustness to viewpoint variation, relative motion representations have been widely adopted for the assessment of repetitive and cyclic motor skills. In many performance-oriented tasks, skill quality is defined not by isolated movement instances, but by the consistency, stability, and rhythmic regularity of repeated actions over time.

Research in vision-based motion analysis and biomechanics has consistently shown that relative joint coordination patterns capture essential aspects of skilled performance more effectively than absolute positional measures [12]. Reviews of motion analysis techniques emphasize that stable relational patterns between joints are closely associated with movement efficiency, coordination, and motor control, particularly in repetitive tasks.

In cyclic upper-body motion analysis, temporal regularity and directional stability have been identified as key indicators of motion quality. Relative representations enable these characteristics to be evaluated without requiring precise spatial calibration or standardized sensor placement, making them suitable for environments with diverse recording conditions [12]. This perspective aligns well with the characteristics of CPR compressions, which involve repetitive upper-body motion with strict requirements for consistency and rhythm.

G. Educational Interpretability in Motion-Based Training Feedback

In addition to analytical robustness, educational research has increasingly emphasized the importance of feedback interpretability in skill acquisition. In training-oriented systems, feedback that supports understanding of movement structure has been shown to promote deeper learning and more effective self-correction than purely numerical performance indicators.

Motor learning research indicates that feedback directing learners' attention toward meaningful aspects of movement coordination and stability enhances motivation and learning outcomes [13]. Such feedback helps learners understand why a movement is inadequate, rather than merely indicating that it fails to meet a predefined numerical threshold.

Within medical education, studies on CPR training similarly report that feedback effectiveness depends not only on measurement accuracy, but also on clarity and interpretability. Systematic reviews of CPR feedback devices highlight that while feedback generally improves performance, learner outcomes are strongly influenced by how feedback information is presented [14]. Comparative studies of CPR instructional modalities further emphasize that understandable and actionable feedback plays a critical role in skill retention and performance improvement [15].
These findings suggest that CPR training systems should prioritize feedback designs that reflect motion stability and consistency over time, rather than focusing exclusively on absolute depth measurements.

H. Implications for Non-Contact and Scalable CPR Training Systems

The convergence of research on viewpoint-robust motion analysis, relative representation of repetitive skills, and educational feedback design highlights important implications for CPR training system development. Existing CPR assessment approaches, whether sensor-based or vision-based, often remain tightly coupled to absolute measurements or hardware-dependent configurations.

Guidelines for CPR education emphasize the need for scalable training solutions that support repeated practice and consistent skill improvement across diverse learning environments [16]. However, equipment-intensive systems may impose practical constraints related to cost, setup complexity, and accessibility, particularly in large-scale or resource-limited training contexts.

Prior work in human motion analysis and motor learning suggests that relative, body-centered motion representations can mitigate these limitations by enabling robust motion interpretation under unconstrained conditions while supporting educationally interpretable feedback generation. These characteristics align closely with the requirements of non-contact CPR education systems, where adaptability and interpretability are essential.

I. Summary and Research Positioning

Taken together, existing literature provides substantial theoretical support for the use of relative motion modeling and interpretable feedback design in skill-oriented training systems. Prior studies in human motion analysis indicate that relational and body-centered representations offer improved robustness against viewpoint variation and environmental constraints, while research in motor learning emphasizes the importance of feedback that supports learners' understanding of movement structure and consistency.

Nevertheless, the application of these principles to CPR compression depth analysis remains limited. Most existing CPR studies focus on absolute performance metrics, such as compression depth and rate, often relying on sensor-based systems or controlled experimental settings. While these approaches provide accurate numerical measurements, they exhibit limitations in adaptability and educational interpretability when applied to real-world training environments.

In this context, the present study adopts a design-oriented perspective by focusing on relative body-movement relationships rather than absolute coordinates. This approach enables robust analysis under varying viewpoints and rescuer positions, while supporting feedback that aligns with educational objectives in CPR training.

