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Skeletal Muscle Mass Predicts SmO_2 and Physical Performance in Adolescent Badminton Athletes Using NIRS

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Keywords

Skeletal Muscle Mass; Physical Performance; Badminton

Abstract

Near-Infrared Spectroscopy (NIRS) allows real-time assessment of muscle oxygenation via muscle oxygen saturation (SmO_2). This study investigated how skeletal muscle mass (SMM) influences the SmO_2 ratio and physical performance in adolescent badminton players. Using a quasi-experimental, one-time case study design, ten adolescent athletes from PB Mutiara Cardinal Bandung were selected by purposive sampling. SMM was measured with a Tanita Body Composition Analyzer, SmO_2 ratio recorded by a NIRS-based Moxy Monitor, and aerobic capacity (VO_2Max) estimated through the Bleep Test. Data underwent descriptive analysis, Shapiro–Wilk normality testing, linearity assessment, and simple linear regression. Results indicated a positive association between SMM and SmO_2 ratio ($R = 0.625$; $R^2 = 0.390$; Sig = 0.053), with SMM accounting for 39.0% of SmO_2 ratio variance, though this relationship did not reach statistical significance. Conversely, SMM showed a significant positive effect on physical performance ($R = 0.709$; $R^2 = 0.503$; Sig = 0.022), explaining 50.3% of VO_2Max variance. These results imply that while greater skeletal muscle mass predicts better aerobic performance in adolescent badminton athletes, it is not the primary determinant of SmO_2 ratio.

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INTRODUCTION

Badminton is a high-intensity intermittent sport involving repeated explosive movements, rapid changes of direction, jumping, lunging and high speed rallies, placing great physiological demands upon the athlete. Physical activity plays an important role in promoting the physical performance and health of people (Gumilar et al., 2021). The capacity to maintain performance through a match depends on the interaction between aerobic and anaerobic energy systems underpinning efficiency of movement and postponement of fatigue (Abian-Vicen et al., 2013). Hence, it is important to identify physiological factors associated with athletic performance to optimize training programs and improve competitive outcomes (Reilly et al., 2009).

Skeletal muscle mass (SMM) is one of the physiological characteristics most highly correlated with athletic performance. Skeletal muscle is the primary site of force production and metabolic activity during exercise (Janssen et al., 2000). Generally, the larger the muscle mass of athletes, the greater the strength, power, and exercise capacity, as larger muscle volume increases the ability to generate mechanical work and utilize energy substrates efficiently (Abe et al., 2014). Previous studies have also shown a positive relationship between skeletal muscle mass and aerobic fitness and physical performance in adolescent athletes (Gäbler et al., 2018).

In sports science, physiological monitoring has become ever more important, in addition to morphological features. One variable that has received a lot of attention is muscle oxygen saturation (SmO_2), which is an indicator of the balance between oxygen delivery and oxygen consumption in active muscles (Perrey & Ferrari, 2018). Near-infrared spectroscopy (NIRS) can be used to noninvasively measure SmO_2 to monitor local muscle oxygenation continuously during exercise (Ferrari et al., 2011). Portable NIRS has enabled researchers and practitioners to directly assess muscle metabolic responses in field-based sports environments (Hamaoka et al., 2011).

SmO_2 monitoring provides valuable information on muscular oxygen extraction, fatigue development, and exercise intensity regulation (Crum, 2017). A decrease in SmO_2 during high-intensity exercise indicates greater oxygen utilization of working muscles to meet metabolic demands (Feldmann et al., 2019). Thus, SmO_2 has been recognized as a promising physiological marker for the evaluation of training responses and athletic performance (Yogev et al., 2023). Several studies have demonstrated that muscle oxygenation dynamics are associated with endurance capacity, exercise tolerance, and recovery status in athletes (Nemoto et al., 2024).

