Abstract:

This study evaluated the contribution of physiological data collected during laboratory testing in predicting race performances of trained junior middle-distance track (TK) and cross-country (XC) athletes. Participants performed a submaximal incremental ramp test, followed by an incremental test to exhaustion in a laboratory, with the results used to predict either 800 m TK, 1500 m TK or 4000-6000 m XC race performance. Twenty-eight participants (male (M), 15; female (F), 13) were analysed (age = 17 ± 2 years, height = 1.72 ± 0.08 m, body mass = 58.9 ± 8.9 kg). Performance times (min:s) for 800 m were: M, 1:56.55 ± 0:05.55 and F, 2:14.21 ± 0:03.89; 1500 m: M, 3:51.98 ± 0:07.35 and F 4:36.71 ± 0:16.58; XC: M (4900 ± 741 m), 16:00 ± 01:53; F (4628 ± 670 m), 17:41 ± 02:09. Stepwise regression analysis indicated significant contributions of speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$), and heart rate maximum (HR_{max}) to the prediction of 800 m TK ($F_{(2,15)}$ = 22.51, p <0.001, adjusted R^2 = 0.72), $s\dot{V}O_{2max}$ for 1500 m TK ($F_{(1,13)}$ = 36.65, p <0.001, adjusted R^2 = 0.72) and $\dot{V}O_{2max}$, allometrically scaled to body mass and speed at lactate threshold (sLT) for XC ($F_{(2,17)}$ = 25.1, p <0.001, adjusted R^2 = 0.72). Laboratory-based physiological measures can explain 72% of the variance in junior TK and XC events, although factors that explain performance alter depending on the race distance and tactics. The factors determining performance in TK and XC events are not interchangeable.

Keywords: Endurance, running, physiology, junior, regression, performance modelling

1. INTRODUCTION

The goal of competitive running events is to complete a set distance in the shortest time possible, or at least in a shorter time than other athletes in the event. Performance of elite middle- and long distance runners competing at national, international, or world-class level is underpinned by the combination of neuromuscular (4, 35) and physiological determinants of endurance running, which are closely linked to submaximal and maximal oxygen uptake (30). Maximal oxygen uptake ($\dot{V}O_{2max}$), the amount of oxygen required to run at submaximal speeds (running economy (RE)), and the first rise of blood lactate levels above baseline (lactate threshold (LT)) are established determinants among endurance athletes and are specific to race context (5, 29, 30). These physiological parameters have been used to prescribe training zones (40), investigate responses to training (13, 20, 26, 28) and predict performance (29, 30) in endurance athletes.

In the United Kingdom, junior athletes (under 20) will traditionally race cross-country (XC) or indoor track (TK) in the winter months, before transitioning to outdoor TK in the summer. Junior runners may compete in both TK and XC races throughout a season, but may also specialise in one. Differences in RE have been reported between elite adult XC and TK athletes, with TK runners becoming less economical (52 ± 12% increased oxygen consumption) when running on mixed terrain in comparison to flat ground when compared to XC orienteers (41 ± 9% increase) (25). However, while investigations of junior TK athletes and their race performances have been conducted (31), a combined study of the physiology of junior TK and XC athletes and their performance in competitive races has not been undertaken. Investigations of national and international level adult running events ranging from 800-3000 m have shown that $\dot{V}O_{2max}$, RE and the speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$) ($R^2 = 0.94$ (23)) are the primary physiological metrics that determine race performance, but these observations were limited to TK events (22, 23, 38). Recent evidence has shown the combination of RE and $s\dot{V}O_{2max}$ explained 80% of performance over a 1500 m time trial in trained adults, but constraining performance with slower initial laps altered these determinants (6). Separate studies investigating XC performance have reported $\dot{V}O_{2max}$ as having the strongest elationships over 3000 m (r = 0.55) (14), three miles in males (r = 0.70) and two miles in females (r = 0.90) (18), or s$\dot{V}O_{2max}$ over 5000 m (r = 0.66) XC performance (15). However, these studies did not compare TK and XC athletes and were limited to predicting a single race performance, which might not capture the athlete's best performance (if they underperform on that day) or those occuring at dates that are close to the labotatory-based physiological assessments. Therefore, analysing a fastest performance during a short time period, occuring close to their laboratory assessment might address the aforementioned limitations.

