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Athlete Adaptations to High-Altitude Training: A Behavioral Analysis

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A B S T R A C T

The objective of this study was to explore the behavioral adaptations of athletes to high-altitude training, focusing on their physiological, psychological, and performance strategies, as well as social and environmental factors influencing their training experiences. This qualitative study employed semi-structured interviews to gather in-depth insights from 30 athletes who had undergone high-altitude training for at least three months. Participants were selected through purposive sampling to ensure a diverse representation of sports disciplines and training experiences. The interviews were transcribed and analyzed using NVivo software, with thematic analysis employed to identify key patterns and themes. Data collection continued until theoretical saturation was achieved, ensuring comprehensive coverage of the athletes' experiences. The analysis revealed four main themes: physiological adaptations, mental adaptations, performance strategies, and social and environmental factors. Physiological adaptations included increased lung capacity, enhanced oxygen uptake, higher hemoglobin levels, and improved muscle endurance. Mental adaptations involved enhanced mental resilience, effective stress management, and goal-setting strategies. Performance strategies highlighted the importance of high-intensity training, balanced nutrition, and the use of altitude simulation techniques. Social and environmental factors emphasized the role of peer and coach support, environmental adjustments, and logistical management in facilitating successful high-altitude training. High-altitude training requires athletes to adapt across multiple dimensions, including physiological, psychological, and environmental aspects. The findings underscore the importance of individualized training protocols, comprehensive support systems, and effective management of environmental factors. These insights contribute to a deeper understanding of the holistic impact of high-altitude training, providing valuable guidance for athletes, coaches, and sports scientists to optimize training outcomes and enhance athletic performance.

Keywords: *High-altitude training, athlete adaptations, physiological adaptations, mental resilience, performance strategies*

1. Introduction

High-altitude training typically involves athletes living and/or training at altitudes between 2,000 and 3,000 meters above sea level. This practice exploits the body's natural response to hypoxia, aiming to induce physiological adaptations that enhance oxygen transport and utilization. Chapman et al. (2014) discussed the concept of the optimal "dose" of altitude training, emphasizing the importance of altitude level, duration of exposure, and individual responses in achieving performance gains. Their study highlighted that living at higher altitudes while training at lower ones ("live high, train low") can maximize the erythropoietic response, thereby enhancing sea-level performance (1).

The primary physiological adaptations to high-altitude training include increased hemoglobin mass and red blood cell count, improved capillary density, and enhanced mitochondrial efficiency. These adaptations collectively improve the oxygen-carrying capacity of the blood, allowing athletes to perform more efficiently at sea level. Wilber (2007) underscored the significance of these adaptations, noting that the increased red blood cell mass is a critical factor in improved endurance performance (2).

However, the physiological benefits of high-altitude training are not uniformly experienced by all athletes. Nummela et al. (2020) demonstrated considerable variability in hemoglobin mass response among athletes attending altitude training camps. This variability necessitates personalized altitude training protocols to optimize individual responses and mitigate any potential adverse effects (3).

In addition to physiological changes, high-altitude training impacts the psychological and behavioral dimensions of athletic performance. Athletes must adapt to the unique stressors of high-altitude environments, including hypoxia, altered sleep patterns, and changes in training intensity. Khodaee et al. (2016) emphasized the importance of psychological resilience and effective stress management techniques in coping with these challenges. Their findings suggested that athletes who successfully adapt to high-altitude conditions exhibit enhanced mental toughness and improved coping strategies, which translate into better performance under pressure (4).

The role of motivation and goal-setting in high-altitude training cannot be overstated. Athletes often set specific, measurable goals to track their progress and maintain motivation. According to He et al. (2018), goal-setting is integral to the training process, helping athletes stay focused and committed to their regimen despite the physical and psychological challenges they may face (5).

Training at high altitude also introduces unique environmental and logistical challenges. Athletes must acclimatize to lower oxygen levels, colder temperatures, and increased UV radiation. Roach et al. (2013) found that sleep quality often deteriorates at high altitudes, affecting overall recovery and performance. Their study compared sleep patterns of sea-level natives and high-altitude natives, revealing significant differences that highlight the necessity of acclimatization strategies (6).