The most common method for assessing physical performance is maximal oxygen uptake (VO_2 max), defined as the maximum rate of oxygen transport and utilization during exercise (Bassett & Howley, 2000). VO_2Max is widely recognized as one of the most significant indicators of aerobic fitness and endurance performance (Lee & Zhang, 2021). A good aerobic capacity in badminton allows athletes to perform repeated high-intensity actions and recover better between rallies (Cabello & González-Badillo, 2003). Therefore, VO_2Max is still a relevant indicator for badminton athletes' physical preparedness.

(Negara, 2023) Research on the efficacy of MOXY technology in assessing athletic performance through real-time analysis of oxygen saturation in muscles in cycling athletes. The real-time feedback on local muscular conditions provided by MOXY presents considerable benefits for coaches and sport scientists seeking to implement evidence-based training strategies and personalized recovery programs. Despite these promising developments, the application of MOXY-based monitoring in badminton remains limited. Although skeletal muscle mass, muscle oxygenation, and aerobic performance have been investigated separately in previous studies, there is limited evidence relating these variables, especially in adolescent badminton athletes. Most investigations have been in adult populations or laboratory-based exercise protocols, limiting generalizability of findings to youth athletes and field settings.

Adolescent athletes are a special population because physiological development, muscular adaptation, and aerobic capacity are still processes of maturation (Malina et al., 2015). The relationship between skeletal muscle mass and muscle oxygenation and physical performance during this developmental stage could provide important insights for athlete monitoring and long-term training development. Further investigations are needed to reveal the role of skeletal muscle mass in maintaining physiological responses and physical performance of adolescent badminton players. The purpose of this study was to investigate the relationship of skeletal muscle mass and the SmO_2 ratio and physical performance in adolescent badminton athletes.

Muscle oxygen saturation (SmO_2) is an important physiological indicator of muscle oxygen utilization during exercise. SmO_2 is a measure of the balance between oxygen delivery and oxygen consumption in the active muscle tissue and can be measured non-invasively with near-infrared spectroscopy (NIRS) technology (Perrey & Ferrari, 2018). Also, a study on university badminton players showed that athletes with higher VO_2Max had better SmO_2 optimization and recovery responses compared to athletes with lower VO_2Max, suggesting the importance of aerobic capacity in maintaining muscle oxygen availability during exercise (Negara, 2024).

Based on these considerations, this study was conducted to analyze the effect of skeletal muscle mass (SMM) on muscle oxygen saturation (SmO_2) and physical performance in adolescent badminton athletes. In this study, physical performance was indexed by maximal aerobic capacity (VO_2max) using the Bleep Test. The findings will be of value for understanding physiological determinants of athletic performance, as well as provide practical implications for evidence-based athlete monitoring using wearable NIRS technology.

METHODS

This study employed a quantitative approach with a quasi-experimental design using a one-shot case study model. The effect of skeletal muscle mass (SMM) on muscle oxygen saturationSmO_2) and physical performance in adolescent badminton players. The researcher did not provide any specific intervention or training program but measured the research variables after the participants completed a physical test in the form of a bleep test as a data collection procedure (Campbell & Stanley, 2015; Darajat & Abduljabar, 2014).

Ten adolescent athletes were recruited from PB Mutiara Cardinal Bandung using a purposive sampling technique. Inclusion criteria were (a) adolescent badminton players aged 12–15 years, (b) active club members with at least three years of training experience, (c) free from injuries or medical conditions that might affect training performance, and (d) provided informed consent. The sample size is a study of 10 badminton athletes in training, male (n = 10). The sample size is relatively small, but similar sample sizes have been used in physiological studies in adolescent badminton athletes and specialized monitoring equipment (Green et al., 2023).

