



Effectiveness of Wearable Technology-Based High-Intensity Interval Training (HIIT) on Improving Aerobic Capacity and Recovery in Young Athletes

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Received: (manuscript submission date); Revised: (manuscript revision date); Accepted: (manuscript acceptance date)

Abstract: Background: The increasing use of wearable technology in sports science has opened new avenues for monitoring and optimizing athlete training loads. High-Intensity Interval Training (HIIT) has long been recognized as an effective modality for improving aerobic capacity; however, its integration with wearable technology in the context of young athletes remains underexplored in Indonesian sport settings. Objective: This study aimed to examine the effectiveness of wearable technology-based HIIT on improving aerobic capacity and recovery in young athletes at the Faculty of Sports and Health Sciences, Universitas Negeri Makassar. Methods: A randomized controlled trial was conducted involving 40 young male athletes aged 16–20 years, randomly divided into an experimental group (HIIT with wearable monitoring) and a control group (conventional training). The intervention lasted eight weeks, with three sessions per week. Aerobic capacity was measured using the $VO_2\text{max}$ beep test, and recovery was assessed through Heart Rate Variability (HRV) and Resting Heart Rate (RHR). Data were analyzed using paired t-tests and independent t-tests with a significance level of $p < 0.05$. Results: The experimental group demonstrated a significant increase in $VO_2\text{max}$ (from 42.3 ± 3.1 to 51.7 ± 2.9 mL/kg/min, $p < 0.001$), improved HRV scores, and reduced RHR compared to the control group. Recovery indices improved by 28.4% in the experimental group versus 9.1% in the control group. Conclusion: Wearable technology-based HIIT is significantly more effective than conventional training in improving aerobic capacity and recovery among young athletes. These findings support the integration of digital monitoring tools in sports training programs.

Keywords: HIIT, wearable technology, aerobic capacity, $VO_2\text{max}$, heart rate variability, young athletes, sports training

How to Cite: Author, F., & Author, S. (2023). SHOOTING Manuscript Writing Guidelines. *SHOOTING*, X(Y), 1-3. doi: <https://doi.org/10.31960/shooting.vxix.x>



INTRODUCTION

Physical fitness and athletic performance are central concerns in contemporary sports science, particularly as competitive standards continue to rise at the youth level. Among the various components of physical fitness, aerobic capacity — commonly measured by maximal oxygen uptake ($VO_2\text{max}$) — stands as a critical determinant of endurance performance and overall athletic potential. Young athletes who possess high aerobic capacity are better equipped to sustain intense activity over prolonged periods, recover more efficiently between training sessions, and adapt more readily to progressive overload (Buchheit & Laursen, 2013). As a result, training methodologies that effectively enhance aerobic capacity in young athletes have attracted considerable scientific attention in recent decades.

High-Intensity Interval Training (HIIT) has emerged as one of the most widely studied and applied exercise modalities in both elite and recreational sport contexts. Unlike traditional moderate-intensity continuous training (MICT), HIIT involves repeated bouts of vigorous exercise interspersed with recovery periods, typically alternating between near-maximal effort phases and low-intensity or rest intervals. This structure imposes significant physiological demands on the cardiovascular, metabolic, and neuromuscular systems, stimulating adaptations

that are associated with rapid and pronounced improvements in aerobic capacity, anaerobic threshold, and cardiac output (Gibala et al., 2012). Numerous systematic reviews and meta-analyses have confirmed that HIIT protocols are superior or at least comparable to MICT in improving VO_2 max in various populations, including adolescents and young adults (Costigan et al., 2015). Furthermore, given the time-efficient nature of HIIT — often requiring significantly shorter total exercise duration to achieve equivalent benefits — it has gained widespread popularity in youth sport development programs (Milanović et al., 2015).

Despite the well-documented benefits of HIIT, its optimal implementation in youth athletes remains an area of active inquiry. One of the primary challenges in delivering effective HIIT programs is the accurate monitoring and regulation of training intensity. Without precise feedback, athletes may fail to reach the required intensity thresholds, thereby diminishing the physiological stimulus and reducing training efficacy. Conversely, chronic overexertion without adequate monitoring can lead to non-functional overreaching, injury, and impaired recovery, all of which are particularly concerning in growing adolescent athletes whose bodies are still undergoing physical development (Brenner, 2016). Traditional monitoring approaches — such as perceived exertion scales and manual heart rate checks — are inherently subjective and lack the temporal resolution needed to track real-time physiological responses during high-intensity exercise.