LEARNER RELATIVE BODY-MOVEMENT-BASED CPR COMPRESSION DEPTH ANALYSIS FRAMEWORK

A. Framework Overview

This The proposed CPR compression depth analysis framework consists of five sequential stages, as illustrated in Fig. 1:
(1) non-contact body movement data acquisition, (2) extraction of relative body vectors with respect to the upper-body reference, (3) compression motion modeling, (4) compression depth estimation, and (5) generation of educational feedback indicators.

The framework is designed to reflect practical constraints commonly encountered in CPR training environments. First, rescuers may freely change their position or orientation while performing CPR. Second, enforcing fixed camera viewpoints is often impractical in real educational settings. Third, substantial variations exist among learners in terms of physical characteristics and compression habits.

To address these challenges, the proposed framework intentionally avoids reliance on absolute coordinates, absolute distances, or single-direction motion analysis. Instead, it adopts an analysis structure based solely on relative movement relationships among body segments, enabling robust compression depth analysis under varying viewpoints, rescuer positions, and individual physical differences.

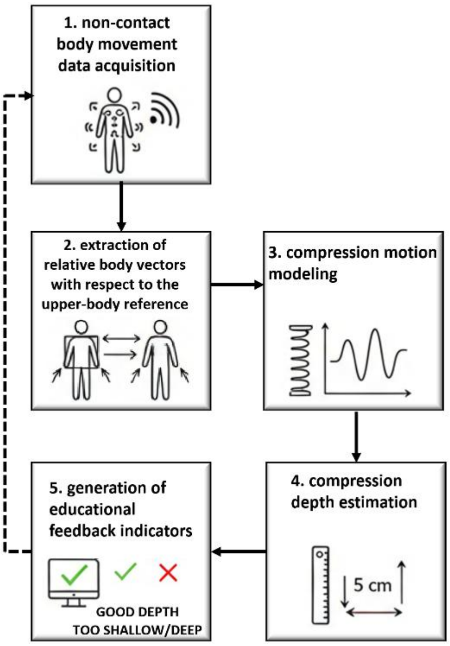

Fig. 1 Overview of the relative body-movement-based CPR compression depth analysis framework

B. Body Movement Data Acquisition and Preprocessing

Non-contact body movement data are acquired by focusing on major upper-body joints, including the shoulders, elbows, and wrists. Since CPR compression actions are primarily determined by vertical upper-body motion and the maintenance of arm posture, lower-body information is excluded from the analysis.

The rescuer's CPR motion can be represented as a set of body joint positions observed over time. Rather than utilizing absolute joint coordinates, this study expresses CPR compression actions using relative vectors between an upper-body reference point and the hand position. This relative representation effectively reduces dependency on camera placement and rescuer orientation, thereby enhancing robustness under varying viewpoints and positional changes.

During preprocessing, simple smoothing operations may be applied to reduce noise and ensure temporal consistency of joint trajectories. To maintain general applicability and avoid dependence on specific sensing devices or motion capture algorithms, the preprocessing stage is designed with minimal assumptions and constraints.

C. Relative Body-Vector-Based CPR Compression Motion Modeling

The CPR compression motions can be modeled through the temporal variations of relative body vectors, which exhibit repetitive periodicity and amplitude characteristics. In the proposed framework, compression depth is defined as a function of the magnitude of relative vector displacement, where the amplitude corresponds to compression depth and the temporal period corresponds to compression rhythm.