Skeletal muscle mass (SMM) was assessed by the Tanita Body Composition Analyzer with bioelectrical impedance analysis (BIA) technology, which has shown acceptable validity and reliability for body composition assessment. The beep test gives a measure of physical performance called "maximal aerobic capacity" (VO_2Max), which is often used to estimate the aerobic fitness of athletes. Muscle oxygen saturation (SmO_2) was measured by the Moxy Monitor Device, utilizing near-infrared spectroscopy (NIRS) technology to non-invasively and in real-time assess muscle oxygenation during the beep test (Negara, 2024). The SmO_2 ratio was calculated as the ratio of change in time to change in SmO_2 during the Beep Test, which provides an integrated measure of the magnitude and rate of oxygen desaturation:

$$SmO_2 \text{ Ratio} = \Delta\text{Time} / \Delta SmO_2 \quad \Delta SmO_2 = (SmO_2 \text{ baseline} - SmO_2 \text{ minimum}) \; \Delta\text{Time} = \text{time elapsed until } SmO_2 \text{ minimum}$$

VO_2Max was calculated from the Beep Test using the protocol of (Leger & Lambert, 1982) and reported in ml/kg/min. The regression equation was VO_2 Max = 31.025 + (3.238 × final speed) − (3.248 × age) + (0.1536 × age × final speed).

The main variable of the study was the SmO2 ratio, obtained by changes in muscle oxygen saturation over time during the test. This ratio is calculated by comparing the absolute decrease of muscle oxygen saturation (ΔSmO_2) with the time taken to reach the lowest point of oxygen saturation during activity. This approach is used to describe the ability of muscles to use oxygen during exercise at an increased intensity.

Physiological measurements and field test results may be used to classify physical performance to provide information to athletes about their aerobic and anaerobic capabilities. Meanwhile the physical condition of athletes is assessed by the use of several biomotor components. Biomotor components are parameters of testing physical condition for sports performance as regulated in Regulation of the Minister of Youth and Sports of the Republic of Indonesia Number 15 Year 2024. The measured components are muscle strength (push-up test), flexibility (sit and reach test and shoulder flexibility test) and arm muscle strength (overhead throw test).

Descriptive statistics (mean, standard deviation, minimum, and maximum values) were employed to summarize participant characteristics and research variables. Prior to hypothesis testing, the Shapiro-Wilk test was performed to evaluate data normality because the sample size was fewer than 50 participants. A linearity test was also conducted to determine whether the relationships between variables met the assumptions required for linear regression analysis. Simple linear regression analysis was used to examine the influence of skeletal muscle mass on muscle oxygen saturation (SmO_2) and physical performance (VO_2Max). Statistical significance was established at $p < .05$ for all analyses.

RESULTS AND DISCUSSION

The participants consisted of 10 badminton athletes adolescents in the range of 12 to 15 years old. 40% were 13 years old, 30% were 15 years old, 20% were 14 years old and 10% were 12 years old. Most of the participants (50%) have 7 years of training experience. 30% have 5-6 years of training experience and 20% have 3-4 years of training experience. Regarding the playing style, half of the participants (50%) plays singles and the other half (50%) plays doubles.

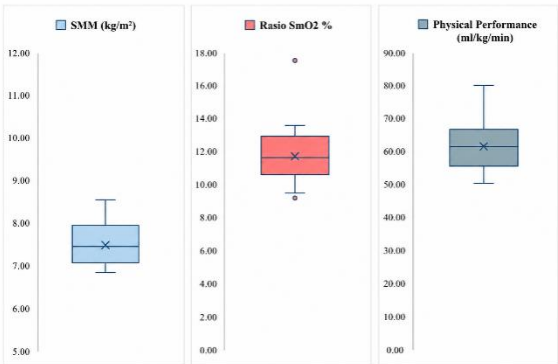

Figure 1. Box Plot of Study Variables

Based on **Figure 1**, The distribution of Skeletal Muscle Mass (SMM), SmO_2 Ratio, and Physical Performance (VO_2 Max) of the 10 adolescent badminton athletes in this study was examined based on Figure 1. The distribution of the SMM variable is relatively symmetric, and the mean is close to the median; this means that the values are evenly distributed among the participants. The box plot for SMM had no outliers, indicating the athletes had relatively homogenous characteristics of skeletal muscle mass. The small interquartile range further suggests limited variability in SMM in the sample.