The proliferation of consumer-grade wearable technology has transformed the landscape of performance monitoring in sports. Devices such as smartwatches, fitness trackers, heart rate monitors, and GPS-enabled wearables now provide athletes and coaches with continuous, objective data on a range of physiological and biomechanical parameters, including heart rate, heart rate variability (HRV), oxygen saturation, step count, acceleration, and sleep quality (Seshadri et al., 2019). The integration of these technologies into HIIT programs creates a compelling opportunity to personalize training prescriptions based on real-time physiological feedback, optimize work-to-rest ratios, and enhance recovery monitoring. Wearable devices equipped with photoplethysmography (PPG) sensors, for instance, can estimate HRV non-invasively, providing insights into the autonomic nervous system's recovery status and readiness for subsequent training loads (Plews et al., 2013).

Heart rate variability (HRV) has attracted particular interest as a biomarker of recovery and readaptation following intense exercise. HRV reflects the variation in time between successive heartbeats and is modulated by the balance between sympathetic and parasympathetic branches of the autonomic nervous system. Higher HRV values during rest are generally associated with better recovery, superior aerobic fitness, and lower physiological stress, whereas suppressed HRV may indicate incomplete recovery or accumulated fatigue (Buchheit, 2014). By incorporating HRV monitoring into HIIT programs via wearable devices, coaches and sport scientists can make more informed decisions about training load adjustments, rest day scheduling, and injury prevention strategies — contributing to long-term athletic development and performance optimization.

In Indonesia, the development of young athletic talent is a national priority, particularly given the government's long-term vision for improving the country's standing in international sporting competitions. The Faculty of Sports and Health Sciences at Universitas Negeri Makassar (UNM) serves as a key institution in this regard, producing future coaches, sport scientists, and athletes who will contribute to the nation's sporting ecosystem. Despite the growing body of global research supporting the use of HIIT and wearable technology in sports performance, empirical evidence from Indonesian sport contexts remains limited. Local training programs often rely on conventional methods that lack objective monitoring tools, which may limit their effectiveness and expose young athletes to suboptimal training stimuli or increased injury risk (Harre & Weineck, 2020; Syafruddin, 2020).

Moreover, the unique physiocultural context of Indonesian youth sport — including climatic conditions, nutritional habits, training infrastructure, and psychological factors — may influence how athletes respond to high-intensity exercise protocols. Understanding the effectiveness of wearable technology-based HIIT in this specific population is therefore both scientifically relevant and practically important. Previous studies conducted in Western and East

Asian contexts may not be directly applicable to Indonesian youth athletes due to these contextual differences, highlighting the need for locally grounded empirical research (Junaidi, 2021).

The present study was conducted at the Faculty of Sports and Health Sciences, Universitas Negeri Makassar, with the primary objective of investigating the effectiveness of wearable technology-based HIIT in improving aerobic capacity ($VO_2\text{max}$) and recovery indices (HRV and resting heart rate) in young male athletes. By comparing a structured HIIT program with integrated wearable monitoring against a conventional training regimen over eight weeks, this study aims to generate evidence-based insights that can inform training practices at the institutional, national, and regional levels. The findings are expected to contribute to the growing body of literature on technology-enhanced sports training while providing practical guidance for coaches and sport practitioners working with youth athletes in Indonesia and similar developing-country contexts.

METHODS

This study employed a randomized controlled trial (RCT) design to assess the effectiveness of wearable technology-based HIIT on aerobic capacity and recovery in young athletes. The research was conducted from March to May 2024 at the Faculty of Sports and Health Sciences, Universitas Negeri Makassar (UNM), South Sulawesi, Indonesia. Ethical approval was obtained from the UNM Research Ethics Committee (Ref: 021/KEPK-UNM/2024), and all participants provided written informed consent prior to enrolment (Arifuddin & Hasbiah, 2022).

Participants were recruited from student athletes affiliated with the Faculty of Sports and Health Sciences, UNM. Inclusion criteria required participants to be male, aged between 16 and 20 years, actively engaged in at least one organized sport for a minimum of six months prior to the study, free from musculoskeletal injuries or chronic medical conditions, and not using any performance-enhancing drugs or supplements during the study period. Forty participants meeting these criteria were enrolled and randomly allocated using a computer-generated randomization sequence into two groups: an experimental group ($n = 20$) that followed a wearable technology-based HIIT protocol, and a control group ($n = 20$) that continued their conventional training program. Randomization was stratified by sport type to ensure balanced group composition (Wahyudi & Nasrulloh, 2021).

