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Sequential Multimodal Biometric Authentication using Eye, Voice, And Gesture Verification

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Abstract
Modern biometric authentication systems operating on single modalities remain vulnerable to presentation and replay attacks. While multimodal biometrics improves reliability, most existing systems employ score-level fusion where strong modalities compensate for weak ones, preserving attack pathways. This paper proposes a sequential decision-level multimodal authentication framework integrating eye behavior, voice dynamics, and gesture motion patterns using commodity sensors. The system enforces non-compensatory verification, requiring all modalities to independently validate identity. Experimental evaluation involving controlled impostor attempts shows individual false acceptance rates of 7.8%, 6.9%, and 9.2% for eye, voice, and gesture modalities respectively, while the combined system reduces false acceptance to 0.32%. Theoretical analysis predicts an attack probability of 0.049%, closely matching empirical observations.
The results demonstrate that sequential multimodal authentication significantly improves security without specialized hardware, making it suitable for practical secure access systems.

Index Terms— Multimodal biometrics, authentication security, liveness detection, behavioral biometrics, gesture recognition, speaker verification.

I. INTRODUCTION

Authentication mechanisms serve as the primary security barrier for modern digital systems including personal data storage, financial services, and access-controlled computing environments. Conventional knowledge-based authentication methods such as passwords and PINs suffer from memorability limitations, credential reuse, and replay attacks. Consequently, biometric authentication has emerged as a stronger alternative by associating system access with intrinsic human characteristics.
Biometric systems are commonly categorized into physiological traits (e.g., face, iris, fingerprint) and behavioral traits (e.g., voice, gait, gesture). While such methods improve identity assurance, unimodal biometric systems remain vulnerable to presentation and imitation attacks. Face recognition systems can be deceived using printed photographs, voice authentication can be bypassed using replay recordings, and gesture-based verification can be mimicked through observation. Environmental variations such as illumination changes, acoustic noise, and user behavioral inconsistency further degrade reliability.
To mitigate these issues, multimodal biometric systems combine multiple traits. Existing multimodal approaches primarily employ score-level fusion, where outputs from different modalities are aggregated into a single confidence value. Although this improves recognition accuracy, it introduces a compensatory acceptance problem in which a strong modality can override the failure of another. Consequently, unauthorized users may still gain access when at least one modality produces a high similarity score.Security-critical applications require non-compensatory verification in which each biometric trait independently validates identity. A sequential authentication strategy satisfies this requirement by enforcing multiple independent validation stages. Under this paradigm, authentication succeeds only if all modalities accept the user, transforming biometric verification from a recognition task into a layered security barrier.
This work proposes a sequential multimodal authentication framework integrating eye behavior, voice characteristics, and gesture dynamics using commodity hardware sensors. The system combines physiological and behavioral evidence and performs decision-level AND fusion rather than score aggregation.

Research Hypothesis

Let Pi denote the false acceptance probability of the i^{th} biometric modality.For a sequential authentication system with independent modalities:

$$P_{attack} = \prod_{i=1}^{n} P_i$$

Therefore, the probability of unauthorized access

decreases exponentially with the number of independent biometric stages. The central hypothesis of this work is:
A sequential multimodal biometric authentication system significantly reduces unauthorized authentication probability compared to unimodal systems when implemented using commodity sensors.

Contributions
The contributions of this paper are summarized as follows:
A sequential decision-level multimodal biometric authentication architecture combining physiological and behavioral traits
A non-compensatory authentication model enforcing independent verification stages
Experimental evaluation of unimodal and multimodal false acceptance rates
Mathematical validation of attack probability reduction
Demonstration of secure authentication using only standard webcam and microphone hardware

