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Real-Time Wearable PPG Analysis of Human Physiology for Alcohol Intoxication Detection: A Controlled Human Study

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***Abstract*—Alcohol intake can impair reaction time, judgment, and motor coordination, creating safety risks in everyday and occupational settings. To support unobtrusive monitoring, this paper investigates passive alcohol-intoxication detection from wearable photoplethysmography (PPG) acquired from a sensor worn on the arm. The approach uses a subject-specific sober baseline and evaluates subsequent PPG windows through frequency-domain and baseline-relative descriptors, while rejecting motion-contaminated data. The detector was deliberately calibrated as a high-confidence trigger, prioritizing Positive Predictive Value (PPV) and low false-positive alerts. Across alcohol-positive sessions with defined PPV, session-level macro-averaged PPV was 96.79%, while mean sensitivity was approximately 40% and showed substantial inter-session variability. These results provide preliminary proof-of-concept evidence supporting wearable PPG for high-confidence alcohol-related physiological alerts, while highlighting the need for independent validation and improved motion handling.**

***Index Terms*—alcohol intoxication detection, photoplethysmography, wearable sensing, frequency-domain analysis, continuous monitoring**

I. Introduction and Related Work

Alcohol intake can impair reaction time, judgment, motor coordination, and cardiovascular regulation, increasing risks in driving, occupational, and other safety-critical environments [1]. Conventional alcohol detection methods, such as breath alcohol analyzers and blood tests, provide useful point measurements but are not designed for passive and continuous monitoring [2].

Wearable photoplethysmography (PPG) provides a non-invasive measurement of blood-volume variations and is widely used for cardiovascular monitoring [3]. Since alcohol affects cardiovascular regulation, heart-rate dynamics, vascular tone, and heart-rate variability [4], [5], PPG may contain information related to alcohol-induced physiological changes.

Alcohol-related changes in blood-pulse and PPG signals have been investigated using spectral characterization [6], [7], frequency partitioning [8], and morphology-based waveform analysis [9], [10]. These studies support the feasibility of PPG-based alcohol detection, although morphology-based methods generally require sufficiently clean pulse-wave acquisition.

Other non-invasive alcohol-monitoring strategies include transdermal sensors, which enable continuous monitoring but exhibit delayed responses relative to breath or blood alcohol variations [2], and gait-based approaches using smartphone or smartwatch inertial sensors [11]. Gait methods can achieve promising performance but inherently depend on movement, making them less applicable while the user is sitting, driving, or performing stationary work.

Recent studies have also explored machine-learning approaches using physiological wearable signals. Kim et al. combined ECG, PPG, and electrodermal activity and evaluated multiple machine-learning classifiers for alcohol-intoxication classification [12]. Kaczor et al. used wrist-worn heart rate, skin temperature, electrodermal activity, and accelerometry with machine-learning models to identify alcohol-related impairment [13]. These results further support the use of physiological sensing, although direct comparison is limited by differences in sensor modality, cohort composition, labeling strategy, and validation protocol.

This work investigates wearable PPG for continuous alcohol-intoxication monitoring using a subject-specific sober baseline and frequency-domain descriptors. The personalized reference accounts for inter-subject cardiovascular variability. Frequency-domain analysis is particularly suitable for the wearable setting because it characterizes periodic and harmonic information over extended windows and may remain informative when individual pulse-wave morphology is degraded by motion or sensor-placement variability [14].

The aim is to report the sensing rationale, experimental protocol, methodological feature categories, and aggregate performance of the proposed framework. Implementation-specific feature combinations, weights, and decision thresholds are not disclosed because the algorithmic framework is the subject of a pending patent application.

This work was supported by Sleep Advice Technologies. The algorithmic framework described in this paper is the subject of a pending patent application.

II. Methods

A. Study Design and Wearable Protocol

This preliminary human pilot study included 20 adult volunteers (9 females, mean age 27.6 ± 7.35 years), above 21 years of age, during moderate and voluntary alcohol intake. The study followed a prospective, single-arm, pre-post design in which each participant served as their own control. The protocol was approved by the Research Ethics Committee of Politecnico di Torino (CER-Polito), under protocol no. 31587/2026. The alcohol-intake and safety procedures were designed with clinical-scientific input from Dr. Andrea Romigi.