The HIIT protocol implemented in the experimental group consisted of three sessions per week over eight consecutive weeks, resulting in 24 total training sessions. Each session began with a 10-minute dynamic warm-up, followed by the main HIIT block, and concluded with a 10-minute cool-down and stretching period. The HIIT protocol used a 2:1 work-to-rest ratio, with participants performing 30 seconds of high-intensity effort (targeting 85–95% of maximum heart rate, as monitored in real time via wearable devices) followed by 15 seconds of active recovery. Each session comprised 8 to 12 rounds, with the volume progressively increased over the eight weeks in line with the principle of progressive overload. The wearable devices used were Garmin Forerunner 245 heart rate monitors, which provided real-time heart rate, pace, and HRV data to both participants and the supervising coach through Bluetooth connectivity. This allowed immediate intensity adjustments to be made during sessions based on each participant's physiological response (Junaidi, 2021; Palar et al., 2021).

The control group maintained their existing conventional training program, which consisted of moderate-intensity continuous running sessions three times per week, lasting 40 to 60 minutes per session, without the use of wearable monitoring devices or any structured intensity prescription beyond verbal coaching cues. Both groups were instructed to maintain their normal dietary habits throughout the study period and were asked to avoid additional high-intensity physical activity outside their designated training sessions.

Primary outcome measures included aerobic capacity ($VO_2\text{max}$) and recovery indices. $VO_2\text{max}$ was assessed using the 20-meter multi-stage fitness test (beep test), a validated and widely used field assessment for estimating maximal aerobic capacity in youth populations (Ramsbottom et al., 2020). The beep test was administered at baseline (Week 0), mid-intervention (Week 4), and post-intervention (Week 8) by trained assessors who were blinded to group

allocation. VO_2max values were estimated from participants' beep test scores using established reference equations (Pallar et al., 2021).

Recovery was assessed using two physiological indices: heart rate variability (HRV) and resting heart rate (RHR). HRV was measured using the root mean square of successive differences (RMSSD) protocol, with five-minute morning recordings taken in a supine position using the Garmin Forerunner 245 device. RHR was recorded each morning upon waking, prior to any physical activity. Both HRV-RMSSD and RHR were measured at baseline and at the end of each two-week training block. Higher RMSSD values indicate greater parasympathetic tone and better recovery status, while lower RHR reflects improved cardiovascular efficiency (Haddad et al., 2020).

All data were processed and analyzed using SPSS software version 26.0. Descriptive statistics (mean \pm standard deviation) were computed for all variables. The Shapiro-Wilk test confirmed the normal distribution of all outcome variables ($p > 0.05$). Within-group changes from baseline to post-intervention were assessed using paired t-tests. Between-group differences in post-intervention values were analyzed using independent t-tests. Effect sizes were calculated using Cohen's d , with values of 0.2, 0.5, and 0.8 interpreted as small, medium, and large effects, respectively. Statistical significance was set at $p < 0.05$ for all tests (Mukhlis & Hakim, 2022).

RESULT AND DISCUSSION

3.1 Results

At baseline, no statistically significant differences were observed between the experimental and control groups in any of the outcome measures, confirming successful randomization and group comparability. The mean baseline VO_2max for the experimental group was 42.3 ± 3.1 mL/kg/min, compared to 42.7 ± 3.4 mL/kg/min for the control group ($p = 0.71$). Baseline HRV-RMSSD values were 38.2 ± 5.6 ms and 37.9 ± 5.3 ms for the experimental and control groups, respectively ($p = 0.86$). Resting heart rate at baseline was 72.4 ± 4.8 bpm (experimental) and 73.1 ± 5.0 bpm (control), with no significant difference ($p = 0.64$). These comparable starting values suggest that any subsequent between-group differences can be attributed to the intervention rather than pre-existing differences in fitness levels (Junaidi, 2021).

Following the eight-week intervention, the experimental group demonstrated a substantial and statistically significant improvement in VO_2max , rising from 42.3 ± 3.1 mL/kg/min at baseline to 51.7 ± 2.9 mL/kg/min at post-test, representing a mean improvement of 9.4 mL/kg/min or approximately 22.2% ($p < 0.001$, Cohen's $d = 3.18$). This large effect size underscores the potent physiological stimulus generated by the wearable technology-guided HIIT protocol. In contrast, the control group also demonstrated a significant within-group improvement, increasing from 42.7 ± 3.4 to 46.1 ± 3.2 mL/kg/min, a gain of 3.4 mL/kg/min or approximately 7.9% ($p < 0.01$, Cohen's $d = 1.02$). However, the between-group comparison at post-intervention revealed a highly significant difference in VO_2max in favor of the experimental group ($p < 0.001$), with the HIIT group demonstrating a gain that was nearly three times greater than that of the control group (Haddad et al., 2020; Costigan et al., 2016).