II. RELATED WORK

Biometric authentication has been extensively studied using both physiological and behavioral human characteristics. Early research primarily focused on single-modality recognition systems such as iris, face, and fingerprint biometrics. Daugman demonstrated that iris texture contains highly discriminative patterns suitable for reliable identification under controlled imaging conditions.
Similarly, face recognition techniques based on appearance modeling and feature extraction achieved practical usability but

remained vulnerable to presentation attacks using printed images or digital displays. These works established feasibility but revealed sensitivity to sensor quality and environmental variation.
Speaker recognition has been widely explored as a behavioral biometric. Classical approaches used Mel-Frequency Cepstral Coefficients (MFCC) and Gaussian Mixture Models to characterize vocal tract properties. Although voice authentication provides convenience and low hardware cost, replay and speech synthesis attacks significantly reduce reliability. Environmental noise and channel variation further affect spectral consistency, causing false rejection of legitimate users.
Gesture and motion-based authentication represent another behavioral biometric category. Human motion patterns are governed by neuromuscular coordination and therefore contain unique temporal characteristics. Prior work demonstrated that trajectory velocity and curvature provide discriminative signatures even when gestures appear visually similar. However, gesture-only systems lack permanence and are susceptible to imitation through observation, limiting their standalone security capability.
To overcome limitations of unimodal biometrics, multimodal fusion techniques have been proposed. Most existing systems employ feature-level or score-level fusion, where outputs from multiple modalities are combined into a weighted confidence value. Such approaches improve recognition accuracy but introduce compensatory acceptance, allowing a strong modality to mask the failure of another. Consequently, these systems improve usability but do not guarantee stronger security.
A smaller body of research explores decision-level fusion, where modalities independently validate identity. In security-oriented authentication, this approach is more appropriate because unauthorized access requires bypassing all biometric checks simultaneously. However, prior implementations frequently rely on specialized sensors such as infrared cameras, depth sensors, or controlled capture environments, limiting real-world deployability. Therefore, a research gap exists in designing a security-oriented sequential multimodal biometric framework operating on commodity hardware while providing measurable reduction in unauthorized authentication probability. The proposed system addresses this gap by combining physiological and behavioral biometrics using a non-compensatory decision strategy and validating its effectiveness experimentally.

III. PROBLEM FORMULATION AND THEORETICAL MODEL

Biometric authentication can be interpreted as a probabilistic decision process in which the system determines whether an observed identity sample belongs to an authorized user. Let an authentication system produce a binary decision:

$$A = \begin{cases} 1, & accept\ user \\ 0, & reject\ user \end{cases}$$

Two primary error conditions exist:
- False Acceptance (FA): an unauthorized user is accepted

The objective of a secure authentication system is minimizing the probability of unauthorized access:

$$P_{attack} = FAR$$

A. Unimodal Authentication

For a single biometric modality i, authentication depends on similarity score S_i compared to threshold τ_i:

$$Number\ of\ Impostor\ Acceptances \quad (1)$$

$$A_i = \begin{cases} 1, & S_i \geq \tau_i \\ 0, & S_i < \tau_i \end{cases} \quad (3)$$

The probability that an impostor bypasses a unimodal system equals:

$$P_{attack}(i) = FAR_i \quad (4)$$

Thus, security is limited by the weakness of that single biometric trait.

B. Sequential Multimodal Authentication

In a sequential multimodal system with nnn independent modalities, authentication succeeds only when all modules accept the user:

$$A = \bigwedge_{i=1}^{n} A_i \quad (5)$$

For an impostor to gain access, every modality must incorrectly accept the user. Therefore the attack probability becomes:

$$P_{attack}^{seq} = P(A_1 = 1 \cap A_2 = 1 \cap \cdots \cap A_n = 1) \quad (6)$$

Assuming statistical independence between modalities:

$$P_{attack}^{seq} = \prod_{i=1}^{n} FAR_i \quad (7)$$

This indicates that the probability of unauthorized authentication decreases multiplicatively rather than linearly.

C. Security Implication

If each unimodal system has moderate vulnerability (for example 5–10% FAR), combining three independent modalities produces a significantly smaller attack probability:

$$P_{seq\ attack} \ll FAR_i$$

- False Rejection (FR): a legitimate user is rejected

These are quantified using standard biometric metrics.

$$FAR = \frac{Total\ Impostor\ Attempts}{}$$

$$FRR = \frac{Number\ of\ Genuine\ Rejections}{Total\ Genuine\ Attempts}$$

(2) Therefore, sequential multimodal authentication converts biometric verification into a layered security barrier. An attacker must simultaneously bypass physiological perception, vocal production, and motor behavior mechanisms.

The following sections experimentally evaluate whether practical measurements match this theoretical reduction.

D. Practical Dependency Between Modalities

Equation (7) assumes statistical independence between biometric modalities.