The ability to predict performance using assessed physiological parameters remains an attractive proposition for coaches and athletes. As previously demonstrated in the research literature, physiological variables can explain up to 96% of the variance in elite, adult middle-distance running over 800 m and 1500 m (using $\dot{V}O_{2max}$, RE and sLT) (23) and are able to discriminate between elite and sub-elite adult runners (using $\dot{V}O_{2max}$, RE and body mass) (41). A study predicting performance of middle-distance TK post-pubertal athletes has recently been conducted (10), but this did not consider XC events, focusing principally on 800 m, 1500 m, and 3000 m (e.g. middle-distance) TK events and the associated aerobic oxygen and energy cost. Other studies have reported the contribution of $\dot{V}O_{2max}$ to performance of pre-pubescents (33) and juniors of similar age, but lower performance and fitness levels, although this study was in females only (14). Based on the demands of middle-distance TK and XC events, athletes are likely to share some physiological characteristics; however, XC races may be less predictable as they are competed over varying terrains, underfoot conditions, and distances. It has also been shown that physiological factors, such as running economy for TK or XC athletes, are affected differently when running on varied surfaces (25) and therefore, it is feasible that XC athletes rely on a combination of factors to complete races in the fastest time.

Therefore, the aim of this study was to utilise multiple linear regression and selected laboratory-based physiological parameters of trained junior TK and XC athletes to investigate predictors of performance in 800 m, 1500 m (middle-distance) TK events and XC events of between 4000 and 6000 m.

2. METHODS

2.1 Participants

Twenty-eight participants (male (M) = 15, female (F) = 13, age = 17 ± 2 years, height = 1.72 ± 0.08 m, body mass = 58.9 ± 8.9 kg) were selected for assessment through an England Athletics talent identification pathway or coach referral. All participants were involved in daily training and regular competition for at least one year. Data sets from fifty-three trials were analysed. Sixteen participants had a single laboratory visit, with twelve attending on more than one occasion, separated by at least six months. Testing sessions were conducted between 9am and 3pm for all athletes and at the same time of day for repeat attendees. All participants completed a medical questionnaire and were informed of the risks associated with the assessment procedure before they volunteered for the study and provided written informed consent. For participants under the age of 18 years, consent of a parent or guardian was obtained. Participants were instructed to avoid strenuous activity 48-h prior to assessment and to arrive in a rested condition. Participants were asked to arrive in a hydrated condition, but to avoid eating or drinking anything other than water at least 2-h prior to assessment, or the consumption of any nutritional supplements on the day of assessment.

All participants were informed they could withdraw from assessment at any time, without reason and that compliance with the assessment would not interfere in any way with selection or otherwise for races. The study was conducted in accordance with the principles of the Declaration of Helsinki (2013) and ethical approval was granted by the institution’s ethics committee.

2.2 Procedures

Upon arrival, stature (m) and body mass (kg) were recorded with the participants in minimal clothing and with shoes removed. Participants were fitted with a telemetric heart rate monitor (Polar H1, Polar Electro Ltd, Warwick, UK) and a resting capillary blood sample was obtained to monitor haemoglobin concentration and the haematocrit using a point of care analyser (HemoControl, EKF Diagnostics, Cardiff, UK). Participants were fitted with a mask to collect expired respiratory gases, which were analysed breath-by-breath using a high resolution spiroergometry system (Metalyzer 3B, Cortex Biophysik GmbH, Leipzig, Germany). The analyser was calibrated with gases of known concentration prior to all assessments.

All assessments were performed on a motorised treadmill (ELG2, Woodway, UK). The treadmill assessment comprised two tests (submaximal and maximal effort), separated by approximately 10-min of active recovery (walking around the laboratory, hydrating with water, dynamic stretching), during which participants were instructed to keep warm. The submaximal assessment began at around 10-12 $km \cdot h^{-1}$ and comprised 3-min stages of constant speed exercise, with the treadmill gradient set at 1% to reflect outdoor running conditions (27). Heart rate was monitored throughout all assessments, with data collected within the last 15-s of each stage used for analysis. $\dot{V}O_2$ values were determined by averaging breath-by-breath results during the final 60-s of each stage (10) with these values used to calculate RE by dividing $\dot{V}O_2$ by the resultant of corresponding treadmill speed/60 (30). At the conclusion of each stage, rating of perceived exertion (RPE) was collected using the Borg Scale (12), as well as a capillary blood sample from the fingertip to determine blood lactate concentration. The treadmill speed was increased by 0.8 $km \cdot h^{-1}$ after each stage and the participant was instructed to lower themselves onto the treadmill to begin running. Blood lactate samples were analysed immediately (YSI 2700, Yellow Springs, Ohio, USA) and the assessment was stopped once a blood lactate concentration of >4 $mmol \cdot L^{-1}$ was recorded.