Participants were healthy adults providing written informed consent. Exclusion criteria included cardiovascular or other relevant medical conditions, medications affecting cardiovascular parameters or alcohol metabolism, pregnancy or suspected pregnancy, adverse reactions to alcohol, history of alcohol or drug dependence, or other conditions incompatible with moderate alcohol intake.

Controlled sessions were standardized to reduce physiological variability unrelated to alcohol. Participants consumed a light standardized breakfast at approximately 06:00 and were asked to avoid alcohol, caffeine, nicotine, and moderate-to-heavy physical activity for 12 h before the session. Only water was allowed afterward. Sessions started at approximately 08:00, with alcohol administration around 09:00 to reduce circadian variability.

Physiological data were acquired using a wearable optical PPG sensor worn on the arm, providing continuous PPG and heart-rate measurements throughout the protocol.

At baseline, a breath alcohol measurement confirmed the initial sober condition, while PPG and heart-rate data were recorded with the participant seated and still. The subject-specific reference used by the algorithm was selected as the stable sober pre-intake window with the lowest mean heart rate, intended to approximate a resting cardiovascular condition.

Alcohol was administered as lager beer at approximately 5% ABV or red wine at approximately 12% ABV. The dose was calculated using a Watson/Widmark-based estimation to target a BrAC of approximately 0.08–0.10 g/dL, with safety caps of 0.6 g/kg for men and 0.5 g/kg for women. The calculated amount was divided into three aliquots, each consumed within approximately 5 min and approximately 20 min apart. Administration was stopped if BrAC exceeded 0.10 g/dL or adverse symptoms occurred.

BrAC was measured at baseline and approximately every 10 min during drinking and post-intake phases using a portable breath analyzer. Around each measurement, participants remained seated and still with the monitored arm resting on a table to reduce motion artifacts. Monitoring continued until BrAC decreased to ≤ 0.02 g/dL. The controlled workflow is summarized in Fig. 1.

Additional recordings were collected under less constrained real-life conditions to assess robustness. The real-life dataset included seven alcohol-positive sessions recorded during social drinking scenarios involving wine or beer, food intake, and less controlled movement, together with three sober recordings. BrAC measurements were available only for part of these recordings; consequently, sessions without repeated measurements did not provide continuous objective BrAC ground truth.

B. Frequency-Domain Wearable Analysis

Raw PPG was analyzed in the frequency domain because the target application is continuous wearable monitoring. Unlike morphology-based approaches, which require consistently clean beat-level waveforms, frequency-domain representations can retain cardiovascular information over longer windows even when individual pulses are partially distorted.

PPG signals were divided into 5-min analysis windows with a 15-s step. Each window underwent low-pass filtering, baseline correction, FFT transformation, and spectral smoothing using a five-point moving mean before feature extraction.

The considered descriptor families included spectral peak amplitudes and frequencies, harmonic relationships, total spectral energy, raw and preprocessed PPG-amplitude trends, heart-rate-related quantities, PPI-derived variability measures, and spectral-shape descriptors.

For a generic feature f, a normalized baseline-relative change can be represented as

$$r_f(t) = \frac{f(t) - f_{\text{base}}}{f_{\text{base}}}, \tag{1}$$

where f_{base} is the corresponding value from the subject-specific sober reference.

Multiple baseline-relative descriptors were jointly evaluated, and alerts required consistent evidence across consecutive windows. Exact feature combinations and thresholds are omitted because they form part of the pending patent application.

Motion handling preceded the final alcohol classification. For each 5-min PPG analysis window, signal-quality information was used to identify unreliable or motion-affected data. A window was excluded from alcohol classification when at least 80% of the corresponding data were classified as unreliable or affected by movement. This conservative rejection strategy reduces the amount of data available for classification and may consequently decrease detection coverage.

Fig. 2 provides a session-level illustration of the heterogeneous baseline-relative behavior observed in selected recordings. FFT area and the Ph2/Ph1 ratio generally showed more positive changes in the illustrated alcohol-positive recordings than in sober recordings, whereas Ph1 showed greater inter-session variability. This behavior supports the use of multiple subject-specific descriptors rather than a single universal physiological threshold.