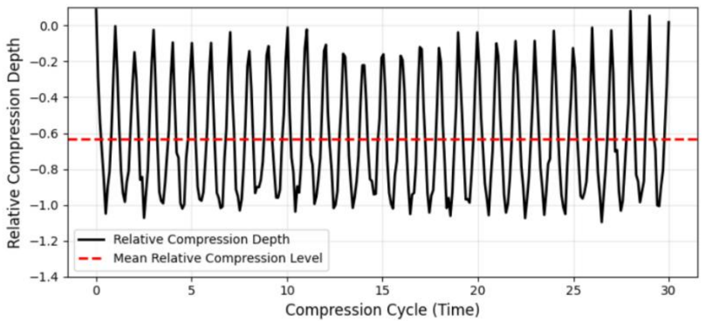

Fig. 2 Conceptual time-series representation of relative CPR compression vector variation

As illustrated in Fig. 2, the relative body vector demonstrates a periodic pattern during CPR performance. This relative vector represents a core structural component of CPR compression motions. Specifically, the vector defined between an upper-body reference point and the hand position remains invariant to changes in rescuer orientation and camera viewpoint.

The temporal evolution of the relative vector simultaneously reflects the repetitive nature and depth of CPR compressions, enabling both compression depth estimation and stability assessment within a unified modeling framework.

Compression depth is estimated from the temporal displacement of the relative body vector and is expressed in a normalized form to mitigate inter-individual physical differences among rescuers.

$$\widehat{d}(t) = \frac{||\boldsymbol{c}(t) - \boldsymbol{c}(t - \Delta t)||}{max_t \, ||\boldsymbol{c}(t) - \boldsymbol{c}(t - \Delta t)||}$$

This normalization process eliminates absolute displacement differences caused by individual body size variations, allowing relative compression magnitude and stability to be compared across learners in a consistent manner.

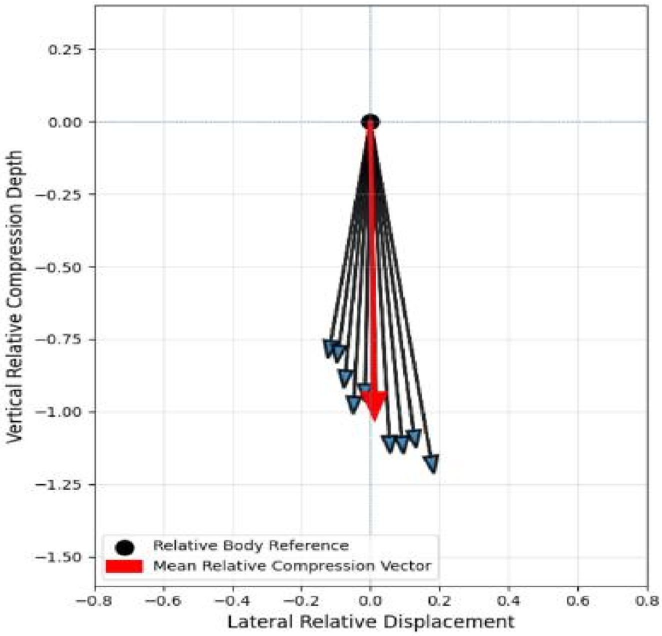

Fig. 3 Conceptual illustration of the distribution and mean of relative CPR compression vectors

Beyond compression depth estimation, the proposed framework interprets CPR compression motions as directional relative vectors. Fig. 3 conceptually illustrates the distribution of compression vectors observed with respect to a body-centered reference coordinate system, along with their mean compression vector.

Although individual compression actions may exhibit small directional deviations, applying a relative body-centered reference reveals a stable mean compression vector. This representation highlights that, rather than absolute compression depth alone, the directional dispersion and consistency of compression vectors are critical indicators of CPR performance quality. Such a vector-based interpretation provides an intuitive explanation of compression stability that is particularly valuable in educational contexts. The proposed algorithmic procedure for evaluating CPR quality is structured into four primary stages, as illustrated in Fig. 4.