The distribution of values for the SmO_2 Ratio variable is moderate, with the mean and median being relatively close. But an observation is seen above the upper whisker, suggesting there is an outlier with a substantially higher SmO_2 ratio than the other athletes. This result shows that one athlete had a clearly different muscle oxygenation response during the physical test. This outlier does not alter the fact that most of the observations are within a fairly narrow range, indicating that the variability among the participants is within acceptable limits.

The physical performance variable VO_2Max has a greater spread of values than SMM and SMO_2 Ratio. The box plot illustrates this by the larger interquartile range and longer whiskers. The mean and median are still relatively close, indicating a fairly balanced distribution. One athlete had a really high VO_2 max compared to the others, but there were no extreme outliers. These results suggest an increased variability in aerobic performance in athletes, with a normal distribution overall.

In general, the box plots show satisfactory distributions of the study variables with few extreme values. The data appear relatively homogeneous and approximately symmetric except for one outlier in the SmO_2 Ratio variable. These findings are consistent with the Shapiro-Wilk normality test and demonstrate that the assumptions required for further parametric analyses, such as simple linear regression, have been sufficiently satisfied.

The results of the Shapiro-Wilk test showed that all the dependent variables were normally distributed: Skeletal Muscle Mass ($W = 0.926$, $p = 0.414$); SmO 2 Ratio ($W = 0.866$, $p = 0.089$); Physical Performance ($W = 0.946$, $p = 0.617$). The linearity test indicated that the relationship between skeletal muscle mass and SmO_2 ratio was linear (deviation from linearity Sig. = 0.148), and the relationship between skeletal muscle mass and physical performance was linear (deviation from linearity Sig. = 0.177). Therefore, the assumptions required for simple linear regression analysis were fulfilled.

Table 1. Simple Linear Regression Analysis

Relationship	β	R^2	p
SMM→Rasio SmO_2	0.625	0.390	0.053
SMM→Physical Performance	0.709	0.503	0.022

Table 1 presents the results of the simple linear regression analyses examining the effect of skeletal muscle mass (SMM) on the SmO_2 ratio and physical performance in adolescent badminton athletes.

The results of a simple linear regression analysis showed a coefficient of determination ($R^2 = 0.390$), indicating that skeletal muscle mass explained 39.0% of the variance in SmO_2. However, the significance value obtained was $p = 0.053$, which exceeds the significance threshold of 0.05. Therefore, the impact of skeletal muscle mass on SmO_2 was not significant.

This finding indicates that athletes with a larger skeletal muscle mass tend to have a larger response of SmO_2 during exercise, but the relation was not strong enough to reach the level of statistical significance. The remaining 61.0% of the variation in SmO_2 is due to other physiological factors including capillary density, mitochondrial content, local blood flow regulation, aerobic fitness level, and muscle oxidative capacity. A simple linear regression analysis showed a strong positive relationship The coefficient of determination ($R^2 = 0.503$) indicated that 50.3% of the variance in VO_2max was accounted for by skeletal muscle mass.

The regression analysis revealed a significance value of $p=0.022$, which indicates a statistically significant effect of skeletal muscle mass on physical performance. These findings suggest that athletes with a higher skeletal muscle mass tend to have higher aerobic capacity and physical performance. The other 49.7% of the variance in VO_2max may be explained by other factors such as cardiovascular function, lung capacity, training status, nutritional intake, and genetic characteristics.

This study found that skeletal muscle mass was positively associated with muscle oxygen saturation (SmO_2), although the relationship was not significant. Conversely, skeletal muscle mass was shown to have a positive and significant effect on physical performance. This finding suggests that increasing muscle mass alone may not necessarily lead to improved muscle oxygenation during exercise. Muscle oxygen utilization is influenced by several physiological mechanisms beyond muscle size, including oxygen delivery capacity, microvascular perfusion, mitochondrial density, and aerobic adaptations.