Additionally, logistical considerations such as travel, accommodation, and access to training facilities are critical in the planning and execution of high-altitude training programs. Effective management of these factors is essential to minimize disruptions and maximize the benefits of the training regimen. Schommer et al. (2012) highlighted the health risks associated with moderate altitude and normobaric hypoxia, suggesting that careful planning and monitoring are vital to ensure athlete safety and well-being (7).

Nutrition plays a pivotal role in supporting the adaptations to high-altitude training. Iron supplementation, for example, is commonly used to combat the increased demand for erythropoiesis induced by hypoxia. Garvican-Lewis et al. (2017) explored the influence of combined iron supplementation and simulated hypoxia on the haematological module of the athlete biological passport, demonstrating significant improvements in hemoglobin mass and red blood cell volume (8).

Moreover, proper hydration and balanced diet plans are crucial for maintaining energy levels and optimizing performance. Park et al. (2016) conducted a meta-analysis on the effects of altitude/hypoxic training on oxygen delivery capacity and aerobic exercise capacity, underscoring the importance of tailored nutritional strategies to support these physiological adaptations (9).

The ultimate goal of high-altitude training is to enhance athletic performance at sea level. Numerous studies have documented performance improvements across various sports disciplines. Stray-Gundersen et al. (2002)

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demonstrated that "living high, training low" significantly improved sea-level performance in elite runners (10). Similarly, Saunders et al. (2019) reviewed the effects of altitude training on performance, highlighting that optimal altitude training protocols can lead to substantial gains in endurance sports (11). Quan and Yi-gang (2023) examined the impact of high-altitude training on tennis players, reporting significant improvements in physical conditioning and performance metrics. Their study adds to the growing body of evidence supporting the efficacy of altitude training across different sports (12).

Despite the extensive research on the physiological and performance benefits of high-altitude training, there remains a gap in understanding the behavioral and psychological adaptations athletes undergo. This study aims to fill this gap by providing a qualitative analysis of the experiences and perceptions of athletes engaged in high-altitude training. By using semi-structured interviews, this research seeks to uncover the strategies athletes employ to cope with the unique challenges of high-altitude environments and the broader implications for their training and performance.

2. Methods and Materials

2.1. Study Design and Participants

This qualitative research study aimed to explore the behavioral adaptations of athletes to high-altitude training. The research design was chosen to provide a deep, comprehensive understanding of the personal experiences, strategies, and perceptions of athletes undergoing high-altitude training regimes. Given the exploratory nature of this study, a qualitative approach was deemed most appropriate to capture the nuanced and subjective aspects of these adaptations.

Participants in this study were selected through purposive sampling to ensure that they met the specific criteria relevant to the research objectives. The criteria for inclusion were:

- Athletes who have undergone high-altitude training for at least three months.
- Athletes from a variety of sports disciplines, including endurance sports such as marathon running, cycling, and cross-country skiing.
- Athletes who are willing to share their experiences and insights regarding high-altitude training.

A total of 20 athletes participated in the study, with an equal distribution of male and female athletes to provide a balanced perspective.

Interviews were conducted in a quiet and comfortable setting, either in person or via video conferencing platforms, depending on the participants' location and preference. Each interview lasted approximately 60 to 90 minutes.

Interviews were conducted until theoretical saturation was achieved, meaning that no new themes or insights were emerging from the data. This approach ensured a comprehensive understanding of the behavioral adaptations without redundancy.

2.2. Measures

2.2.1. Semi-Structured Interview

Data was collected through semi-structured interviews, which were chosen for their flexibility in exploring the experiences and perceptions of the participants. The semi-structured format allowed the interviewer to follow a guided framework of questions while also enabling the participants to freely express their thoughts and elaborate on their experiences.

Interview Guide: An interview guide was developed to ensure consistency across interviews while allowing for the exploration of individual differences. The guide included open-ended questions such as:

- Can you describe your initial experiences with high-altitude training?
- What specific behavioral changes have you noticed in yourself since starting high-altitude training?
- How do you perceive the impact of high-altitude training on your performance and overall well-being?
- What strategies do you use to cope with the challenges of high-altitude training?

2.3. Data Analysis

The interview data were transcribed verbatim and analyzed using NVivo software, a qualitative data analysis tool that facilitated the organization and coding of the data.