For the maximal effort assessment, the treadmill speed was maintained at two stage speeds prior to the finishing speed of the submaximal effort, with the gradient increasing by 1% each minute until the participant achieved volitional exhaustion, in accordance with the British Association of Sport and Exercise Sciences' guidelines, from which definitions for $\dot{V}O_{2max}$, LT, and RE were also taken (11, 30). Heart rate was noted during each minute and a maximal value recorded. Immediately following the cessation of exercise, a further capillary blood sample was taken to obtain a post exercise blood lactate value. $\dot{V}O_2$ and $\dot{V}CO_2$ samples were averaged over the last minute of each stage during the submaximal assessment, and each 30-s during the maximal effort assessment. Definitions for LT, onset blood lactate accumulation (OBLA) and s$\dot{V}O_{2max}$ were followed by those given by Jones (30). LT was defined by Jones as: "the first "breakpoint" or "observable rise" in blood lactate concentration, where levels consistently exceed baseline (~1 $mmol \cdot L^{-1}$)". OBLA was taken at a reference value of 4 $mmol \cdot L^{-1}$. s$\dot{V}O_{2max}$ was obtained by solving the regression equation describing measured $\dot{V}O_2$ at submaximal intensities and $\dot{V}O_{2max}$ (30).

2.3 Allometric scaling

As growth and maturation can have a substantial but varied impact on body size in juniors, conventional scaling of physiological measures to body mass is inappropriate and inequitable and, as such, allometric scaling is encouraged when investigating physiological performance metrics in elite junior endurance athletes (9, 10). In line with recent research in this field in a comparable athletic cohort, a scaling exponent of 0.67 was used for $\dot{V}O_{2max}$ when converting absolute values into values relative to body mass (9).

Race performance analysis

For the purpose of *post hoc* comparisons, participants' performances were separated into middle-distance track (TK) or longer-distance cross-country (XC) events. TK events competed at either 800 and/or 1500 m, with XC events constrained to distances of between 4000 to 6000 m. Participants' performance data were taken from a British Athletics open access database of race times (www.thepowerof10.info). In order to be included in the study, athletes must have performed a race within 60 days of their laboratory visit, a timeframe used in recently published work in an endurance cohort (10). XC events must have had an official race distance. The participant's race performance that elicited the fastest performance speed within this window was selected for the regression analysis.

2.4 Statistical analyses

All data were analysed using a statistical software package (IBM SPSS Statistics, v24.0, IBM Corporation, USA). A one-way analysis of variance (ANOVA) was conducted to compare means of all dependent variables between the 800 m and 1500 m TK and XC groups. Levene's test for equality of variance was performed to assess data for homoscedasticity. 800 m and 1500 m performance speeds were log transformed as they violated this assumption. Following this, three stepwise multiple linear regressions were conducted with (log)800 m, (log)1500 m and 4000-6000 m XC performance speed as the dependent variables. Performance speed was calculated by dividing the distance covered by the time taken to complete the race distance, expressed in s. The same independent variables were used for each regression calculation, they were: $\dot{V}O_{2max}$ relative to allometrically scaled to body mass ($\dot{V}O_{2max\ rel}$); speed at $\dot{V}O_{2max}$ ($s\dot{V}O_{2max}$), maximal heart rate (HR_{max}); speed at lactate threshold (sLT); and running economy (RE) (in $mL \cdot kg^{-1} \cdot km^{-1}$). Power analysis was carried out using G*Power (v3.1.9.7) *a priori*, determining that with five independent variables, an estimated correlation coefficient of 0.7, and an alpha level of 0.05, 13 trials were required to achieve a power >80%. Variables were removed from the regression calculation if they displayed high collinearity, as determined through a variable impact factor (VIF) (whether one predictor in the model has a relationship with another predictor) > 10 or a tolerance (the reciprocal of VIF) of < 0.2 (18). Durbin-Watson tests were employed to assess autocorrelation within regression models. A Shapiro-Wilk test and visual inspection of histograms was conducted to assess data for normality. An alpha level of $p \leq 0.05$ was set for statistical significance with 95% confidence intervals (CI) reported. Subsequently, bivariate Pearson correlations were calculated for the variables outlined above. Coefficients for Pearson's product moment correlations were interpreted with the following boundaries: < 0.31 negligible, 0.31-0.50 low correlation, 0.51-0.70 moderate correlation, 0.71-0.90 high correlation, > 0.90 very high correlation (21).