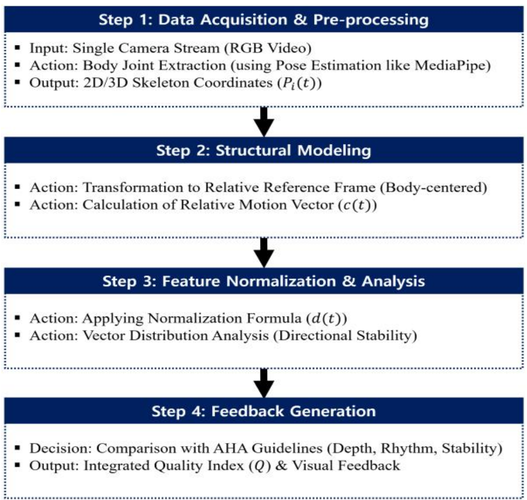

Fig. 4 Sequential pipeline of the proposed CPR performance evaluation framework

1. Data Acquisition and Joint Extraction: The process begins by capturing a single RGB video stream of the trainee. Leveraging real-time pose estimation, the system extracts critical skeletal joints ($P_i(t)$) necessary for CPR analysis, such as the wrists, elbows, and shoulders.

2. Structural Relative Transformation: To achieve viewpoint invariance, the extracted absolute coordinates are transformed into a body-centered reference frame. This stage generates the relative motion vector $c(t)$, which represents the hand's movement relative to the trainee's upper body, effectively neutralizing external camera parameters.
3. Feature Normalization and Stability Analysis: The relative vectors are processed through the normalization formula to derive $d(t)$, the normalized compression depth. Simultaneously, the system performs vector distribution analysis to quantify directional stability, identifying any lateral swaying or postural imbalances during the compressions.
4. Integrated Feedback and Scoring: In the final stage, the extracted temporal and structural features are synthesized to calculate the Integrated Quality Index (Q). This index provides a holistic score that reflects adherence to standard guidelines (depth and rate) alongside the newly introduced structural stability metric.

D. Analysis Procedure and Educational Feedback Metric Generation

Unlike the conceptual framework illustrated in Fig. 1, Fig. 5 focuses on the detailed analytical and interpretive procedure, explicitly illustrating how relative motion information is transformed into educationally meaningful feedback indicators.

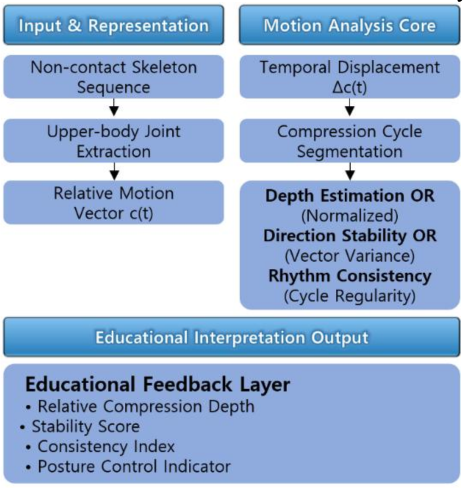

Fig. 5 Analytical and interpretive pipeline of the proposed relative body motion–based CPR compression depth analysis, highlighting both quantitative estimation and educational feedback generation

The overall analytical procedure of the proposed framework is summarized in Fig. 5. Unlike conventional CPR assessment systems that primarily output numerical values, the proposed framework aims to generate educationally interpretable feedback metrics that can be intuitively understood by learners and instructors.

Through The proposed analysis pipeline consists of the following five sequential stages:

1. Non-contact body motion input acquisition.
2. Relative vector computation based on an upper-body reference.
3. Compression cycle detection.
4. Compression depth and stability estimation.
5. Educational feedback metric generation.

In the first stage, non-contact body motion data are obtained using vision-based motion capture or pose estimation techniques. The second stage computes relative body vectors with respect to an upper-body reference point, thereby removing dependencies on absolute coordinates, camera viewpoints, and rescuer positioning.

In the third stage, CPR compression cycles are detected from the temporal patterns of relative vector displacement. This step enables segmentation of continuous motion into individual compression events. Subsequently, compression depth and stability are estimated by analyzing the amplitude and consistency of the relative vector displacement within each detected cycle.