During adolescence physiological maturation is not yet complete, and there is a high interindividual variability in muscle metabolism and capacity of oxygen utilization. Thus, athletes with similar muscle mass may have different responses of oxygenation according to their training history and physiological adaptations (Malina et al., 2015; Perrey & Ferrari, 2018).

These results are in line with previous In the current study, skeletal muscle mass was positively correlated with SmO_2, but this relationship was not significant. Skeletal muscle mass, on the other hand, was a positive and statistically significant predictor of physical performance. The finding suggests that increasing muscle mass alone may not increase muscle oxygenation during exercise. Muscle size is not the only determinant of muscle oxygen utilization. Other physiological mechanisms such as oxygen delivery capacity, microvascular perfusion, mitochondrial density, and aerobic adaptations also influence muscle oxygen utilization. Studies describing positive relationships between skeletal muscle mass and physical performance measures. The main site of oxygen use and energy production during exercise is skeletal muscle. Higher skeletal muscle mass is associated with better functional capacity. Furthermore, athletes with higher muscle mass are usually characterized by higher oxidative capacity, better exercise tolerance, and higher endurance performance, all of which result in better athletic performance (Bassett & Howley, 2000; Hargreaves & Spriet, 2020).

This study's results partially support previous literature suggesting that muscle morphology contributes to exercise performance but does not independently determine oxygenation responses (Suchomel et al., 2020). However, SmO_2 seems to be more affected by the dynamic interaction between oxygen supply and oxygen extraction, rather than muscle mass alone (Kirby et al., 2021).

In the present study, skeletal muscle mass had a positive and significant effect on physical performance expressed by VO_2Max. This outcome is consistent with the notion that enhanced aerobic capacity is related to larger muscle mass due to a greater proportion of metabolically active tissue for oxygen utilization during exercise (Janssen et al., 2000).

From a physiological point of view, skeletal muscle is the main site of oxygen uptake and energy production during exercise. Athletes with increased muscle mass tend to have improved oxidative capacity, improved muscular endurance, and improved tolerance to exercise, resulting in improved aerobic performance (Abe et al., 2018). The findings of this study present interesting views on research conducted by (Negara 2024) on university badminton athletes. The study demonstrated that VO_2max was a significant predictor of muscle oxygen saturation (SmO_2), suggesting that athletes with higher aerobic capacity experience more optimal muscle oxygenation and recovery.

In this study, skeletal muscle mass was a significant factor for VO 2 max but not for the SmO_2 ratio. Both of these findings can be considered together, and it can be assumed that skeletal muscle mass has a contribution to the increase in aerobic capacity in athletes and that aerobic capacity does have a more direct relationship to muscle oxygenation response during physical activity.

The results indicate that the increase in skeletal muscle mass was more closely related to the improvement in physical performance than the change in SmO_2 ratio determined by near-infrared spectroscopy (NIRS) technology. This means that athlete performance is not just about muscle oxygenation but also about the ability of the muscle to produce force and power during exercise. The findings of this study add to the existing literature by demonstrating that skeletal muscle mass is an important determinant of physical performance in adolescent badminton players, but its contribution to muscle oxygenation responses is limited. These results underline the importance of including morphological and physiological variables in the evaluation of athlete performance and the development of training programs. The relatively small sample size limits the generalizability of the results. Future studies should include larger samples from different badminton clubs and competitive athletes.

CONCLUSION

In the present study, there was a positive association between skeletal muscle mass and SmO_2 ratio, although it was not significant. In contrast, skeletal muscle mass was positively and significantly associated with physical performance assessed by VO_2max in adolescent badminton athletes. The results suggest that skeletal muscle mass is a significant predictor of aerobic performance but not the primary determinant of the muscle oxygenation response.

Thus, strategies to optimize skeletal muscle development may improve physical performance of adolescent badminton athletes.

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