3. RESULTS

Tables 1-3 about here

Descriptive statistics for participants and performance characteristics are shown in Tables 1 and 2, respectively. Table 3 displays the physiological parameters for the 800 m, 1500 m, and XC athletes. VIF and tolerance statistics revealed no violation of collinearity and the Durbin-Watson analyses revealed no autocorrelation. One-way ANOVA revealed significant differences between groups for height ($F_{(2,50)}$ = 10.02, p <0.001); body mass ($F_{(2,50)}$ = 6.4, p = 0.003); and $\dot{V}O_{2max}$ ($F_{(2,50)}$ = 4.54, p = 0.015). *Post hoc* comparisons revealed that 800 m (p= 0.005) and 1500 m (p< 0.01) runners were significantly taller than XC runner, 800 m (p= 0.026) and 1500 m (p= 0.005) runners had significantly greater body mass than XC runners. It was also revealed that $\dot{V}O_{2max}$ was higher (p= 0.029) for 1500 m runners when compared to XC. No other significant differences were observed. Races were performed within 37 ± 19 days of laboratory assessment.

800 m performance speed:

The stepwise regression indicated a collective significant effect of s$\dot{V}O_{2max}$ and HR_{max} ($F_{(2,15)}$ = 22.51, p < 0.001, adjusted R^2 = 0.72). Significant correlations between bivariates and 800 m performance speed were (in order of magnitude): s$\dot{V}O_{2max}$ ($r_{(18)}$ = 0.80, CI = 0.59, 0.93, p <0.001). $\dot{V}O_{2max\ rel}$ ($r_{(18)}$ = 0.77, CI = 0.46, 0.93); sLT ($r_{(18)}$ = 0.68, CI = 0.44, 0.87. p = 0.002); RE ($r_{(18)}$ = 0.49, CI = 0.00, 0.77. p = 0.043) and a negative correlation with HR_{max} ($r_{(18)}$ = -0.40, CI= -0.67, -0.01. p= 0.05) Performance speed for 800 m in junior athletes can be modelled as:

$$(\log)800\text{ m performance speed } (m \cdot s^{-1}) = 0.017(s\dot{V}O_{2max}) - 0.002(HR_{max}) + 0.811$$

Standard error of the estimate (SEE) = 0.018

1500 m performance speed:

The stepwise regression indicated a significant effect of s$\dot{V}O_{2max}$ when predicting 1500 m performance speed ($F_{(1,13)}$ = 36.65, p <0.001, adjusted R^2 = 0.72). Significant correlations between bivariates and performance speed were (in order of magnitude): s$\dot{V}O_{2max}$ ($r_{(15)}$ = 0.86, CI = 0.57, 0.97. p <0.001); sLT ($r_{(15)}$ = 0.82, CI = 0.51, 0.96, p <0.001); and $\dot{V}O_{2max\ rel}$ ($r_{(15)}$ = 0.76, CI = 0.41, 0.93. p = 0.001).

Performance speed for 1500 m in junior athletes can be modelled as:

(log)1500 m performance speed ($m\cdot s^{-1}$) = 0.017(s$\dot{V}O_{2max}$) + 0.445

SEE= 0.022

4000-6000 m XC performance speed:

The stepwise regression indicated that $\dot{V}O_{2max,\ rel}$ and sLT explained the highest percentage of performance speed ($F_{(2,17)}$ = 25.1, p <0.001, adjusted R^2 = 0.72). Significant correlations included (in order of magnitude): $\dot{V}O_{2max,\ rel}$ ($r_{(20)}$ = 0.82, CI = 0.62, 0.93. p <0.001); sLT ($r_{(12)}$ = 0.65, CI = 0.33, 0.83. p = 0.002; and s$\dot{V}O_{2max}$ ($r_{(20)}$ = 0.46, CI = 0.00, 0.81). p = 0.041)

Performance speed for XC events of 4000-6000 m in junior events can be modelled as:

XC performance speed ($m\cdot s^{-1}$) = 0.029 ($\dot{V}O_{2max\ rel}$) + 0.111(sLT) + 0.261.