The dataset also included sober physical-activity recordings to evaluate false-positive behavior under relevant non-alcohol conditions. Windows acquired during active movement were rejected, whereas post-exercise windows were retained because heart rate and cardiovascular activity may remain elevated after movement.

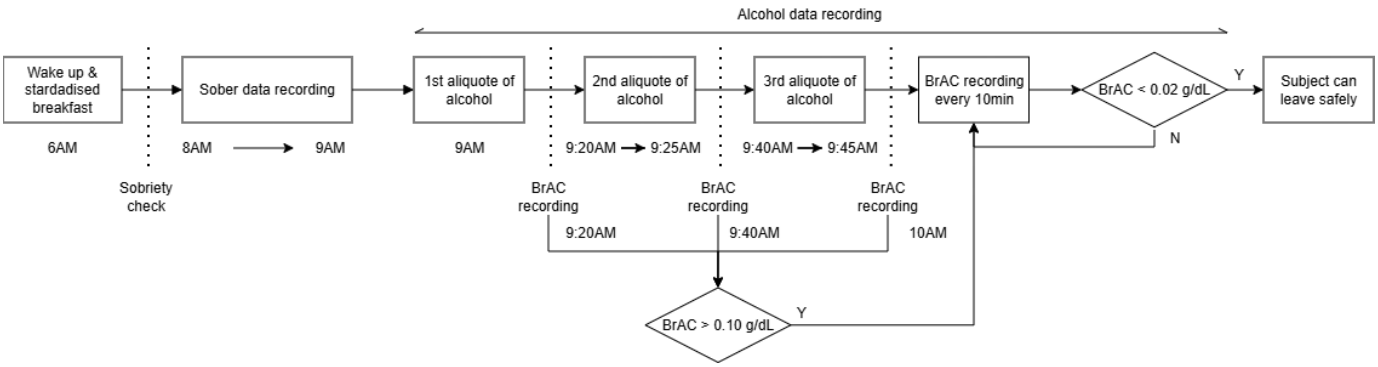

Fig. 1. Block diagram of the controlled data-collection protocol. The protocol includes a standardized breakfast, sober baseline acquisition, three supervised alcohol aliquots, repeated BrAC measurements, and post-intake monitoring.

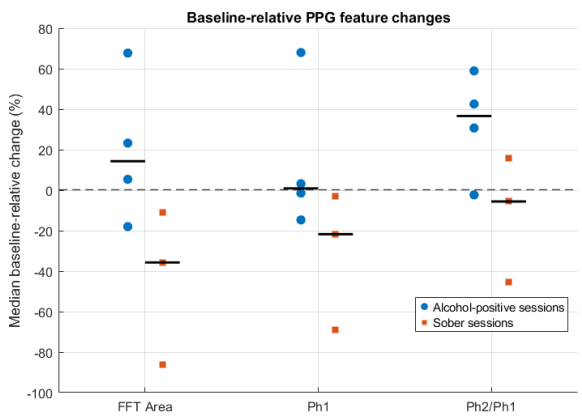

Fig. 2. Baseline-relative changes in selected representative PPG frequency-domain descriptors in an illustrative subset of alcohol-positive and sober sessions. Each point represents the median percentage change across valid windows of one session relative to its subject-specific sober baseline. Horizontal segments indicate group medians. Windows identified as unreliable or motion-affected were excluded.

III. Results and Discussion

Alcohol-related baseline-relative changes varied across participants, supporting a personalized multi-feature detection framework.

The detector was deliberately calibrated as a high-confidence trigger. In safety-oriented continuous monitoring, false-positive alerts are particularly undesirable because they may reduce user trust or generate unnecessary intervention. The operating point was therefore selected to prioritize PPV over complete detection coverage.

Feature selection and decision thresholds were defined through exploratory analysis of the controlled-study dataset and iteratively adjusted to favor high PPV and reduce false-positive alerts. Since the same controlled dataset contributed to both algorithm development and performance evaluation, the reported controlled results may be affected by optimistic bias and should not be interpreted as independent validation.

As summarized in Table **??**, PPV remained high in both controlled and real-life recordings, whereas sensitivity showed substantial inter-session variability. Across sessions with defined PPV, values ranged from 66.67% to 100%, while sensitivity ranged from 3.23% to 95.05%.

TABLE I
Summary of the pilot study and session-level detection results.

