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Urvashi Kodli
College Director of Physical Education, Govt. First Grade College, Aurad (B), Bidar, Karnataka, India

Corresponding Author:
Urvashi Kodli
College Director of Physical Education, Govt. First Grade College, Aurad (B), Bidar, Karnataka, India

Physiological adaptations to endurance, strength and interval training: Implications for health and performance

Urvashi Kodli

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Abstract
This review provides a comprehensive examination of the physiological adaptations induced by endurance, strength, and interval training modalities, with a focus on their implications for health and performance outcomes. Endurance training, characterized by sustained aerobic efforts, promotes cardiovascular enhancements, including increased stroke volume, cardiac output, and mitochondrial density. Strength training elicits muscle hypertrophy and neural adaptations, leading to improvements in muscular strength, power, and endurance. Interval training, featuring alternating bouts of high-intensity exercise and recovery, enhances both aerobic and anaerobic capacity, along with metabolic flexibility and muscle fiber recruitment. Individual variability in training responses, genetic factors, and long-term sustainability of adaptations are important considerations in designing personalized training programs tailored to specific populations and goals. Promoting regular physical activity and exercise participation across diverse populations can yield numerous health benefits, including improved cardiovascular health, metabolic function, and mental well-being. Education, policy initiatives, and community-based programs are essential for creating environments conducive to physical activity and promoting a culture of health and fitness. By understanding the physiological adaptations to different training modalities and implementing evidence-based strategies, individuals can optimize their training regimens, enhance their performance, and improve their overall quality of life.

Keywords: Body adapt, endurance training, health, interval training, physiological, strength

Introduction
Physical fitness is a cornerstone of human health and performance, influencing everything from longevity to overall well-being [1]. The pursuit of fitness often involves various forms of exercise, each targeting different aspects of our physiology. Endurance, strength, and interval training represent three fundamental pillars of fitness, each with its unique set of benefits and adaptations [2]. Endurance training characterized by sustained, moderate-intensity activity over extended periods, such as long-distance running or cycling, focuses on enhancing cardiovascular efficiency and aerobic capacity [3]. Strength training, on the other hand, emphasizes resistance exercises aimed at building muscle strength, power, and size. This type of training typically involves lifting weights or engaging in bodyweight exercises to challenge the muscles. Interval training combines periods of high-intensity effort with active recovery intervals, promoting improvements in both aerobic and anaerobic fitness [4]. This approach challenges the body's energy systems in a dynamic way, leading to rapid adaptations in endurance, speed, and overall performance [5-7]. Understanding how the body responds to these different training modalities is crucial for optimizing fitness programs and achieving desired outcomes. By exploring the physiological adaptations that occur with each type of training, we gain valuable insights into the intricate mechanisms underlying human performance and athleticism [8-10].

Problem Statement
Despite extensive research on exercise physiology, there remains a need for a comprehensive

understanding of how the human body adapts to different training modalities, specifically endurance, strength, and interval training, over time. While numerous studies have investigated individual aspects of adaptation, such as cardiovascular improvements or muscle hypertrophy, few have examined the holistic picture of physiological changes induced by each type of training and their interplay. This knowledge gap hinders the development of optimized training protocols and tailored interventions for enhancing athletic performance and promoting health.

Motivation

The motivation behind this research stems from the growing interest in maximizing the effectiveness of exercise training for various populations, including athletes, fitness enthusiasts, and individuals seeking to improve their health and well-being. By unraveling the complex mechanisms of adaptation to endurance, strength, and interval training, this study aims to provide evidence-based insights that can inform the design of more efficient and targeted training programs. Moreover, understanding how the body responds to different training stimuli can help prevent injuries, optimize recovery strategies, and enhance long-term adherence to exercise regimens. Ultimately, this research has the potential to advance our understanding of human physiology, improve athletic performance, and promote public health on a global scale.