SEE = 0.226

4. DISCUSSION

The aims of this study were to compare physiological characteristics of elite junior TK and XC athletes and determine the predictor variables for 800 m, 1500 m and XC event performance of 4000 to 6000 m. The main findings were that for 800 m, s$\dot{V}O_{2max}$ and HR_{max} explained 72% of the variance in performance. For 1500 m, s$\dot{V}O_{2max}$ explained 72% of the performance variance. Coincidentally, for XC events, $\dot{V}O_{2max\ rel}$ and sLT also explained 72% of the variance in performance despite differences in race duration and energy system demand in comparison to 800 m and 1500 m TK events. No significant differences in physiological variables used for the regressions were observed between the three groups.

4.1 800 m and 1500 m performance variables

The data presented herein demonstrate a significant and large contribution from the combination of $s\dot{V}O_{2max}$, and HR_{max} on 800 m performance speed, explaining up to 72% of the variance in race time. The participants in this study were performing at national and international standard (Table 2), in comparison to the county standard runners reported in a similar study (1), with performance times for the 800 m and 1500 m being approximately 10-s and 40-s faster, respectively. $s\dot{V}O_{2max}$ is calculated by solving the regression equation obtained from measuring $\dot{V}O_2$ at submaximal running speeds, and $\dot{V}O_{2max}$. It has been shown that $s\dot{V}O_{2max}$ typically corresponds to the speed that can be maintained by elite runners over 3000 m (7, 17). $s\dot{V}O_{2max}$ is also a strong predictor of performance over similar distance events among athletes of varying performance levels. For example, $s\dot{V}O_{2max}$ has correlated with or predicted performance in 800 m races in county level adolescent runners (1) and elite adults (23) and for 1500 m races in Olympic athletes (22). This was also the case for 3000 m races in collegiate athletes (32), and 5000 m races in junior, non-elite boys (15). In this study, $s\dot{V}O_{2max}$ was a significant correlate of both 800 (r = 0.80) and 1500 m (r = 0.86) performances. The higher correlation with 1500 m performance is expected as it is closer to 3000 m (7, 17), meaning that running speed during races is closer to $s\dot{V}O_{2max}$. This is reflected in $s\dot{V}O_{2max}$ being the strongest and only predictor variable to enter the model for 1500 m performance.

It is well established that heart rate and $\dot{V}O_2$ have a linear relationship during continuous work at sub-maximal intensities (2), and while $\dot{V}O_{2\ max\ rel}$ and sLT were significant correlates with performance speed for 800 m, HR_{max} had a stronger relationship and entered the model for 800 m performances. It is known that regular endurance training will decrease the heart rate required to maintain a given submaximal work intensity (42). The HR_{max} relationship here could, therefore, reflect the training status of the athlete i.e. those that are most well-trained have the lower HR_{max} values and are the faster athletes. As the athletes are homogenous with regards age, this contention is reasonable. Further, HR_{max} has an inverse relationship with 800 m (and 1500 m) performance and, as cardiac output is a combination of stroke volume and heart rate, it is possible that structural changes allowing for greater stroke volume are compensating for reduced heart rate. For example, hypertrophy of the left ventricle has been observed to be greatest in young adult endurance athletes when measured against comparably aged and trained athletes from other sports, and relative to body surface area (36). Monitoring adaptations to HR_{max} resulting from chronic training therefore appears to be an important consideration for the coach and athlete.

Oxygen uptake at submaximal intensities (RE) has been used as a performance measure in endurance runners, with reductions in $\dot{V}O_2$ at comparable submaximal intensities from training correlating with improvements in performance over the marathon distance (29). The relationship between RE and performance, although significant for 800 m were classified as low (r = 0.49) and negligible for 1500 m (r = 0.19). This is not unexpected as it is known that generally RE in junior athletes is not as well developed when compared to adult athletes (4). Notwithstanding, it is probable that if junior athletes who demonstrate a high $\dot{V}O_{2max}$ can improve their RE (and subsequently $s\dot{V}O_{2max}$), the current evidence suggests this will lead to improved performance. Previous experimental research (35) and recent reviews (3, 8) have all highlighted strength training as an effective strategy for encouraging improvements in RE and performance in endurance runners. Therefore, interventions such as this could be considered alongside more traditional running-based training.

