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Original Article

Wearable-Derived Cardiovascular Phenotyping of Smokers During Intense Physical Activity: A Cross-Sectional Precision Exercise Study

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ABSTRACT

Background: Smoking is a major modifiable risk factor for cardiovascular and pulmonary disease, yet its impact on individualized cardiovascular response patterns during intense physical activity remains insufficiently characterized. Advances in wearable technology offer opportunities for continuous physiological monitoring and precision exercise assessment. Objective: To evaluate wearable-derived cardiovascular response profiles and exercise performance among smokers and non-smokers during standardized physical activity protocols. Methods: In this analytical cross-sectional study, 43 young adults (22 smokers, 21 non-smokers) underwent the Six-Minute Walk Distance test, Balke treadmill protocol, and Ekblom-Bak cycle ergometer test. Heart rate was continuously monitored using a smartwatch, and perceived exertion was assessed using the Borg CR-10 scale. Between-group comparisons were performed using independent samples t-tests. Results: Smokers demonstrated significantly lower exercise-induced heart rate responses during the Balke treadmill and Ekblom-Bak tests ($p = 0.001$ and $p < 0.001$, respectively), while no significant difference was observed during the Six-Minute Walk test. Smokers also covered shorter walking distances and achieved lower work rates and exercise durations at higher intensities. Conclusion: Smoking is associated with blunted chronotropic adaptability and reduced exercise tolerance during intense physical activity. Wearable-derived monitoring reveals distinct cardiovascular response phenotypes, supporting its role in precision exercise assessment and personalized cardiovascular risk evaluation. Keywords: Precision exercise medicine, Smoking, Wearable technology, Cardiovascular response, Heart rate, Physical performance

INTRODUCTION

Physical activity comprises a spectrum of bodily movements shaped by behavioral, social, and environmental influences and is strongly associated with cardiometabolic health and functional capacity (1). Regular physical activity is protective against multiple non-communicable diseases, whereas physical inactivity is consistently associated with adverse health outcomes, including hypertension, dyslipidemia, and type 2 diabetes (2). Because cardiovascular and pulmonary systems directly mediate exercise tolerance, any exposure that alters vascular function, autonomic regulation, gas exchange, or skeletal muscle metabolism can meaningfully change an individual's physiological response to physical exertion (3).

Cigarette smoking remains a major modifiable exposure associated with cardiovascular morbidity and mortality and is independently linked to endothelial dysfunction, dyslipidemia, and accelerated atherosclerotic processes, thereby increasing the risk of myocardial infarction, ischemic stroke, and sudden cardiac death (3-6). Beyond macrovascular disease, smoking-related effects on microcirculation and autonomic balance may impair the capacity to appropriately augment cardiac output during physical stress. Long-term smoking is also associated with pulmonary toxicity and chronic airflow limitation, which can further restrict oxygen delivery during exercise (7-10). At the skeletal muscle level, smoking has been associated with impaired endurance and force generation, potentially through altered muscle protein turnover, oxidative stress, and reduced oxygen-carrying capacity due to carbon monoxide exposure (11,12). Collectively, these mechanisms suggest that smokers may demonstrate distinct exercise-response profiles characterized by earlier fatigability and altered cardiovascular kinetics, even in young adults without overt cardiopulmonary disease (13).

Despite the extensive literature on smoking-related disease risk, comparatively fewer studies have focused on how smoking shapes individual cardiovascular response phenotypes during standardized intense physical activity, particularly when responses are captured continuously rather than at isolated time points. This gap is increasingly relevant within the framework of precision medicine, which emphasizes inter-individual variability and the tailoring of assessment and intervention based on measurable physiological characteristics. In parallel, wearable devices capable of real-time heart rate monitoring have expanded opportunities for digital phenotyping by enabling continuous, ecologically scalable capture of physiological signals during activity. Wearable-derived measures, when combined with structured exercise protocols, can help identify patterns suggestive of blunted chronotropic response, reduced exercise tolerance, or atypical recovery trajectories, features with potential implications for individualized fitness counseling and cardiovascular risk stratification (14).

Accordingly, this study aimed to evaluate wearable-derived cardiovascular responses and functional performance during intense physical activity among smokers and non-smokers using standardized protocols, including the Six-Minute Walk Distance test, the Balke treadmill protocol, and the Ekblom-Bak cycle ergometer test. Heart rate was continuously monitored using a smartwatch to compare exercise-related cardiovascular response patterns between groups. By integrating field-relevant exercise tests with wearable-based monitoring, this work seeks to contribute evidence on whether smoking status is associated with distinct cardiovascular phenotypes during intense activity, supporting more individualized approaches to physical fitness assessment and health promotion (15).