Coding: The transcribed data were coded inductively. Initial coding involved identifying and labeling significant statements and phrases related to the research questions.

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These codes were then grouped into broader themes and sub-themes that emerged from the data.

Thematic Analysis: Thematic analysis was employed to identify patterns and relationships within the data. This involved an iterative process of reading and re-reading the transcripts, refining the codes, and verifying the themes with the research objectives.

Data Validation: To ensure the credibility and reliability of the findings, member checking was conducted. This involved sharing the preliminary findings with a subset of the participants to confirm that the interpretations accurately reflected their experiences.

3. Findings and Results

The study included a total of 30 athletes, comprising 15 male and 15 female participants, ensuring gender balance. Participants ranged in age from 20 to 35 years, with an average age of 27. The athletes represented a variety of sports disciplines, including marathon running (10 participants), cycling (8 participants), cross-country skiing (6 participants), and triathlon (6 participants). All participants had undergone high-altitude training for a minimum of three months, with the duration of training ranging from 3 to 18 months. The distribution of training experience was as follows: 10 athletes had 3-6 months of high-altitude training experience, 12 athletes had 7-12 months, and 8 athletes had more than 12 months. This diverse representation provided a comprehensive perspective on the behavioral adaptations to high-altitude training across different sports and levels of experience.

Table 1

The Results of Qualitative Analysis

Category	Subcategory	Concepts
Physiological Adaptations	Respiratory Changes	Increased lung capacity, Improved oxygen uptake, Adaptation to thin air
	Hemoglobin and Red Blood Cell Production	Higher hemoglobin levels, Increased RBC count, Enhanced oxygen delivery
	Muscle Adaptations	Increased muscle endurance, Enhanced mitochondrial density, Improved lactic acid tolerance
	Energy Utilization	Better fat utilization, Increased glycogen storage, Efficient energy use
	Acclimatization Process	Altitude sickness management, Gradual exposure techniques, Acclimatization schedules
	Sleep Patterns	Sleep disruptions, Sleep quality improvements, Adaptation to sleep at altitude
	Recovery Process	Faster muscle recovery, Reduced inflammation, Increased muscle repair
Mental Adaptations	Motivation and Goal Setting	Setting realistic goals, Long-term motivation, Tracking progress
	Mental Resilience	Building mental toughness, Overcoming mental barriers, Positive self-talk
	Stress and Anxiety Management	Stress reduction techniques, Anxiety management, Relaxation exercises
	Focus and Concentration	Improved focus, Enhanced concentration, Mindfulness practices
	Cognitive Functioning	Memory retention, Problem-solving skills, Cognitive sharpness
	Mental Fatigue	Managing mental fatigue, Avoiding burnout, Mental rest strategies
	Visualization Techniques	Imagery training, Visualization practices, Mental rehearsal
Performance Strategies	Training Regimens	High-intensity interval training, Endurance workouts, Strength training
	Nutrition and Hydration	Balanced diet plans, Hydration strategies, Supplement use
	Rest and Recovery Protocols	Rest day scheduling, Sleep hygiene practices, Active recovery methods
	Altitude Simulation	Altitude tents, Hypoxic chambers, Simulated altitude training
	Pacing and Timing Strategies	Optimal pacing techniques, Time management, Race day strategies
	Injury Prevention Techniques	Prevention exercises, Injury risk assessments, Rehabilitation protocols
Social and Environmental Factors	Peer Support	Team bonding, Training partners, Group motivation
	Coach and Trainer Support	Coach feedback, Trainer adjustments, Supportive coaching
	Community and Family Support	Family encouragement, Community involvement, Local support systems
	Environmental Conditions	Weather conditions, Altitude-specific gear, Training environment adjustments
	Travel and Logistics	Travel planning, Logistics management, Adaptation to new locations

The qualitative analysis of the semi-structured interviews revealed four main themes with several subcategories under

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each. The themes and subcategories provide a comprehensive understanding of the athletes' behavioral adaptations to high-altitude training.

3.1. Physiological Adaptations

Respiratory Changes: Athletes reported noticeable improvements in their respiratory function, including increased lung capacity and improved oxygen uptake. One participant mentioned, "Breathing became easier over time, and I felt I could take in more air with each breath."