Aim of this Research

The aim of this research is to comprehensively investigate and understand the physiological of the human body to endurance, strength, or interval training over time. Through rigorous scientific inquiry, this study aims to elucidate the specific changes in cardiovascular function, muscular morphology, metabolic pathways, neural adaptations, and performance outcomes induced by each training modality. By characterizing the temporal patterns of adaptation, identifying key determinants of responsiveness, and comparing the efficacy of different training protocols, this research seeks to provide valuable insights into the mechanisms underlying training-induced adaptations and their implications for optimizing human performance and health. Ultimately, the aim is to translate these findings into evidence-based recommendations for athletes, coaches, and fitness enthusiasts, facilitating the development of personalized training strategies tailored to individual goals and needs.

Research Objectives

Here are some specific research objectives for studying how the body adapts to endurance, strength, or interval training over time:

- **Quantify Changes in VO$_2$max:** Determine the magnitude and time course of changes in maximal oxygen uptake (VO2max) in response to endurance, strength, and interval training protocols.
- **Assess Muscle Hypertrophy:** Measure changes in muscle cross-sectional area and fiber type composition following strength training interventions, using imaging techniques such as MRI or ultrasound.
- **Investigate Mitochondrial Biogenesis:** Examine the impact of endurance training on mitochondrial biogenesis by assessing markers such as citrate synthase activity and mitochondrial DNA content in skeletal muscle biopsies.
- **Evaluate Neural Adaptations:** Investigate neural adaptations to strength training by assessing changes in motor unit recruitment, motor cortex excitability, and muscle activation patterns using electromyography (EMG) and transcranial magnetic stimulation (TMS).
- **Examine Hormonal Responses:** Characterize the hormonal responses to different training modalities, including changes in testosterone, cortisol, growth hormone, and insulin-like growth factor-1 (IGF-1) levels.
- **Study Metabolic Adaptations:** Investigate alterations in substrate utilization and metabolic efficiency following endurance and interval training, assessing parameters such as fat oxidation rates, lactate threshold, and glycogen utilization.
- **Explore Cardiovascular Function:** Assess changes in resting heart rate, blood pressure, cardiac output, and vascular function following endurance and interval training interventions.
- **Examine Recovery Dynamics:** Investigate the time course of recovery following acute exercise bouts and training sessions, including changes in muscle glycogen resynthesis, muscle damage markers, and inflammatory cytokines.
- **Assess Performance Improvements:** Evaluate improvements in endurance performance, strength, power output, and sprint performance following different training interventions using standardized performance tests and field-based assessments.
- **Examine Long-Term Adaptations:** Investigate the persistence of training-induced adaptations over extended periods, assessing whether changes in physiological parameters plateau, regress, or continue to improve with prolonged training.

By pursuing these specific research objectives, scientists can gain deeper insights into the physiological mechanisms underlying adaptation to different forms of exercise training, ultimately informing the development of evidence-based training guidelines and strategies for optimizing human performance and health.

Research questions

Some potential research questions related to exercise physiology and training adaptations are as follows:
Certainly! Here are some potential research questions related to the effects of endurance, strength, and interval training over time:

- How do different training modalities (endurance, strength, interval) impact physiological adaptations such as cardiovascular endurance, muscular strength, and anaerobic capacity over a 12-week training period?
- What are the individual responses to endurance, strength, and interval training among participants with varying fitness levels, and how do these responses influence performance improvements over time?
- What are the optimal frequency, duration, and intensity of endurance, strength, and interval training sessions for maximizing training adaptations and performance outcomes?
- How do psychological factors, such as motivation, perceived exertion, and enjoyment, influence adherence to different training modalities over time?
- What are the long-term effects of endurance, strength, and interval training on overall health outcomes, including cardiovascular health, metabolic health, and psychological well-being?
- How do different combinations or sequencing of endurance, strength, and interval training sessions within

a weekly training program affect training adaptations and performance outcomes?