MATERIALS AND METHODS

Study Design and Setting

This analytical cross-sectional study was conducted to examine wearable-derived cardiovascular response patterns during intense physical activity among smokers and non-smokers. The study was carried out at Northwest General Hospital, where all assessments and data collection procedures were performed in a controlled clinical environment. The cross-sectional design was selected to enable comparative analysis of cardiovascular and functional exercise responses between groups at a single time point, consistent with precision exercise phenotyping approaches.

Sample Size and Participants

A total of 43 participants were enrolled in the study. The sample size was calculated using the infinite population proportion formula $n = p(1-p)(z/e)^2$, ensuring adequate statistical power for between-group comparisons. Participants were categorized into smokers and non-smokers based on self-reported smoking status. Recruitment was performed using a non-probability snowball sampling technique, which facilitated identification of individuals meeting the study criteria within the hospital and surrounding community. All participants provided written informed consent prior to participation. The study objectives, procedures, and potential risks were explained in detail before enrollment.

Eligibility Criteria

Participants aged 20–30 years who were apparently healthy and capable of performing moderate-to-intense physical activity were eligible for inclusion. Individuals were excluded if they had a known history of cardiovascular, pulmonary, metabolic, or neuromuscular disease; were taking medications known to influence heart rate or exercise tolerance; or had recent musculoskeletal injuries that could limit physical performance. These criteria were applied to reduce confounding and ensure that observed differences in cardiovascular response were primarily attributable to smoking status.

Exercise Protocols and Functional Performance Assessment

Each participant completed a series of standardized exercise tests designed to impose progressively increasing cardiovascular and metabolic demands. The test battery included the Six-Minute Walk Distance (6MWD) test, the Balke treadmill protocol, and the Ekblom-Bak cycle ergometer test. The 6MWD test was conducted along a marked indoor corridor in accordance with standardized guidelines, allowing participants to walk at a self-selected pace while covering the maximum possible distance within six minutes. The Balke treadmill protocol was performed on a motorized treadmill with gradual increases in workload, enabling assessment of cardiovascular response to graded ambulation. The Ekblom-Bak test was administered using a cycle ergometer, providing a controlled assessment of cardiovascular and muscular endurance under incrementally increasing resistance. These complementary protocols were selected to capture functional capacity across different exercise modalities and to facilitate comprehensive evaluation of exercise-induced cardiovascular responses.

Perceived Exertion Monitoring

Perceived exertion during exercise was assessed using the Borg Category Ratio (CR-10) scale. Participants were instructed to continue each exercise protocol until reaching a perceived exertion rating of 7, corresponding to high-intensity but submaximal effort. This approach ensured participant safety while eliciting robust physiological responses suitable for cardiovascular phenotyping.

Wearable-Based Cardiovascular Monitoring

Continuous heart rate monitoring was conducted using a Garmin Vivosmart 4 smartwatch, worn on the non-dominant wrist throughout all testing procedures. The smartwatch enabled real-time acquisition of heart rate data, including resting heart rate and exercise-induced heart rate responses. Wearable-derived heart rate measurements were treated as digital cardiovascular biomarkers, allowing characterization of individual chronotropic response patterns during physical exertion.

Data Collection Procedure

Prior to exercise testing, demographic and anthropometric data, including age, height, weight, and body mass index, were recorded for all participants. All testing sessions were conducted between 2:00 pm and 4:00 pm to minimize the influence of diurnal variation on cardiovascular performance. Participants were familiarized with all exercise protocols and the Borg scale before testing to ensure standardized execution.

Statistical Analysis

Data were analyzed using SPSS version 26.0. Descriptive statistics were computed for all demographic, cardiovascular, and performance variables. Continuous variables were expressed as mean ± standard deviation. Independent sample t-tests were used to compare heart rate responses and functional performance outcomes between smokers and non-smokers. Statistical significance was set at $p < 0.05$.

Methodological Strengths for Precision Medicine

The integration of wearable-based heart rate monitoring with standardized exercise protocols enabled detailed assessment of individualized cardiovascular response patterns. This methodological approach supports precision exercise assessment by moving beyond static measurements toward dynamic, physiologically meaningful phenotyping.

RESULTS

A total of 43 participants were included in the final analysis, comprising 22 smokers and 21 non-smokers. All participants successfully completed the Six-Minute Walk Distance (6MWD), Balke treadmill, and Ekblom-Bak cycle ergometer protocols. No adverse events were reported during testing.