Hemoglobin and Red Blood Cell Production: Participants observed higher hemoglobin levels and increased red blood cell counts, which enhanced oxygen delivery to their muscles. As one athlete noted, "My endurance improved significantly because my body was more efficient at using oxygen."

Muscle Adaptations: Increased muscle endurance, enhanced mitochondrial density, and improved lactic acid tolerance were common adaptations. An interviewee stated, "My muscles didn't fatigue as quickly, allowing me to train harder and longer."

Energy Utilization: Athletes experienced better fat utilization, increased glycogen storage, and more efficient energy use. One participant shared, "I felt I had more energy reserves and could sustain my performance for longer periods."

Acclimatization Process: The process of acclimatization involved managing altitude sickness, gradual exposure techniques, and following acclimatization schedules. A respondent described, "Initially, I felt dizzy and nauseous, but following a structured acclimatization plan helped me adapt."

Sleep Patterns: Adaptations in sleep included disruptions initially, followed by improvements in sleep quality and adaptation to sleeping at altitude. One athlete remarked, "I had trouble sleeping at first, but over time, my body adjusted, and my sleep improved."

Recovery Process: Faster muscle recovery, reduced inflammation, and increased muscle repair were reported benefits. An athlete noted, "I recovered quicker between sessions, which helped me maintain my training intensity."

3.2. Mental Adaptations

Motivation and Goal Setting: Setting realistic goals, maintaining long-term motivation, and tracking progress were crucial for athletes. One participant said, "Having clear goals kept me motivated throughout the high-altitude training."

Mental Resilience: Building mental toughness, overcoming mental barriers, and using positive self-talk were key strategies. A participant highlighted, "I became mentally stronger and could push through tough training sessions."

Stress and Anxiety Management: Techniques for stress reduction, anxiety management, and relaxation exercises were frequently mentioned. One athlete explained, "I learned to manage my anxiety better and stay calm under pressure."

Focus and Concentration: Improved focus, enhanced concentration, and mindfulness practices were common adaptations. An interviewee stated, "Staying focused became easier, and I could concentrate better during training."

Cognitive Functioning: Athletes reported better memory retention, problem-solving skills, and cognitive sharpness. One participant noted, "My cognitive abilities improved, which helped in strategizing my training and competitions."

Mental Fatigue: Managing mental fatigue, avoiding burnout, and employing mental rest strategies were essential. An athlete mentioned, "Taking mental breaks was important to avoid burnout and stay mentally fresh."

Visualization Techniques: Imagery training, visualization practices, and mental rehearsal were used by athletes. One respondent shared, "Visualizing my performance helped me prepare mentally and boost my confidence."

3.3. Performance Strategies

Training Regimens: High-intensity interval training, endurance workouts, and strength training were key components. One athlete explained, "Mixing different training types helped me improve my overall performance."

Nutrition and Hydration: Balanced diet plans, hydration strategies, and supplement use were essential for maintaining performance. A participant said, "Proper nutrition and staying hydrated were critical for my endurance."

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Rest and Recovery Protocols: Rest day scheduling, sleep hygiene practices, and active recovery methods were emphasized. An interviewee stated, "Incorporating rest days and proper recovery techniques was crucial for avoiding injuries."

Altitude Simulation: The use of altitude tents, hypoxic chambers, and simulated altitude training were common practices. One athlete remarked, "Simulating altitude conditions helped me adapt better when I trained at high altitudes."

Pacing and Timing Strategies: Optimal pacing techniques, time management, and race day strategies were developed. A participant shared, "Learning to pace myself properly made a big difference in my performance."

Injury Prevention Techniques: Prevention exercises, injury risk assessments, and rehabilitation protocols were important. One athlete mentioned, "Focusing on injury prevention allowed me to train consistently without setbacks."

3.4. Social and Environmental Factors

Peer Support: Team bonding, training partners, and group motivation were vital for athletes. One respondent noted, "Having a supportive team environment kept me motivated and accountable."

Coach and Trainer Support: Coach feedback, trainer adjustments, and supportive coaching were essential. An athlete said, "My coach's feedback and adjustments to my training were invaluable."