Rather than providing raw numerical measurements, the final stage focuses on generating educational feedback metrics that can be directly applied in CPR training scenarios. Specifically, the relative magnitude of compression depth, the stability of compression cycles, and the consistency of repeated compressions are presented as intuitive indicators for learners. These metrics play a critical role in supporting self-correction during CPR training, allowing learners to adjust their posture and motion patterns based on continuous feedback.

In CPR education, the stability and consistency of repeated compressions are often more important than the depth of a single compression. Accordingly, this study defines a compression quality metric that integrates multiple aspects of CPR performance, such as depth consistency and rhythmic stability.

$$Q = \alpha \cdot Var(\hat{d}) + \beta \cdot Var(T)$$

This quality metric enables a comprehensive assessment of CPR performance by capturing both the effectiveness and stability of compressions. By emphasizing interpretability and educational relevance, the proposed framework bridges the gap between motion analysis and practical CPR training, making it suitable for scalable, non-contact CPR education environments.

ANALYTICAL DISCUSSION

A. Robustness to Viewpoint Variations

The simulation results Fig. 6 demonstrate that the proposed structural relative motion modeling framework significantly outperforms conventional absolute coordinate-based methods in terms of viewpoint robustness. In traditional approaches, the measured compression depth is highly sensitive to the camera's positioning; as the filming angle deviates from the frontal view, a "cosine loss" occurs, leading to a measurement error of up to 30% at a 45° angle. In contrast, the proposed normalized relative vector model ($d(t)$) ensures that the compression trajectories converge into a consistent profile across all tested viewpoints. This invariance indicates that the framework can provide reliable performance evaluations in diverse and unconstrained educational settings without the need for complex camera calibration or fixed equipment setups.

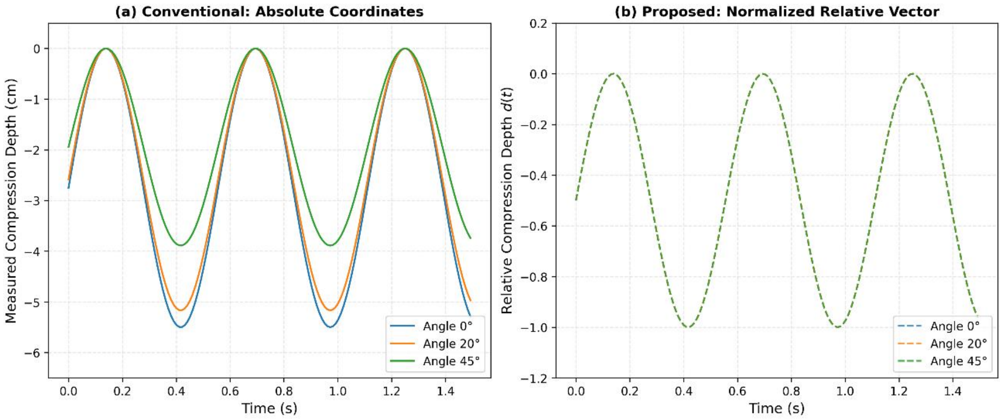

Fig. 6 Comparative analysis of compression depth estimation: Conventional absolute coordinate method vs. Proposed normalized relative motion model under varying camera viewpoints ($0°$, $20°$, $45°$).

B. Structural Stability Evaluation via Compression Vector Distribution

Beyond simple vertical displacement, the proposed vector distribution analysis Fig. 7 serves as a critical metric for quantifying the 'structural quality' of CPR performance. While existing vision-based methods focus primarily on the linear travel distance of the hands, this framework extracts the directionality and consistency of each compression relative to the body-centered reference frame.