Baseline demographic and anthropometric characteristics of smokers and non-smokers are presented in Table 1. The mean age of smokers was 24.1 ± 1.3 years, compared with 23.4 ± 1.1 years among non-smokers. Mean height was comparable between groups. Non-smokers demonstrated slightly higher body weight (73.8 ± 9.1 kg vs. 69.4 ± 11.6 kg) and body mass index (25.2 ± 3.0 vs. 22.9 ± 3.5 kg/m²); however, these differences did not reach statistical significance, indicating general baseline comparability between groups.

Table 1. Demographic characteristics of smokers and non-smokers

Variable	Smokers (n = 22)	Non-Smokers (n = 21)	p-value
Age (years)	24.1 ± 1.3	23.4 ± 1.1	0.08
Height (cm)	171.8 ± 8.9	171.2 ± 9.0	0.82
Weight (kg)	69.4 ± 11.6	73.8 ± 9.1	0.17
BMI (kg/m²)	22.9 ± 3.5	25.2 ± 3.0	0.06

Comparative cardiovascular and functional performance outcomes derived from smartwatch-based heart rate monitoring and standardized exercise testing are summarized in Table 2. At rest, smokers exhibited a slightly lower heart rate (83.1 ± 10.2 bpm) compared with non-smokers (86.0 ± 7.6 bpm), although this difference was not statistically significant. Following the 6MWD test, non-smokers demonstrated a higher exercise-induced heart rate (91.5 ± 11.2 bpm) than smokers (83.4 ± 17.1 bpm) and covered a greater walking distance (0.27 ± 0.06 km vs. 0.23 ± 0.05 km). The difference in walking distance reached statistical significance, whereas the heart rate difference did not.

During the Balke treadmill protocol, smokers showed a markedly attenuated cardiovascular response. Peak heart rate was significantly lower in smokers (97.2 ± 21.4 bpm) compared with non-smokers (141.6 ± 26.3 bpm). While total distance covered was similar between groups, non-smokers achieved marginally higher final treadmill speeds and exercised for a longer duration. A similar pattern was observed during the Ekblom-Bak cycle ergometer test. Smokers demonstrated substantially lower peak heart rates (96.3 ± 27.5 bpm) relative to non-smokers (138.8 ± 24.6 bpm). Additionally, non-smokers achieved higher work rates and sustained exercise for a longer duration before reaching a perceived exertion level of 7 on the Borg CR-10 scale.

Table 2. Cardiovascular and performance outcomes (mean ± SD)

Variable	Smokers (n = 22)	Non-Smokers (n = 21)	p-value
Resting HR (bpm)	83.1 ± 10.2	86.0 ± 7.6	0.28
HR at end of 6MWD (bpm)	83.4 ± 17.1	91.5 ± 11.2	0.11
6MWD distance (km)	0.23 ± 0.05	0.27 ± 0.06	0.02
HR at end of Balke test (bpm)	97.2 ± 21.4	141.6 ± 26.3	0.001
Balke distance (km)	1.10 ± 0.22	1.13 ± 0.18	0.61
Final speed Balke (km/h)	6.6 ± 1.0	6.8 ± 0.5	0.34
Time Balke (min)	14.3 ± 2.5	15.2 ± 1.4	0.09
HR at end of Ekblom-Bak (bpm)	96.3 ± 27.5	138.8 ± 24.6	<0.001
Work rate (watt/kg)	113.8 ± 24.9	124.6 ± 30.7	0.18
Final resistance	13.8 ± 2.4	14.9 ± 3.2	0.21
Time Ekblom-Bak (min)	13.4 ± 1.5	14.2 ± 1.4	0.07

Between-Group Statistical Comparisons of Heart Rate Responses Independent-samples t-tests comparing wearable-derived heart rate responses during exercise are presented in Table 3. No statistically significant difference was observed in heart rate at the end of the 6MWD test (p = 0.11). In contrast, highly significant between-group differences were identified during both the Balke treadmill test (p = 0.001) and the Ekblom-Bak test (p < 0.001), with non-smokers demonstrating substantially greater exercise-induced heart rate responses.