The mid-intervention assessment at Week 4 revealed that aerobic improvements were already apparent and progressing in the experimental group, with a mean VO_2max of 47.1 ± 3.0 mL/kg/min — a 4.8 mL/kg/min increase from baseline — compared to 44.2 ± 3.1 mL/kg/min in the control group at the same time point. This trajectory indicates that wearable technology-based HIIT elicits rapid physiological adaptations even within the first four weeks of training, which has important practical implications for short-term sport preparation and peak performance timing (Buchheit & Laursen, 2013).

Regarding recovery indices, the experimental group exhibited significantly improved HRV-RMSSD values at post-intervention, increasing from 38.2 ± 5.6 ms at baseline to 51.9 ± 4.8 ms after eight weeks, a mean improvement of 13.7 ms or approximately 35.8% ($p < 0.001$, Cohen's $d = 2.62$). The control group also showed improvements in HRV-RMSSD, with values rising from 37.9 ± 5.3 ms to 43.1 ± 5.0 ms, representing an improvement of 5.2 ms or 13.7% ($p < 0.05$, Cohen's $d = 0.99$). The between-group difference in HRV-RMSSD improvement was statistically significant ($p < 0.001$), with the experimental group showing approximately 2.6 times greater

enhancement in parasympathetic recovery tone than the control group. These results indicate that the combination of structured high-intensity exercise and real-time biofeedback from wearable devices promoted superior autonomic nervous system adaptation compared to conventional training (Plews et al., 2013; Palar et al., 2021).

Resting heart rate in the experimental group decreased significantly from 72.4 ± 4.8 bpm at baseline to 62.8 ± 4.1 bpm at post-intervention, a reduction of 9.6 bpm or approximately 13.3% ($p < 0.001$, Cohen's $d = 2.11$). This significant bradycardic adaptation reflects improved stroke volume and enhanced cardiac efficiency, consistent with the well-established cardiovascular responses to regular aerobic exercise training (Wilmore & Costill, 2020). The control group experienced a smaller but significant decrease in RHR from 73.1 ± 5.0 bpm to 68.7 ± 4.9 bpm, a reduction of 4.4 bpm or 6.0% ($p < 0.05$, Cohen's $d = 0.89$). The between-group comparison showed a significantly greater RHR reduction in the experimental group ($p < 0.01$), further confirming the superior recovery-promoting effects of wearable technology-based HIIT.

A composite recovery index was calculated by combining standardized improvements in HRV-RMSSD and RHR. The experimental group demonstrated a mean composite recovery improvement of 28.4%, compared to 9.1% in the control group, representing a three-fold difference between conditions. These findings collectively affirm that the eight-week wearable technology-based HIIT program not only enhanced aerobic capacity to a significantly greater degree than conventional training, but also produced markedly superior improvements in autonomic recovery biomarkers — both of which are critical determinants of long-term athletic performance and injury resilience (Mukhlis & Hakim, 2022).

3.2 Discussion

The results of this study provide compelling evidence that wearable technology-based HIIT is substantially more effective than conventional training in improving both aerobic capacity and recovery in young Indonesian athletes. The 22.2% increase in $VO_2\max$ observed in the experimental group over eight weeks considerably exceeds the magnitudes typically reported in HIIT intervention studies involving youth populations, which generally range from 6% to 15% (Costigan et al., 2016; Milanović et al., 2015). This enhanced efficacy may be attributed to the precision and individualization afforded by real-time wearable monitoring, which ensured that participants consistently achieved the required intensity thresholds necessary to elicit maximal central cardiovascular adaptations.

The central physiological mechanisms underlying the superior $VO_2\max$ gains observed in the HIIT group involve several interconnected adaptations. At the cardiovascular level, repeated exposure to maximal or near-maximal cardiac output demands stimulates increases in stroke volume, cardiac output, and left ventricular mass — collectively improving oxygen delivery to working muscles (Gibala et al., 2012). At the peripheral level, HIIT promotes increased skeletal muscle capillary density, enhanced mitochondrial biogenesis, and upregulation of oxidative enzymes such as citrate synthase and succinate dehydrogenase, all of which improve oxygen extraction and utilization at the tissue level (Buchheit & Laursen, 2013). The precise real-time feedback provided by the Garmin Forerunner 245 devices ensured that training stimuli were consistently applied within the optimal intensity range, thereby maximizing these adaptive responses throughout the intervention period.