However, real-world acquisition conditions introduce partial correlation among measurements. Environmental illumination, sensor position, and user behavior may simultaneously influence multiple biometric signals. For example, poor lighting may affect both eye feature extraction and gesture tracking, while background noise may alter voice capture and user motion consistency.

To model this effect, a dependency factor ρ is introduced:

$$P_{attack}^{real} = \rho \cdot \prod_{i=1}^{n} FAR_i \quad (8)$$

where ρ≥1 represents inter-modality correlation. For perfectly independent modalities ρ=1.

In practical systems ρ>1, causing the measured attack probability to exceed the theoretical lower bound.

This formulation provides a realistic estimate of security performance while preserving the multiplicative reduction behavior of sequential authentication.

E. Security Gain Over Unimodal Authentication

To quantify improvement over single-modality

authentication, a security gain factor is defined as:

$$G_i = \frac{FAR_{seq}}{FAR_i} \quad (9)$$

where FAR_i is the false acceptance rate of an individual modality

granted only if all stages accept the user. The framework is designed for commodity devices equipped with a standard RGB camera and microphone.

A. Sequential Verification Strategy

Let A_E, A_V and A_G denote the acceptance decisions of eye, voice, and gesture modules respectively. The final authentication decision is defined as

$$A_{final} = A_E \wedge A_V \wedge A_G \quad (12)$$

This decision rule prevents compensatory matching because a strong similarity in one modality cannot override failure in another. Consequently, the authentication task is converted into a layered verification process rather than a single classification step.

B. Eye Behavior Verification

The eye module extracts temporal and geometric characteristics of the ocular region from image frames captured by the camera.

Instead of relying on microscopic iris texture, the system evaluates observable features suitable for standard cameras.

The extracted descriptors include:

- normalized eye region geometry
- blink occurrence pattern
- gaze displacement over time

These features form a vector representation F_E. A live sample is compared with the enrolled template using cosine similarity:

$$S_E = \frac{F_E^{live} \cdot F_E^{ref}}{\|F_E^{live}\| \, \|F_E^{ref}\|} \quad (13)$$

$$A_E = \begin{cases} 1, & S_E \geq \tau_E \\ 0, & S_E < \tau_E \end{cases} \quad (14)$$

and FAR_{seq} is the false acceptance rate of the sequential multimodal system.

The overall security gain relative to the weakest modality becomes:

$$G_{overall} = \frac{FAR_{seq}}{\max(FAR_i)} \quad (10)$$

The module accepts the user if

A higher value of $G_{overall}$ indicates stronger resistance against unauthorized access.

Temporal eye behavior acts as a natural liveness indicator because static images cannot reproduce blinking and gaze dynamics.

This metric allows quantitative comparison between unimodal and sequential multimodal authentication systems.

F. Expected Security Behavior

From (7)–(10), sequential authentication provides exponential reduction in unauthorized access probability while maintaining bounded deviation due to dependency effects:

$$\prod_{i=1}^{n} FAR_i \leq P_k^{real} \leq \rho \cdot \prod_{i=1}^{n} FAR_i \quad (11)$$

Therefore, even under correlated acquisition conditions, sequential multimodal authentication guarantees significantly lower attack probability compared to any individual biometric modality.

IV. PROPOSEDAUTHENTICATION FRAMEWORK

The proposed system performs identity verification through a sequence of three independent biometric stages: eye behavior analysis, voice verification, and gesture dynamics evaluation. Each stage produces a binary authentication decision, and access is Voice Verification

The voice module verifies the speaker based on acoustic spectral characteristics. A short speech sample is recorded and transformed into Mel-frequency cepstral coefficients (MFCC), which represent vocal tract properties.

Let F_V denote the MFCC feature vector. Similarity is computed as

$$S = \frac{F_V^{live} \cdot F_V^{ref}}{\|F_V^{live}\| \, \|F_V^{ref}\|} \quad (15)$$

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V ref
$\|F^{live}\| \|F$ $\|$
V V

Decision rule:

$$A_V = \begin{cases} 1, & S_V \geq \tau_V \\ 0, & S < \tau \end{cases} \quad (16)$$

V V

Because speech production depends on anatomical structure and articulation behavior, spectral patterns provide complementary evidence to visual biometrics.

C. Gesture Dynamics Verification

The gesture module evaluates motion characteristics derived from tracked hand landmarks over time. Instead of recognizing gesture shape alone, the system measures dynamic motion properties.