Table 3. Independent-samples t-test for heart rate outcomes

Test	Mean Difference (bpm)	Std. Error	p-value (2-tailed)
HR at end of 6MWD	8.1	5.1	0.11
HR at end of Balke test	44.4	9.4	0.001
HR at end of Ekblom-Bak test	42.5	8.9	<0.001

This figure illustrates exercise-induced heart rate response patterns across three standardized exercise modalities (Six-Minute Walk Distance, Balke treadmill, and Ekblom-Bak cycle ergometer) among smokers and non-smokers, incorporating mean values with variability bands (± standard deviation). Non-smokers demonstrated a pronounced, modality-dependent increase in heart rate, rising from 91.5 bpm during the 6MWD to 141.6 bpm during the Balke protocol and remaining elevated at 138.8 bpm during the Ekblom-Bak test. In contrast, smokers exhibited a markedly blunted response trajectory, with heart rate increasing modestly from 83.4 bpm to 97.2 bpm and plateauing at 96.3 bpm despite escalating exercise intensity. The widening separation between group-specific response curves at higher workloads highlights a nonlinear divergence in chronotropic adaptability, suggesting impaired cardiovascular reserve among smokers. The overlapping yet asymmetric variability bands further indicate greater inter-individual dispersion in smokers during intense exercise, reinforcing the presence of distinct wearable-derived cardiovascular phenotypes with potential clinical relevance for personalized exercise prescription and early risk stratification.

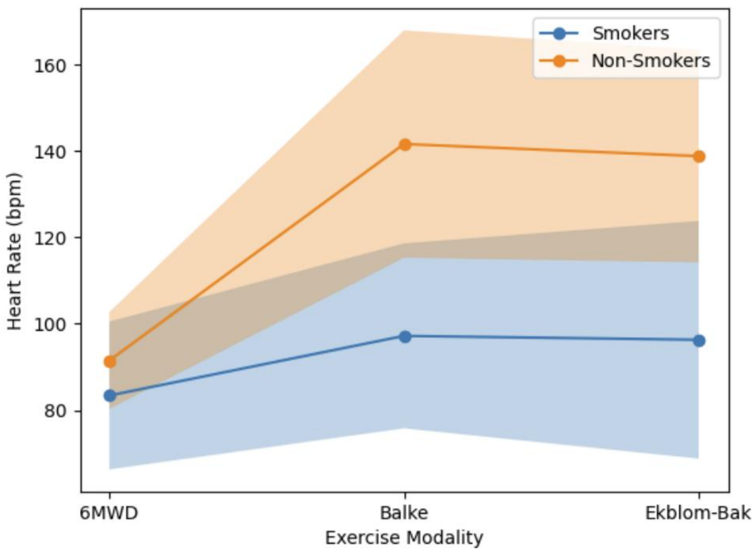

Figure 1 Wearable-Derived Cardiovascular Response Profiles Across Progressive Exercise Modalities

Across multiple exercise modalities, smokers consistently exhibited blunted cardiovascular responses and reduced exercise tolerance relative to non-smokers. Wearable-derived heart rate monitoring revealed distinct cardiovascular response phenotypes, particularly during higher-intensity exercise, with smokers demonstrating attenuated chronotropic adaptability. These findings highlight the utility of smartwatch-based monitoring in identifying individualized physiological differences relevant to precision exercise assessment.

DISCUSSION

The present study examined wearable-derived cardiovascular response patterns during progressively intense physical activity in smokers and non-smokers and demonstrated a consistent attenuation of exercise-induced heart rate responses among smokers across multiple exercise modalities. While resting heart rate and submaximal responses during the Six-Minute Walk Distance test did not differ significantly between groups, marked divergences emerged during higher-intensity treadmill and cycle ergometer testing. These findings suggest that smoking status is associated with impaired chronotropic adaptability that becomes increasingly evident as cardiovascular demand escalates, supporting the concept that smoking-related physiological alterations may remain subclinical during low-intensity activity but manifest during higher workloads.

The absence of a statistically significant difference in heart rate response during the 6MWD test aligns with prior observations that submaximal walking tests may lack sensitivity for detecting early cardiovascular impairment in young or otherwise healthy populations (21). Similar findings have been reported in cohorts where smokers demonstrated preserved heart rate responses at low workloads but exhibited reduced exercise tolerance and performance capacity (2,15). In contrast, the significantly lower distances covered by smokers during the 6MWD in the present study indicate early functional compromise, potentially reflecting reduced muscular endurance or inefficient oxygen utilization despite comparable cardiovascular stimulation. This dissociation between heart rate response and functional output highlights the multifactorial nature of smoking-related exercise impairment.