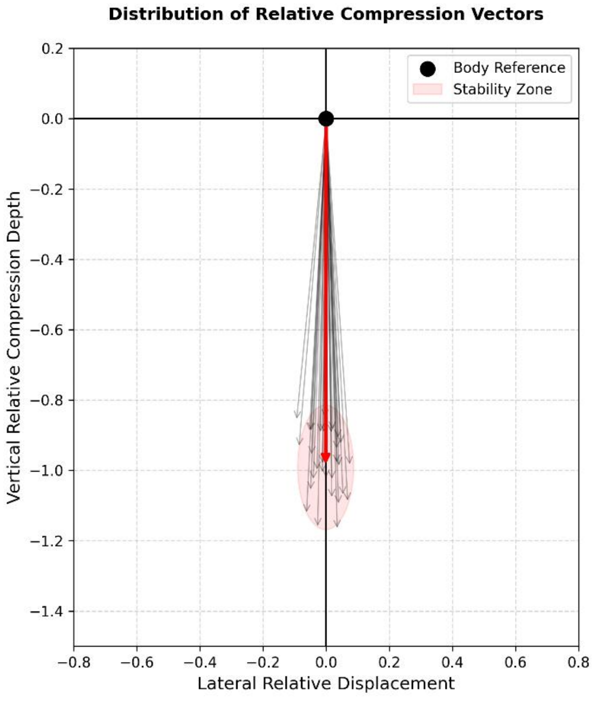

Fig. 7 Spatio-temporal distribution of relative compression vectors and the defined 'Stability Zone' for structural posture evaluation.

The analytical results indicate that proficient CPR performance is characterized by a dense clustering of individual compression vectors within a narrow 'Stability Zone' around the Mean Vector. This clustering visually confirms that the trainee is accurately transferring their body weight in a strictly vertical direction, minimizing lateral displacement. Conversely, a high variance in the vector distribution ($Var(c(t))$) indicates postural instability or inconsistent force application. Such structural insights allow the system to provide sophisticated, qualitative feedback—moving beyond simple quantitative remarks like "insufficient depth" to more instructive guidance, such as "excessive lateral swaying detected, hindering efficient force delivery."

C. *Educational Implications and Scalability*

The integration of the Quality Index (Q), which accounts for both directional stability and rhythmic consistency, ensures that trainees focus on the overall 'integrity' of the life-saving maneuver rather than isolated metrics. By eliminating the dependency on sensor-integrated manikins, this vision-based approach offers superior scalability for large-scale public health training. The ability to derive high-fidelity, sensor-level insights from a single camera stream positions this framework as a viable tool for democratizing high-quality CPR education in home-based or remote learning environments.

CONCLUSIONS

This study presented a structural relative motion modeling framework designed to overcome the inherent limitations of vision-based CPR performance evaluation. By shifting the analytical focus from absolute global coordinates to a body-centered relative reference frame, we addressed the critical issue of viewpoint dependency, which has long hindered the accuracy of non-contact motion analysis.

The primary significance of this research lies in the empirical validation of the proposed normalization technique. Through comparative simulations, we demonstrated that the proposed relative depth indicator ($d(t)$) provides consistent and robust measurements across varying camera angles, effectively mitigating the projection errors (cosine loss) that severely affect conventional absolute coordinate methods. Specifically, while traditional approaches showed significant depth underestimation at a 45° angle, our framework maintained high fidelity, ensuring the reliability of feedback in unconstrained training environments. Furthermore, by introducing vector distribution analysis and the concept of a 'Stability Zone,' this study expanded the scope of CPR evaluation from simple quantitative depth metrics to the qualitative assessment of structural postural stability.

In conclusion, the proposed framework offers a scalable, low-cost, and high-precision alternative to expensive sensor-equipped manikins, facilitating the democratization of high-quality CPR education. Although this work was conducted through analytical validation, it provides a rigorous theoretical foundation for future practical applications. Future research will focus on integrating this framework with real-time human pose estimation libraries and validating its efficacy with diverse demographic groups in real-world settings. Ultimately, this approach is expected to contribute significantly to improving the quality of bystander CPR and increasing survival outcomes in emergency cardiac events.

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