Community and Family Support: Family encouragement, community involvement, and local support systems played significant roles. A participant explained, "The support from my family and community boosted my morale."

Environmental Conditions: Weather conditions, altitude-specific gear, and training environment adjustments were considered. One athlete remarked, "Adapting to different weather conditions and using the right gear were crucial."

Travel and Logistics: Travel planning, logistics management, and adaptation to new locations were important for training and competition. A respondent shared, "Managing travel logistics effectively ensured I could perform at my best."

4. Discussion and Conclusion

The analysis of semi-structured interviews with 30 athletes who underwent high-altitude training revealed several key behavioral and physiological adaptations. These adaptations were categorized into four main themes: physiological adaptations, mental adaptations, performance strategies, and social and environmental factors. The qualitative data highlighted the intricate interplay between these dimensions, demonstrating how high-altitude training impacts athletes' overall training and performance experiences.

Athletes reported significant respiratory changes, including increased lung capacity and improved oxygen uptake. These adaptations are consistent with findings by Chapman et al. (2014), who noted that high-altitude exposure enhances oxygen transport mechanisms, crucial for endurance performance (1). Additionally, the increase in hemoglobin and red blood cell production was a common observation among participants, aligning with Wilber's (2007) assertion that altitude training boosts erythropoiesis, thereby improving oxygen delivery to muscles (2).

Muscle adaptations were also prominent, with athletes experiencing increased muscle endurance, enhanced mitochondrial density, and improved lactic acid tolerance. This corresponds with the results of Park et al. (2016), who demonstrated that altitude training enhances aerobic exercise capacity through physiological changes in muscle tissue (9). Moreover, the acclimatization process, including managing altitude sickness and gradual exposure techniques, was critical for athletes. This is supported by Khodaee et al. (2016), who emphasized the need for effective acclimatization strategies to mitigate the adverse effects of high altitude (4).

Mental resilience and stress management emerged as significant themes. Athletes highlighted the development of mental toughness and the use of positive self-talk to overcome mental barriers. These findings resonate with Khodaee et al. (2016), who noted that psychological resilience is vital for coping with the stressors of high-altitude environments. Stress and anxiety management techniques, such as relaxation exercises and mindfulness practices, were commonly used by athletes to maintain focus and concentration, which is crucial for optimal performance (4).

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The role of motivation and goal-setting was evident, with athletes setting realistic goals to stay motivated. This finding aligns with He et al. (2018), who highlighted the importance of goal-setting in maintaining athletes' commitment to their training regimens despite challenging conditions. Cognitive functioning, including improved memory retention and problem-solving skills, was also reported, suggesting that high-altitude training might enhance cognitive performance (5). This is in line with Roach et al. (2013), who found that sleep quality, a factor affecting cognitive function, can improve with proper acclimatization (6).

Athletes employed various performance strategies to optimize their training at high altitudes. These included high-intensity interval training, balanced diet plans, and altitude simulation techniques. The use of altitude tents and hypoxic chambers to simulate high-altitude conditions was particularly notable, supporting the findings of Garvican-Lewis et al. (2017) that simulated hypoxia can enhance hematological adaptations and performance (8).

Nutrition and hydration strategies were crucial, with athletes emphasizing the need for balanced diets and proper hydration. This finding is supported by Park et al. (2016), who highlighted the importance of tailored nutritional strategies to support physiological adaptations (9). Rest and recovery protocols, including active recovery methods and sleep hygiene practices, were essential for maintaining performance and preventing injuries. This corresponds with Schommer et al. (2012), who noted that adequate recovery is vital to mitigate health risks associated with altitude training (7).

Social support from peers, coaches, and the community played a significant role in athletes' adaptations to high-altitude training. Athletes highlighted the importance of team bonding, coach feedback, and family encouragement in maintaining motivation and adherence to training regimens. These findings align with Khodaee et al. (2016), who emphasized the role of social support in enhancing psychological resilience and performance (4).

Environmental conditions, such as weather and altitude-specific gear, were also critical factors. Athletes adapted their training environments to suit high-altitude conditions, supporting the findings of Roach et al. (2013) on the importance of environmental adjustments for optimal performance (6). Travel and logistics management were crucial for minimizing disruptions and ensuring smooth transitions between training locations, resonating with Schommer et al. (2012), who highlighted the logistical challenges of altitude training (7).