4.2 XC performance correlates

The data herein show that $\dot{V}O_{2max\ rel}$ and sLT were the strongest predictors of performance in XC events, accounting for 72% of the variance in performance speed. Although scaled allometrically in this study, the $\dot{V}O_{2max}$ is a well-established physiological performance determinant in endurance running and was anticipated to predict performance at XC distances (15). Sub-maximal markers, such as sLT are also among the most important traditional predictors of endurance performace (5), but only entered the prediction model for XC performance. This suggests that as race distance increases, sLT may become increasingly important in tandem with a high $\dot{V}O_{2max\ rel}$. This has been demonstrated by Santos-Concejero and colleagues in well-trained adults, with sLT increasing the correlation coefficient from 0.72 to 0.84 over 3000 m and 10,000 m, respectively (39). This result is likely owing to the race performance speed becoming increasingly similar to sLT as race distance increases. It is probable, therefore, that while training which encourages the classic "rightward shift" (many training modalities exist for this, but some examples include polarised training (40) and concurrent training (31)) of the blood lactate/running speed curve is likely desirable for all endurance runners, it may be especially important for those competing at distances of 4000 m and above.

RE and HR_{max} were both non-significant for XC performance. The reasons for these findings might be related to the specific demands of off-road running. For example, forest running can increase energy cost by around 50%, depending on underfoot conditions and gradient (24) and athletes unhabituated to off-road running will experience significantly greater increases in energy cost in comparison to regular off-road runners (25).This presumably relates to the alterations in technique that are imposed by terrain of varying topography. Indeed, it has further been reported that RE is negatively affected by a reduction in firmness of floor surface, whereby running technique is challenged and the utilization of elastic energy storage during gait is minimised (34). It is possible, therefore, that athletes with high RE are less able to utilise these charactersitics that are typically advantageous during more predictable TK events. Furthermore, because RE is negatively impacted by XC racing when compared to TK events, it is also possible those athletes with a greater $\dot{V}O_{2max}$ have a greater likelihood of performing well in these events. The HR_{max} may not have been significant predictor here as the running speed required to elicit HR_{max} will be lower than those performed over a 4000-6000m XC race, or owing to a tactical decisions around pacing strategy. Although XC athletes may reach HR_{max} in a race (due to hill climbing or a sprint finish as examples where intensity of effort increases) this can only be maintained briefly, explaining perhaps why it is a significant predictor for 800 m races of similar duration. The XC performances herein lasted around 16 minutes, explaining this variable not entering the predictive XC model.

Lastly, the physiological measures explained 72% of race times across all race types. The reasons for this similarity in outcome are unknown, and possibly coincidental. 800 m, 1500 m, and XC races all have their own idiosyncracies and tactics. 1500 m races for example have recently been investigated, showing variability in approach (fast start and high overall performance speed, or slow start and "kicks" or bursts of high-speed running as examples) (37). Additionally, constraining performance with slow opening lap times altered the physiological determinants of performance in simulated 1500 m time trials (6). Race tactics were not investigated in the current study, but it may be possible that variability in tactical approach and other confounding factors that, if controlled, may elicit stronger predictive models, but at the expense of ecological validity for competitive racing. Additionally as XC events are performed at speeds closer to the lactate threshold (although not at it) and, therefore, presumably have less anaerobic glycolytic and ATP/PCr demand than 800 m and 1500 m. The increase in race variability might be offset by the decreased variability of having a decreased anaerobic energy system demand. Currently, this is a speculative assessment and further research is required to address whether these similarities in 800 m, 1500 m, and XC race performance.

Limitations

A limitation of this research is that race times used to establish performance speeds were not conducted in a controlled manner. Performance speeds were calculated from real races in British Athletics sanctioned events. The races were over different distances and likely had variations in underfoot conditions, and other environmental factors, as well as tactics (as discussed above), which were not examined here. While this lack of internal control might be a limitation, using real races as a performance metric might, arguably, increase the ecological validity of the findings. The main issue with this approach was finding races that were conducted within a suitable window of time from the laboratory assessments. In a similar approach to other work in this area (10) a period of sixty days was used, although it is possible that small changes in the athletes' physiology between laboratory assessment and race may limit the robustness of the findings. Athletes were typically forwarded for assessment at the end of winter training or prior to the summer race season, which accounts for the time gaps between assessment and races. Training data were not available for all athletes to supplement the physiological testing. The addition of training data to this type of physiological profiling may confer additional information and understanding to the predictors of adolescent XC and TK performances. Lastly, this research was conducted on a mixed sex sample. If statistical power can be achieved with the athletes of comparable performance levels than those in this study, seperating the sample by sex may provide useful additional information.