Item	Value
Participants (female)	20 (9)
Mean age	27.6 ± 7.35 years
Controlled PPV	$97.79 \pm 6.28\%$
Real-life PPV	$94.45 \pm 13.61\%$
Overall PPV	$96.79 \pm 8.84\%$
Controlled sensitivity	$43.38 \pm 31.99\%$
Real-life sensitivity	$30.47 \pm 26.16\%$
Overall sensitivity	$39.51 \pm 30.29\%$

The approximately 40% sensitivity reflects the deliberately conservative operating point. Missed alcohol-positive intervals can result both from negative classifications and from rejection of motion-contaminated windows. Thus, the system should be interpreted as a high-confidence trigger rather than as a complete detector of every alcohol-positive interval.

This operating point is appropriate for applications in which an alert is intended to indicate a sufficiently strong physiological deviation rather than to continuously estimate intoxication status. A negative output therefore does not necessarily indicate a sober condition; it may instead reflect insufficient evidence or inadequate signal quality. Future studies should evaluate alternative operating points, for example through threshold-sensitivity or receiver-operating-characteristic analysis, to quantify the trade-off between false-positive suppression and detection coverage.

Some controlled sessions nevertheless reached substantially higher sensitivity, indicating that detection coverage can increase when the alcohol-related physiological response is sufficiently pronounced and signal quality remains adequate. Conversely, the wide observed sensitivity range highlights the influence of inter-subject physiology and measurement conditions.

Real-life recordings confirmed the same overall trend: positive alerts were generally reliable, while sensitivity was more limited and affected by movement, food intake, posture

changes, and variable alcohol-consumption timing. No-alcohol recordings were included to assess false-positive behavior and generally produced few or no incorrect alerts, consistent with the intended high-PPV operating point.

Compared with prior wearable alcohol-detection studies based on inertial gait features, such as AlcoWear, which reported accuracy values of 89.45% using smartphone data and 79.8% using smartwatch data [11], the present work addresses a different sensing condition: stationary or semi-stationary wearable PPG monitoring. More recent machine-learning work has combined PPG with ECG and EDA [12], or multiple wrist-worn physiological and motion signals [13], showing the feasibility of data-driven intoxication or impairment classification. Direct comparison among existing methods is limited by differences in sensors, datasets, labeling, targets, and evaluation metrics.

From a sensing perspective, PPG-based and transdermal approaches provide complementary information. Transdermal systems measure alcohol-related diffusion through the skin but are affected by physiological transport delay, whereas PPG reflects cardiovascular responses that may occur earlier but are less specific to alcohol and can also be influenced by exercise, stress, food intake, or stimulants. This motivates the personalized baseline-relative approach and highlights the importance of confounder-controlled validation.

IV. Limitations and Future Work

This study has several limitations. The limited sample size and cohort diversity restrict statistical power and generalizability. Moreover, because the controlled dataset contributed to both algorithm development and performance evaluation, independent subject-level validation is required to estimate performance on unseen participants.

Movement remains a major challenge because rejected PPG windows reduce usable monitoring time and contribute to missed detections. Relevant confounders including food intake, caffeine, nicotine, stress, and physical activity were controlled or observed only in selected conditions rather than systematically evaluated independently.

The lowest-HR sober reference was selected empirically and was not formally compared with alternative baseline strategies. Likewise, the relative contribution of individual descriptor families was not quantified; an ablation study on an independent dataset would help determine whether performance depends on a small subset of descriptors or on their combined behavior. Future work will focus on larger independent datasets, improved motion handling, systematic confounder evaluation, and adaptive or baseline-free reference strategies.

V. Conclusion

This paper presented a wearable PPG-based approach for alcohol-intoxication detection using a subject-specific sober baseline and frequency-domain physiological descriptors. Across alcohol-positive sessions with defined PPV, the system achieved a session-level macro-averaged PPV of 96.79%, while sensitivity averaged approximately 40% and showed substantial inter-session variability.

The results support the feasibility of wearable PPG as a conservative high-confidence alcohol-related physiological trigger, but should be interpreted as preliminary proof-of-concept evidence rather than independent validation of a complete alcohol detector or definitive BAC estimator. Larger independent datasets and improved motion handling are required before practical deployment.

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