In comparison, the Balke treadmill and Ekblom-Bak protocols revealed pronounced between-group differences in peak heart rate, with smokers exhibiting substantially blunted responses relative to non-smokers. These findings are consistent with previous reports describing reduced maximal or near-maximal heart rate responses in smokers, often attributed to impaired autonomic regulation and diminished β-adrenergic sensitivity (3,15). Chronic exposure to nicotine and other tobacco constituents has been shown to alter sympathetic–parasympathetic balance, leading to chronotropic incompetence during exertion (4,17). The present results extend this evidence by demonstrating that such alterations can be detected using wearable-based monitoring during standardized exercise testing, reinforcing the utility of digital biomarkers in identifying early cardiovascular dysfunction.

The attenuated heart rate response observed among smokers during high-intensity exercise may also be explained by peripheral and muscular mechanisms. Smoking-induced endothelial dysfunction, reduced nitric oxide bioavailability, and microvascular impairment can limit skeletal muscle perfusion during exercise, thereby constraining metabolic demand and attenuating cardiac output requirements (3,7). Additionally, carbon monoxide binding to hemoglobin reduces arterial oxygen content, leading to earlier onset of fatigue and lower achievable workloads (11,12). The lower work rates and shorter exercise durations observed among smokers during the Ekblom-Bak test support this interpretation and align with prior studies demonstrating impaired oxidative capacity and increased oxidative stress in smokers during intense physical activity (7,22).

From a precision medicine perspective, the findings underscore the importance of evaluating individual cardiovascular response patterns rather than relying solely on population-level averages or resting measurements. Wearable-derived heart rate trajectories revealed distinct phenotypic differences between smokers and non-smokers, particularly during higher-intensity exercise, suggesting that smokers may constitute a subgroup with reduced cardiovascular reserve despite young age and apparent health. Such phenotyping has clinical relevance for personalized exercise prescription, as standardized training intensities based on age-predicted heart rate may overestimate safe or effective workloads for smokers. The integration of wearable technology into exercise assessment may therefore facilitate early risk stratification and individualized intervention strategies, particularly in populations with modifiable lifestyle risk factors (17,24).

Several strengths of this study merit consideration. The use of multiple standardized exercise protocols enabled assessment of cardiovascular responses across a spectrum of functional demands, while continuous heart rate monitoring via smartwatch provided dynamic physiological data reflective of real-world applicability. Conducting all testing within a controlled clinical setting further enhanced internal consistency. However, certain limitations should be acknowledged. The cross-sectional design precludes causal inference, and the modest sample size limits statistical power for subgroup analyses. Smoking status was self-reported, and detailed quantification of smoking exposure (e.g., pack-years) was not incorporated, which may have contributed to within-group variability. Additionally, the relatively young and homogeneous study population restricts generalizability to older individuals or those with established cardiopulmonary disease.

Future research should aim to incorporate longitudinal designs to evaluate the progression and reversibility of smoking-related cardiovascular phenotypes, particularly in response to smoking cessation or structured exercise interventions. Larger studies integrating biochemical markers, heart rate variability, and direct measures of autonomic function may further elucidate underlying mechanisms. Expanding wearable-based phenotyping to diverse populations could enhance understanding of inter-individual variability and support the development of precision-guided exercise recommendations. Collectively, the present findings contribute to a growing body of evidence that smoking exerts measurable effects on cardiovascular responsiveness during intense physical activity and highlight the potential of wearable technologies in advancing personalized cardiovascular assessment.

CONCLUSION

This study demonstrates that smoking is associated with a distinct pattern of attenuated cardiovascular responsiveness during intense physical activity, despite relatively preserved responses during low-intensity functional exercise. While submaximal activity such as the Six-Minute Walk Distance test failed to reveal significant heart rate differences, progressively demanding exercise protocols uncovered marked blunting of chronotropic response and reduced exercise tolerance among smokers. These findings suggest that smoking-related cardiovascular impairment may remain clinically silent during routine activity but becomes evident under higher physiological stress. The integration of wearable-based heart rate monitoring enabled continuous characterization of exercise-induced cardiovascular dynamics, highlighting its value in detecting subtle yet clinically meaningful physiological alterations.

From a precision medicine perspective, the identification of smoking-associated cardiovascular phenotypes has important implications for individualized exercise prescription, early risk stratification, and targeted lifestyle interventions. Although limited by sample size, cross-sectional design, and reliance on self-reported smoking status, this study provides evidence supporting the use of wearable technologies in personalized cardiovascular assessment. Future longitudinal and mechanistic studies incorporating detailed smoking exposure metrics and autonomic markers are warranted to further refine precision-guided exercise and preventive strategies.

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