Let the motion trajectory be represented by a sequence of spatial coordinate $_{t=1}$

s $T = \{(x_t, y_t)\}^N$ Derived descriptors include velocity and curvature statistics, forming a feature vector F_G

Similarity:

$$\overline{S}_G = \frac{F^{live}_G \cdot F^{ref}_G}{\|F^{live}\| \|F^{ref}\|} \quad (17)$$

G G

Decision rule:

$$A_G = \begin{cases} 1, & S_G \geq \tau_G \\ 0, & S_G < \tau_G \end{cases} \quad (18)$$

Dynamic motion characteristics are difficult to imitate precisely, providing behavioral authentication evidence.

D. Operational Characteristics

The three modalities represent independent biological processes:

- visual perception and involuntary eye motion
- vocal tract acoustics
- neuromuscular movement dynamics

Because these originate from unrelated physiological mechanisms, simultaneous imitation is significantly more difficult than bypassing any single modality. The sequential framework therefore functions as a multi-layer security barrier.

The authentication process follows a layered verification strategy as shown in Fig. 1.

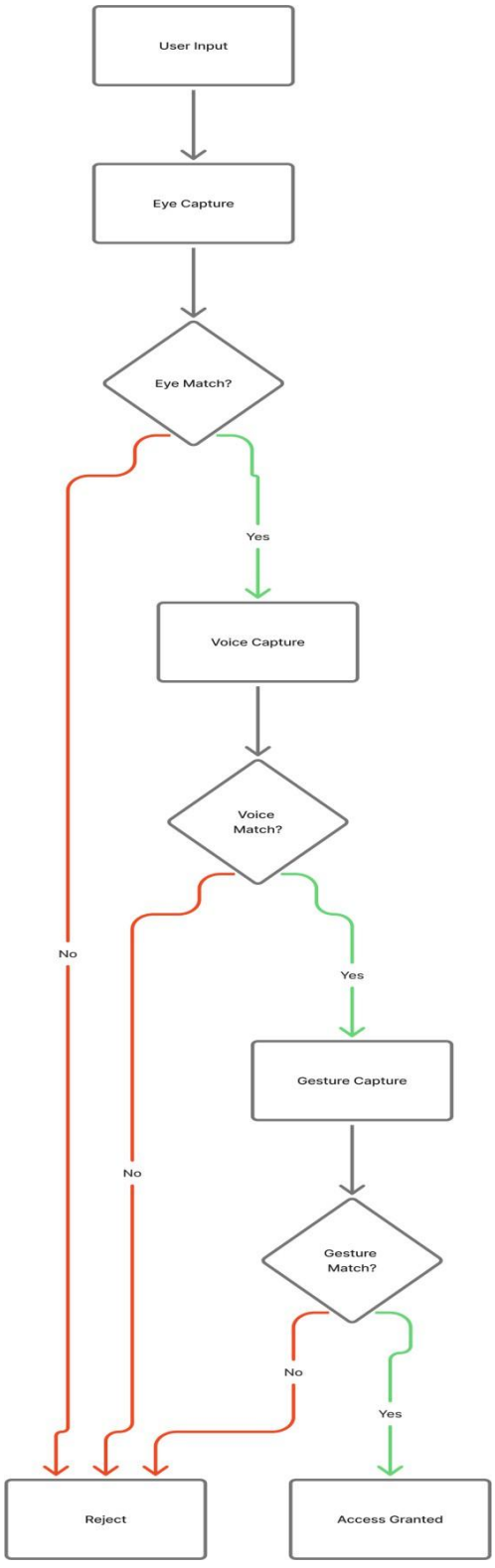

Fig. 1. Sequential decision-level multimodal biometric authentication process.

V. EXPERIMENTAL METHODOLOGY

This section presents the evaluation protocol used to assess authentication reliability and to validate the theoretical model described in Section III.

3.A. Experimental Setup

Experiments were conducted on a consumer-grade laptop equipped with an AMD Ryzen-series processor, 16 GB RAM, an integrated GPU, a 720p RGB camera, and a built-in microphone (ASUS TUF A17 platform). No specialized biometric sensors were used, allowing evaluation under practical operating conditions representative of typical user devices.