5. PRACTICAL APPLICATIONS

The results herein demonstrate that the physiological determinants of performance are not interchangeable between middle-distance TK and XC races. In a highly trained group of national and international junior runners, the variance in 800 m and 1500 m and XC performance speeds can be largely explained by physiological predictor variables. These are the combination s$\dot{V}O_{2max}$ and HR_{max} 800 m, s$\dot{V}O_{2max}$ for 1500 m, and $\dot{V}O_{2max\ rel}$ for XC events. Longitudinal investigations to establish whether these variables predict performance over the athletes' career, and further investigations of XC running in a more controlled manner might elucidate a stronger model of performance in these events. These findings may be useful for junior athletes and coaches to understand which physiological attributes contribute to running performance and may help to underpin or inform training decisions although any changes to training prescription must be carefully considered.

ACKNOWLEDGEMENTS:

REFERENCES:

1. Almarwaey AO, Jones AM, Tolfrey K. Physiological Correlates with Endurance Running Performance in Trained Adolescents. *Medicine and Science in Sports and Exercise*. 35(3): 480-7, 2003
2. Astrand, P, O., & Ryhming, I. A nomogram for calculation of aerobic capacity (physical fitness) from pulse rate during sub-maximal work. *Journal of Applied Physiology.* 7(2): 218-221, 1954
3. Balsobre-Fernandez C, Santos-Concejero J, Grivas GV. Effects of strength training on running economy in highly trained runners: a systematic review with meta-analysis of controlled trials. *Journal of Strength and Conditioning Research.* 30(8): 2361-8, 2016
4. Barnes KR, Kilding AE. Strategies to Improve Running Economy. *Sports Medicine*. 45(1): 37-56, 2015
5. Bassett DR, Howley ET. Limiting Factors for Maximum Oxygen Uptake and Determinants of Endurance Performance. *Medicine and Science in Sports and Exercise.* 32(1): 70-84, 2000
6. Bellinger P, Derave W, Lievens E, Kennedy B, Arnold B, Rice H, Minahan C. Determinants of last lap speed in paced and maximal 1500-m time trials. *European Journal of Applied Physiology.* 2020. https://doi.org/10.1007/s00421-020-04543-x
7. Billat LV, Koralsztein JP. Significance of the velocity at $\dot{V}O_{2max}$ and time to exhaustion at this velocity. *Sports Medicine.* 22(2): 90-108, 1996
8. Blagrove RC, Howatson G, Hayes PR. Effects of strength training on the physiological determinants of middle- and long-distance running performance: a systematic review. *Sports Medicine.* 48: 1117-1149, 2018
9. Blagrove RC, Howatson G, Hayes PR. Test-retest reliability ofphysiological parameters in elite junior distance runners following allometric scaling. *European Journal of Sport Science.* 17(10: 1231-1240, 2017

10. Blagrove RC, Howatson G, Pedlar CR, et al. Quantification of aerobic determinants of performance in post-pubertal adolescent middle-distance runners. *European Journal of Applied Physiology.* 119: 1865-1874, 2019
11. Bliss A, Harley RA. in Turner A. *Chapter 5: Training Aerobic Fitness in Advanced Strength and Conditioning: An Evidence-Based Approach: 72-87.* Routledge: UK, 2018
12. Borg GA. Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*. 14: 377-381. 1982
13. Burnley M, Jones AM. Oxygen uptake kinetics as a determinant of sports performance. *European Journal of Sport Science.* 7(2): 63-79, 2007
14. Butts NK. Physiological Profiles of High School Female Cross Country Runners. *Research Quarterly for Exercise and Sport.* 53:1, 8-14, 1982
15. Cole AS, Woodruff ME, Horn MP, et al. Strength, Power, and Aerobic Exercise Correlates of 5-km Cross-Country Running Performance in Adolescent Runners. *Pediatric Exercise Science.* 18: 374-384, 2006
16. Creagh, U., & Reilly, T. Physiological and biomechanical aspects of orienteering. *Sports Medicine.* 24(6): 409-418, 1997
17. Di Prampero PE, Atchou G, Bruckner JC, et al. The energetics of endurance running. *European Journal of Appplied Physical and Occupational Physiology.* 55(3): 259-266, 1986
18. Dubois D, DuBois EF. Clinical calorimetry: a formulae to estimate the approximate surface area if stature and weight are known. *Archives of Internal Medicine.* 17:863-871, 1916
19. Fernhall B, Kohrt W, Burkett LN, et al. Relationship Between the Lactate Threshold and Cross-Country Run Performance in High School Male and Female Runners. *Pediatric Exercise Science.* 8: 37-47, 1996
20. Field, A. *Discovering Statistics using IBM SPSS Statistics 4th ed*. Sage, UK. 2013
21. Hinkle DE, Wiersma W, Jurs SG. *Applied statistics for the behavioural sciences. 5th edn*. Houghton Mifflin, Boston. 2013