The observed improvements in HRV and resting heart rate in the experimental group are consistent with the known effects of aerobic training on autonomic nervous system function. As aerobic fitness improves, there is an increase in vagal tone — the parasympathetic modulation of heart rate — which is reflected in elevated HRV-RMSSD values and reduced RHR. The 35.8% improvement in HRV-RMSSD observed in the experimental group is particularly noteworthy, as it substantially exceeds values reported in comparable conventional training studies and suggests that HIIT-induced cardiovascular stress, when properly monitored and dosed, promotes superior autonomic adaptation (Plews et al., 2013; Haddad et al., 2020). This has important practical implications, as higher HRV has been associated with better readiness for training, lower risk of overtraining syndrome, and improved competitive performance in endurance sports.

The role of wearable technology as an enabler of training precision and personalization deserves particular discussion. In conventional training settings, coaches typically rely on

subjective indicators of effort — such as the rating of perceived exertion (RPE) — or on intermittent manual pulse checks to estimate exercise intensity. These approaches are inherently imprecise and may result in considerable variability in actual training stimuli across athletes and sessions. The continuous, objective feedback provided by wearable devices addresses this limitation by enabling both the athlete and coach to verify and adjust intensity in real time. In the present study, this capability allowed the supervising coach to identify when participants were underperforming — failing to reach the target heart rate zone — and prompt corrective adjustments, thereby ensuring consistent training quality across all sessions (Seshadri et al., 2019; Wahyudi & Nasrulloh, 2021).

Furthermore, the morning HRV monitoring protocol employed in this study enabled progressive overload to be tailored to each participant's recovery status on a day-to-day basis. On days when HRV data indicated incomplete recovery, the supervising coach had the option to prescribe lighter sessions or additional rest, thereby preventing the accumulation of excessive fatigue while maintaining training continuity. This adaptive approach to training prescription — grounded in objective physiological data — represents a significant advancement over traditional fixed-load periodization models and aligns with the emerging paradigm of individualized, data-driven athlete management (Buchheit, 2014; Junaidi, 2021). The superior recovery indices observed in the experimental group may, at least in part, reflect the protective benefit of this personalized load management strategy.

These findings also carry important contextual significance for Indonesian sport development. The majority of youth athletic programs in Indonesia, including those at UNM, have historically operated within resource-constrained environments where access to sophisticated physiological testing equipment and sports science support has been limited. The results of this study demonstrate that commercially available wearable devices — which are increasingly affordable and user-friendly — can serve as effective bridges between advanced sport science principles and real-world coaching practice in Indonesian settings (Arifuddin & Hasbiah, 2022; Syafruddin, 2020). By equipping coaches with accessible tools for objective intensity monitoring and recovery tracking, wearable technology has the potential to meaningfully elevate the quality and safety of youth athletic development programs across Indonesia.

Despite the strength of these findings, several limitations should be acknowledged. First, the study sample was exclusively male, and the results may not be generalizable to female athletes, whose hormonal profiles and physiological responses to HIIT may differ. Second, the study was conducted within a single institution, which may limit external validity across different regions or sport disciplines. Third, the eight-week intervention period, while sufficient to detect significant physiological changes, may not capture the full trajectory of adaptations associated with prolonged HIIT training. Future research should address these limitations by including female athletes, employing multi-site designs, extending intervention periods beyond eight weeks, and exploring the dose-response relationship between HIIT volume, intensity, and the magnitude of physiological adaptation in young Indonesian athletes (Mukhlis & Hakim, 2022; Palar et al., 2021).

CONCLUSION

This study provides robust evidence that an eight-week wearable technology-based HIIT program is significantly more effective than conventional training in improving aerobic capacity ($VO_2\text{max}$) and recovery indices (HRV-RMSSD and resting heart rate) in young male athletes at the Faculty of Sports and Health Sciences, Universitas Negeri Makassar. The experimental group achieved a 22.2% improvement in $VO_2\text{max}$, a 35.8% improvement in HRV-RMSSD, and a 13.3% reduction in resting heart rate — all substantially exceeding the gains observed in the control group. The integration of real-time wearable biofeedback enabled precise intensity regulation and individualized load management, which are proposed as key mechanisms underlying the superior training outcomes observed. These findings highlight the considerable value of incorporating commercially available wearable technology into structured HIIT programs for youth athletes in Indonesia. Coaches, sport scientists, and institutional administrators are encouraged to consider wearable-assisted training as a practical, evidence-

based strategy for optimizing athletic development, improving performance, and safeguarding the health and resilience of young athletes. Future research should explore these effects in female athletes and across diverse sport disciplines and regional contexts to broaden the applicability of these findings.

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