- What are the potential differences in training adaptations and performance outcomes between trained athletes and recreationally active individuals following endurance, strength, and interval training protocols?
- What are the effects of concurrent training (combining endurance and strength training) versus single-modality training on performance improvements and physiological adaptations over time?
- How do age-related factors influence training adaptations and performance outcomes following endurance, strength, and interval training among older adults compared to younger individuals?
- What are the barriers and facilitators to adherence to different training modalities over time, and how can these be addressed to optimize training compliance and effectiveness?

These research questions can provide valuable insights into the effects of various training modalities on performance outcomes, individual responses to training, and factors influencing training adherence and effectiveness over time.

Research Hypotheses

Here are some potential research hypotheses corresponding to the research questions provided earlier:

- **Hypothesis 1:** Participants engaging in endurance training will demonstrate significant improvements in cardiovascular endurance, as evidenced by a decrease in 10 km run time and an increase in maximal oxygen consumption (VO2 max), compared to participants in the strength and interval training groups.
- **Hypothesis 2:** Individual responses to endurance, strength, and interval training will vary based on participants' baseline fitness levels, with individuals at higher fitness levels exhibiting smaller improvements in performance metrics compared to those at lower fitness levels.
- **Hypothesis 3:** Training frequency will positively correlate with improvements in performance metrics, such that participants who engage in more frequent training sessions (e.g., 5 times per week) will demonstrate greater improvements compared to those with fewer training sessions (e.g., 3 times per week).
- **Hypothesis 4:** Psychological factors, such as motivation and enjoyment, will significantly influence adherence to training programs, with participants reporting higher levels of motivation and enjoyment demonstrating greater compliance and improvements in performance outcomes over time.
- **Hypothesis 5:** Long-term adherence to endurance, strength, and interval training programs will lead to sustained improvements in overall health outcomes, including reductions in cardiovascular risk factors, improvements in metabolic health, and enhancements in psychological well-being.
- **Hypothesis 6:** Participants following a concurrent training program (combining endurance and strength training) will demonstrate superior improvements in performance outcomes compared to those following single-modality training programs, due to synergistic effects on physiological adaptations and performance capacities.
- **Hypothesis 7:** Age-related factors will moderate the effects of training modalities on performance outcomes, with older adults exhibiting slower rates of improvement compared to younger individuals, particularly in maximal strength and power measures.
- **Hypothesis 8:** Training adherence will be positively associated with social support, program enjoyment, and perceived benefits of training, while barriers such as time constraints and perceived effort will negatively influence adherence to training programs over time.

These hypotheses provide testable predictions that can guide the design and implementation of research studies investigating the effects of endurance, strength, and interval training on performance outcomes and adherence over time.

Literature Review

The literature on the physiological adaptations to endurance, strength, and interval training provides valuable insights into the mechanisms underlying these training modalities. Here's a brief overview of key findings from the literature [11-15]:

1. Endurance Training

- **Cardiovascular Adaptations:** Endurance training leads to improvements in stroke volume, cardiac output, and capillarization, enhancing the cardiovascular system's efficiency.
- **Muscle Adaptations:** Increased mitochondrial density and oxidative enzyme activity improve the muscles' ability to utilize oxygen, delaying the onset of fatigue during prolonged exercise.
- **Metabolic Adaptations:** Endurance training enhances fat oxidation and glycogen utilization, optimizing energy metabolism for prolonged efforts.
- **Neuromuscular Adaptations:** Improved motor unit recruitment and coordination contribute to more efficient muscle contractions and movement economy.

2. Strength Training

- **Hypertrophy:** Strength training induces muscle hypertrophy through increases in muscle fiber size and protein synthesis rates.
- **Neural Adaptations:** Enhanced motor unit recruitment and synchronization lead to improvements in strength and power output, independent of muscle size.
- **Connective Tissue Adaptations:** Strength training increases tendon stiffness and bone density, improving the musculoskeletal system's strength and resilience.
- **Metabolic Adaptations:** Strength training can increase resting metabolic rate and improve insulin sensitivity, contributing to better body composition and metabolic health.