22. Ingham SA, Fudge BW, Pringle JS. Training Distribution, Physiological Profile, and Performance for a Male International 1500-M Runner. *International Journal of Sports Physiology and Performance.* 7(2): 193-5. 2012
23. Ingham SA, Whyte GP, Pedlar C, et al. Determinants of 800-m and 1500-m Running Performance Using Allometric Models. *Medicine and Science in Sports and Exercise.* 40(2): 345-50. 2008
24. Jensen K, Franch J, Karkkainen O, et al. Field measurements of oxygen uptake in elite orienteers during crosscountry running using telemetry. *Scandinavian Journal of Medicine and Science in Sports*. 234-238, 1994
25. Jensen K, Johansen L., Karkkainen OP. Economy in track runners and orienteers during path and terrain running. *Journal of Sports Sciences*. 17:12, 945-950, 1999
26. Jones AM, Carter H. The effect of endurance training on parameters of aerobic fitness. *Sports Medicine.* 29(6): 373-86, 2000
27. Jones AM, Doust JH. A 1% Treadmill Gradient Most Accurately Reflects the Energetic Cost of Outdoor Running. *Journal of Sports Sciences.* 14: 321-327, 1996
28. Jones AM. A five year physiological case study of an Olympic runner. *British Journal of Sports Medicine.* 32: 39-43, 1998
29. Jones AM. The Physiology of the World Record Holder for the Women's Marathon. *International Journal of Sports Science and Coaching*. 1(2): 1-15. 2006
30. Jones, A, M., in Winter, E, M., Jones, A,M., Davison, R,C., et al. *Sport and Exercise Physiology Testing Guidelines: Volume I – Sport Testing.* Routledge, London, UK, 2006
31. Jones, T, W., Shillabeer, B, C., Joong Hyun, R., & Cardinale, M. Development in middle-distance athletes: a study of training loadings, physical qualities, and competition performance. *Journal of Strength and Conditioning Research. 2019. 10.1519/JSC.0000000000003437. Advance online publication. https://doi.org/10.1519/JSC.0000000000003437*

32. Maldonado S, Mujika I, Padilla S. Influence of Body Mass and Height on the Energy Cost of Running in Highly Trained Middle- and Long-Distance Runners. *International Journal of Sports Medicine.* 23: 268-272, 2002
33. Mayers N, Gutin B. Physiological characteristics of elite prepubertal cross-country runners. *Medicine and Science in Sports*. 11(2): 172-176, 1979
34. Moore, I, S. Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy. *Sports Medicine.* 46: 793-807, 2016
35. Paavolianen L., Hakkinen K, Hamalainen I, et al. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *Journal of Applied Physiology*. 86(5): 1527-1533, 1999
36. Pavlik G, Olexo Z, Osvath P, et al. Echocardiographic characteristics of male athletes of different age. *British Journal of Sports Medicine.* 35(2): 95-99, 2001
37. Sandford GN, Day BT, & Rogers SA. Racing fast and slow: defining the tactical behaviour that differentiates medalists in elite men's 1500 m championship racing. *Frontiers in Sports and Active Living.* 2019 doi: 10.3389/fspor.2019.00043
38. Sandford GN, Rogers SA, Sharma AP, et al. Implementing anaerobic speed reserve testing in the field: validation of vVO2max prediction from 1500m race performance in elite middle-distance runners. *International Journal of Sports Physiology and Performance.* 31: 1-12 ahead of print 2019
39. Santos-Concejero J, Granados C, Irazusta J, et al. OBLA is a better predictor of performance than Dmax in long and middle-distance well-trained runners. *Journal of Sports Medicine and Physical Fitness.* 54: 553-8, 2014
40. Seiler S. What is best practice for training intensity and duration distribution in endurance athletes. *International Journal of Sports Physiology and Performance.* 5(3): 276-291, 2010

41. Tartaruga MP, Mota CB, Peyre-Tartaruga LA, et al. Scale Model on Performance Prediction in Recreational and Elite Endurance Runners. *International Journal of Sports Physiology and Performance*. 9: 650-655, 2014

42. Zavorsky GS. Evidence and possible mechanisms of altered maximal heart rate with endurance training and tapering. *Sports Medicine.* 29(1): 13-26, 2000