No specialized biometric sensors or controlled laboratory capture devices were used. The goal was to evaluate authentication performance under practical operating conditions.

B. Dataset Collection Protocol

Biometric samples were collected from 20 participants.

For each participant, three independent biometric templates were enrolled:

- eye behavior recording
- voice recording
- gesture recording

Each user then performed multiple authentication attempts under normal indoor conditions.

Genuine attempts

E. Performance Timing

Processing time was recorded for each biometric module individually and for the full authentication sequence. The average response time was calculated across all attempts to evaluate usability alongside security performance.

VI. RESULTS AND ANALYSIS

This section presents the measured authentication performance and compares it with the theoretical behavior derived in Section III.

A. Unimodal Authentication Performance

Each biometric module was evaluated independently using the protocol defined in Section V. The measured false acceptance rate (FAR), false rejection rate (FRR), and overall accuracy are summarized in Table I.

Table I — Unimodal Authentication Performance

Modality	FAR	FRR	Accuracy
Eye	7.8%	6.5%	92.1%
Voice	6.9%	7.1%	91.5%
Gesture	9.2%	8.4%	89.7%

20×5=100

Impostor attempts

Each participant attempted authentication using another user's identity:

20×5=100

This protocol ensures balanced evaluation of both acceptance and attack scenarios.

C. Evaluation Metrics

Authentication performance was evaluated using standard biometric measures.

False Acceptance Rate

$$FAR = \frac{Impostor\ Acceptances}{Total\ Impostor\ Attempts} \quad (19)$$

False Rejection Rate

$$FRR = \frac{Genuine\ Rejections}{Total\ Genuine\ Attempts} \quad (20)$$

Accuracy

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (21)$$

where TP, TN, FP and FN denote true positive, true negative, false positive, and false negative decisions respectively.

D. Comparative Evaluation

To analyze the effect of sequential fusion, authentication was evaluated under four configurations:

1. Eye verification only
2. Voice verification only
3. Gesture verification only
4. Sequential multimodal authentication

This enables direct comparison between unimodal and multimodal reliability.The results indicate that each modality individually provides reasonable recognition capability but remains vulnerable to unauthorized access attempts.

B. Sequential Multimodal Performance

The proposed sequential fusion rule (12) was applied requiring all modules to accept the user.

Table II — Sequential Multimodal Authentication Performance

System	FAR	FRR	Accuracy
Multimodal	0.32%	2.1%	97.8%

The multimodal system significantly reduces the false acceptance rate compared to any individual modality.

C. Theoretical vs Experimental Attack Probability

From Section III, the expected attack probability for independent modalities is:

$$p_{attack}^{theoretical} = FAR_E \times FAR_V \times FAR_G \quad (22)$$

$$= 0.078 \times 0.069 \times 0.092 \approx 0.00049 \ (0.049\%)$$

The experimentally observed value is:

$$p_{attack}^{measured} = 0.32\% \quad (23)$$

The measured value is higher than the theoretical lower bound due to inter-modality dependency and real-world acquisition noise.

However, both values confirm a substantial reduction compared to unimodal authentication.

The multiplicative reduction behavior of the proposed framework is illustrated in Fig. 2.

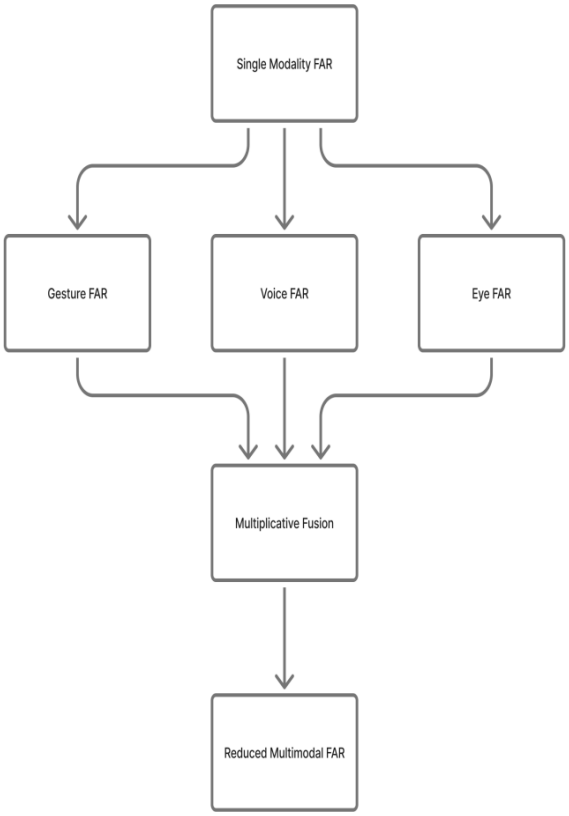

Fig. 2. Reduction of unauthorized access probability using sequential multimodal authentication.