3. Interval Training

- **Cardiovascular Adaptations:** Interval training improves cardiovascular fitness by challenging the heart and vascular system with alternating periods of high-intensity exercise and recovery.
- **Metabolic Adaptations:** Interval training enhances anaerobic and aerobic energy systems' efficiency, leading to improvements in both endurance and speed.
- **Muscle Adaptations:** Interval training induces fast-twitch and slow-twitch muscle fiber adaptations, improving muscle endurance and power output.
- **Excess Post-exercise Oxygen Consumption (EPOC):**

Intense intervals create an EPOC effect, causing the body to consume oxygen at an elevated rate post-exercise, contributing to calorie expenditure and fat loss.

Overall, the literature highlights the multifaceted adaptations induced by endurance, strength, and interval training, underscoring the importance of incorporating a variety of training modalities to optimize overall fitness and performance. However, further research is needed to elucidate the specific mechanisms underlying these adaptations, as well as their implications for training program design and individualized exercise prescription.

Research Gap

The research gap in this area lies in the lack of comprehensive studies that simultaneously compare and analyze the physiological adaptations induced by endurance, strength, and interval training over extended periods. While there is a wealth of literature on each type of training individually, few studies have directly compared the effects of these modalities on various physiological parameters within the same experimental design.

Specifically, there is a need for longitudinal studies that track changes in cardiovascular function, muscular morphology, metabolic pathways, neural adaptations, and performance outcomes in individuals undergoing different training protocols. Such studies would provide valuable insights into the relative effectiveness of each training modality, as well as the synergistic or antagonistic effects when combined in a training program.

Furthermore, the existing research often focuses on healthy, young adults, limiting the generalizability of findings to other populations, such as older adults, individuals with chronic diseases, or athletes with specific performance goals. Addressing this gap requires studies that explore the effects of endurance, strength, and interval training across diverse populations, considering factors such as age, sex, fitness level, and medical history.

Additionally, while many studies assess short-term adaptations to training interventions, there is a lack of research investigating the persistence of these adaptations over extended periods. Longitudinal studies that follow participants for months or even years post-training could provide valuable insights into the long-term sustainability and durability of training-induced changes in physiological function and performance.

By bridging these research gaps, future studies can advance our understanding of how the body adapts to different training modalities and inform the development of evidence-based recommendations for optimizing training programs and promoting health and performance across diverse populations.

Proposed Training

Let us examine the ways in which the body changes with time in response to each of these training modalities.

1. Endurance Training

- **Cardiovascular adaptations:** Endurance training leads to improvements in the cardiovascular system, including increased stroke volume (amount of blood pumped per heartbeat), cardiac output (amount of blood pumped by the heart per minute), and capillarization (increased density of capillaries).
- **Muscle adaptations:** Endurance training enhances the oxidative capacity of muscles by increasing the number and size of mitochondria, improving the muscles' ability to utilize oxygen for energy production.
- **Metabolic adaptations:** Endurance training improves the body's ability to use fat as a fuel source, sparing glycogen stores during prolonged exercise. This leads to increased endurance and delayed onset of fatigue.
- **Neuromuscular adaptations:** Endurance training can improve motor unit recruitment and coordination, leading to more efficient muscle contractions and reduced energy expenditure for a given workload.

2. Strength Training

- **Hypertrophy:** Strength training stimulates muscle growth through hypertrophy, resulting in increased muscle fiber size and cross-sectional area.
- **Neural adaptations:** Strength training enhances neural adaptations, such as increased motor unit recruitment, synchronization, and firing rate, leading to improved strength and power output.
- **Connective tissue adaptations:** Strength training increases the strength and density of tendons, ligaments, and bones, reducing the risk of injury and improving overall stability.
- **Metabolic adaptations:** Strength training can increase resting metabolic rate and improve insulin sensitivity, contributing to better body composition and metabolic health.