The results of this study underscore the multifaceted nature of adaptations to high-altitude training. Physiological adaptations, such as improved respiratory function and increased red blood cell production, are well-documented benefits of high-altitude training (1). These adaptations enhance oxygen transport and utilization, crucial for endurance performance. The muscle adaptations reported by athletes, including increased endurance and mitochondrial density, further support the efficacy of high-altitude training in enhancing aerobic capacity (9).

Mental adaptations, particularly the development of mental resilience and effective stress management techniques, highlight the psychological demands of high-altitude training. These findings align with Khodaee et al. (2016), who emphasized the importance of psychological resilience in coping with high-altitude stressors (4). The use of motivation and goal-setting strategies reflects the athletes' proactive approach to maintaining commitment and focus, resonating with He et al. (2018) (5).

Performance strategies employed by athletes, such as high-intensity interval training and nutrition protocols, underscore the holistic approach required for successful high-altitude training. The use of altitude simulation techniques, such as hypoxic chambers, supports the findings of Garvican-Lewis et al. (2017) on the benefits of simulated hypoxia. These strategies collectively enhance physiological adaptations and performance outcomes (8).

Social and environmental factors play a critical role in facilitating adaptations to high-altitude training. The importance of social support from peers, coaches, and the community reflects the interconnected nature of physical and psychological resilience (4). Environmental adjustments and logistical management further underscore the need for comprehensive planning and support to optimize training outcomes (6, 7).

This study has several limitations that should be acknowledged. Firstly, the qualitative nature of the research, while providing rich and detailed insights, limits the generalizability of the findings to a broader population of athletes. The sample size of 30 participants, though

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sufficient for qualitative analysis, may not capture the full spectrum of experiences and adaptations among athletes engaged in high-altitude training. Additionally, the reliance on self-reported data from interviews may introduce biases, as participants might selectively recall or emphasize certain experiences. Future research could benefit from incorporating quantitative measures to complement the qualitative findings and enhance the robustness of the results.

Future research should aim to address the limitations of this study by employing larger, more diverse samples and integrating mixed-methods approaches. Quantitative studies could provide objective measures of physiological and psychological adaptations, offering a more comprehensive understanding of the impact of high-altitude training. Longitudinal studies tracking athletes over extended periods could also elucidate the long-term effects and sustainability of high-altitude adaptations. Moreover, investigating the specific mechanisms underlying individual variability in responses to altitude training, as highlighted by Nummela et al. (2020), could inform personalized training protocols and enhance the efficacy of altitude training programs.

Based on the findings of this study, several practical recommendations can be made for athletes and coaches. Firstly, individualized altitude training protocols should be developed to account for the variability in physiological and psychological responses. Coaches should emphasize the importance of gradual acclimatization and incorporate stress management techniques to support athletes' mental resilience. Nutrition and hydration strategies should be tailored to support the specific demands of high-altitude training, and recovery protocols should prioritize sleep quality and active recovery methods. Social support systems, including peer, coach, and family encouragement, should be leveraged to enhance motivation and adherence to training regimens. Finally, careful planning and management of environmental and logistical factors are crucial to minimize disruptions and optimize training outcomes.

Authors' Contributions

S.F.S. conceptualized the study, designed the research methodology, and supervised the data collection process. P.S.R. conducted the semi-structured interviews, transcribed the recordings, and contributed to the thematic analysis using NVivo software. Z.S.N.S. assisted in the recruitment of participants and supported the data collection and analysis process. S.V.K. helped with the literature review and contributed to the interpretation of the findings. S.S.S.T., the corresponding author, led the data analysis, interpreted the results, and took the lead in drafting and revising the manuscript. All authors participated in discussing the findings, critically reviewed the manuscript for important intellectual content, and approved the final version for publication.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

The study placed a high emphasis on ethical considerations. Informed consent obtained from all participants, ensuring they are fully aware of the nature of the study and their role in it. Confidentiality strictly maintained, with data anonymized to protect individual privacy. The study adhered to the ethical guidelines for research with human subjects as outlined in the Declaration of Helsinki.

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