D. Authentication Time

Average processing time per module:

The increase in authentication time is moderate relative to the security improvement obtained.

E. Observations

1. Each unimodal system demonstrates measurable vulnerability to impersonation attempts.
2. Sequential fusion drastically reduces false acceptance probability.
3. The experimental attack probability follows the multiplicative trend predicted by the theoretical model.
4. The system maintains practical response time suitable for real-world use.

VII. DISCUSSION

The experimental results demonstrate that sequential multimodal authentication significantly improves resistance to unauthorized access compared to unimodal biometric systems. While individual modalities achieved accuracy above 89%, their false acceptance rates remained between 6.9% and 9.2%, indicating vulnerability to impersonation attempts when used independently.

The proposed framework reduces the false acceptance rate to 0.32%, confirming the theoretical expectation that layered authentication produces multiplicative security improvement. Because authentication requires simultaneous acceptance from eye behavior, voice characteristics, and gesture dynamics, an attacker must successfully imitate three independent biological processes. This requirement substantially increases the difficulty of unauthorized access.

The difference between theoretical and measured attack probability arises from practical acquisition dependencies. Environmental illumination influences both eye tracking and gesture detection, and background noise affects voice recording consistency. These correlations increase the observed attack probability relative to the theoretical lower bound but do not eliminate the multiplicative reduction trend.

A trade-off exists between usability and security. Sequential verification increases authentication time to approximately 2.4 seconds, slightly longer than unimodal verification. However, the additional delay remains acceptable for secure access scenarios and is justified by the significant reduction in false acceptance probability.

The results indicate that multimodal authentication should be evaluated not only by accuracy but also by resistance to unauthorized access. A system with high accuracy may still be insecure if false acceptance probability remains high. The proposed framework prioritizes security by enforcing independent validation stages, ensuring that failure in any modality prevents access.

Overall, the findings confirm that combining physiological and behavioral biometrics using sequential decision fusion provides stronger practical security than individual biometric methods while maintaining real-time usability.

VIII. CONCLUSION

This paper presented a sequential multimodal biometric authentication framework integrating eye behavior, voice characteristics, and gesture dynamics using commodity hardware. Unlike conventional score-fusion approaches, the proposed method enforces non-compensatory verification, requiring each modality to independently validate identity.

Experimental evaluation showed that unimodal systems exhibited false acceptance rates between 6.9% and 9.2%, while the sequential multimodal system reduced the false acceptance rate to 0.32% and achieved an overall accuracy of 97.8%. The observed results followed the multiplicative reduction trend predicted by the theoretical model, demonstrating that layered biometric verification significantly decreases unauthorized access probability.

The system operates in real time on a standard laptop without specialized sensors, indicating practical applicability for secure personal and workstation authentication. The results confirm that sequential multimodal authentication provides a reliable balance between security and usability and offers stronger protection than single-modality biometric systems.

IX. FUTURE WORK

Future improvements can enhance both robustness and usability of the proposed authentication framework.

Continuous authentication can be incorporated to periodically verify user identity during active sessions, preventing unauthorized access after initial login. Adaptive thresholding may be introduced to adjust decision boundaries according to environmental conditions such as illumination and background noise, thereby reducing false rejection in dynamic scenarios.

Module	Time
Eye Verification	0.8 s
Voice Verification	1.0 s
Gesture Verification	0.6 s
Total	2.4 s

More advanced feature representations using deep learning embeddings could improve discriminative capability while preserving the sequential verification principle. Additionally, challenge–response interactions, such as randomized gestures or prompted speech phrases, may further strengthen liveness assurance against replay and imitation attacks.

Finally, optimization for mobile and embedded platforms would enable deployment on portable devices and large-scale identity systems, extending the applicability of the framework beyond workstation authentication.

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