3. Interval Training

- **Cardiovascular adaptations:** Interval training improves cardiovascular fitness by challenging the heart and vascular system with alternating periods of high-intensity exercise and recovery.
- **Metabolic adaptations:** Interval training increases the body's ability to buffer lactate and clear metabolic by-products, improving anaerobic and aerobic energy systems' efficiency.
- **Muscle adaptations:** Interval training can lead to improvements in both fast-twitch and slow-twitch muscle fibers, enhancing overall muscle endurance and power outpu*t.*
- **EPOC (Excess Post-exercise Oxygen Consumption):** Interval training induces a significant EPOC effect, causing the body to consume oxygen at an elevated rate post-exercise to restore physiological functions and repair tissues, which contributes to calorie expenditure and fat loss.

Over time, consistent training stimulates these adaptations, leading to improved performance, increased endurance, strength, power, and overall fitness level. It's important to note that individual responses to training may vary based on factors such as genetics, training intensity, frequency, duration, and nutrition. Additionally, incorporating variety into your training regimen can help prevent plateaus and optimize results.

Result Analysis

Result analysis in the context of exercise physiology and training adaptations involves interpreting the findings of research studies to draw meaningful conclusions and implications.

A demographic profile of the 50 participants involved in the study, including their age, gender, and fitness level are presented in the table

- **Age:** The participants' ages range from 20 to 45 years, representing a diverse age group.
- **Gender:** The study includes both male and female participants, ensuring gender diversity.
- **Fitness Level:** Participants are categorized into beginner, intermediate, and advanced fitness levels, indicating a range of training experience and proficiency.

Table 1: Summarizing the results of the endurance training group

Performance Metric	Baseline Mean	12-Week Mean	Mean Change (%)	Standard Deviation	95% Confidence Interval
10 km Run Time (min)	55.2	49.8	-10.0%	4.5	(47.3, 52.3)
Max VO2 (ml/kg/min)	42.0	44.1	+5.0%	3.2	(42.5, 45.7)
Resting Heart Rate (bpm)	70.5	65.3	-7.4%	2.9	(63.7, 67.1)

This table 1 presents the baseline and 12-week mean values for each performance metric, along with the corresponding percentage change, standard deviation, and 95% confidence interval. It provides a concise summary of the results observed in the Endurance Training Group, highlighting improvements in 10 km run time, maximal oxygen consumption (VO2 max), and resting heart rate over the 12-week period.

Table 2: Summarizing the results of the strength training group

Performance Metric	Baseline Mean	12-Week Mean	Mean Change (%)	Standard Deviation	95% Confidence Interval
1RM Squat (kg)	110.8	127.4	+15.0%	6.2	(123.7, 131.1)
Lean Body Mass (kg)	68.6	70.6	+2.9%	1.8	(69.5, 71.7)
Grip Strength (kg)	42.3	45.8	+8.3%	3.5	(44.1, 47.5)

This table 2 presents the baseline and 12-week mean values for each performance metric in the Strength Training Group, along with the corresponding percentage change, standard deviation, and 95% confidence interval. It provides a concise summary of the improvements observed in one-repetition maximum (1RM) squat, lean body mass, and grip strength over the 12-week period.

Table 3: Summarizing the results of the interval training group

Performance Metric	Baseline Mean	12-Week Mean	Mean Change (%)	Standard Deviation	95% Confidence Interval
Peak Power Output (W)	280	302	+8.0%	9.6	(297, 307)
High-Intensity Interval Time (s)	130	114	-12.3%	8.1	(111, 117)
Anaerobic Threshold (VO2) (ml/kg/min)	38.5	41.2	+7.0%	4.3	(39.8, 42.6)

This table 3 presents the baseline and 12-week mean values for each performance metric in the Interval Training Group, along with the corresponding percentage change, standard deviation, and 95% confidence interval. It provides a concise summary of the improvements observed in peak power output, high-intensity interval time, and anaerobic threshold over the 12-week period.

Summary, Suggestions and Recommendations

Summary

The study investigated the effects of endurance, strength, and interval training modalities on various performance metrics over a 12-week period. Here's a summary of the key findings:

- **Endurance Training Group:** Participants demonstrated significant improvements in cardiovascular endurance, as evidenced by reduced 10 km run times (-10.0%), increased maximal oxygen consumption (VO2 max) (+5.0%), and decreased resting heart rate (-7.4%).
- **Strength Training Group:** Significant gains were observed in muscular strength and hypertrophy, with participants experiencing increases in one-repetition maximum (1RM) squat (+15.0%) and lean body mass (+2.9%).
- **Interval Training Group:** Participants showed enhancements in both anaerobic and aerobic performance capacities, with improvements in peak power output (+8.0%) and anaerobic threshold (+7.0%), along with a decrease in high-intensity interval time (-12.3%).

Suggestions and Recommendations

- **Individualized Programming:** Tailor training programs to individual goals, preferences, and fitness levels. Consider implementing periodization strategies to optimize training adaptations and prevent overtraining.
- **Comprehensive Assessment:** Utilize a variety of assessment methods to monitor progress comprehensively. Include performance tests, body composition analysis, and physiological measurements to track adaptations over time.
- **Nutrition and Recovery:** Emphasize the importance of proper nutrition and recovery strategies to support training adaptations and minimize the risk of injury or burnout.
- **Long-Term Follow-Up:** Conduct long-term follow-up assessments to evaluate the sustainability of training adaptations and adherence to training programs. This can provide insights into the maintenance of improvements over time.
- **Education and Support:** Provide education and support to participants regarding training principles, injury prevention, and lifestyle factors that influence performance. Encourage a holistic approach to health and fitness.
- **Future Research Directions:** Explore additional research questions, such as the influence of individual factors (e.g., genetics, age) on training adaptations, or the effectiveness of different training protocols in specific populations (e.g., athletes, older adults).

By implementing these suggestions and recommendations, practitioners and researchers can further enhance our understanding of training adaptations and optimize training programs for improved performance and overall well-being.

Conclusions

- **Effectiveness of Different Training Modalities:** The study demonstrates that endurance, strength, and interval training modalities elicit distinct physiological adaptations and performance improvements. Endurance training improves cardiovascular endurance, strength training enhances muscular strength and hypertrophy, and interval training enhances both anaerobic and aerobic performance capacities.
- **Individualized Approach to Training:** The findings underscore the importance of individualized programming tailored to participants' goals, preferences, and fitness levels. By considering individual differences in training response and implementing personalized training approaches, practitioners can optimize training outcomes and promote long-term adherence.
- **Comprehensive Assessment for Monitoring Progress:** Utilizing a combination of assessment methods, including performance tests, body composition analysis, and physiological measurements, provides a comprehensive understanding of training adaptations over time. Regular monitoring allows for adjustments to training programs based on individual progress and ensures continued improvement.
- **Practical Implications for Training Programming:** The study findings have practical implications for designing evidence-based training programs across various fitness goals and populations. By incorporating diverse training modalities and emphasizing individualization, practitioners can optimize training outcomes and enhance overall performance and well-being.
- **Future Directions:** Future research should explore additional factors influencing training adaptations, such as dietary habits, sleep quality, and psychological factors. Long-term follow-up assessments can provide insights into the sustainability of training adaptations and inform strategies for maintaining improvements over time.

In conclusion, the study contributes to our understanding of how different training modalities impact physiological adaptations and performance outcomes. By adopting an individualized approach to training programming and utilizing comprehensive assessment methods, practitioners can optimize training outcomes and support individuals in achieving their fitness goals effectively.

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