

Individualisation of Time-Motion Analysis: A Method Comparison and Case Report Series

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Running Title: Individualisation Methods in Time-Motion Analysis

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Abstract

This study compared the intensity distribution of time-motion analysis data, when speed zones were categorized by different methods. Twelve U18 players undertook a routine battery of laboratory- and field-based assessments to determine their running speed corresponding to the respiratory compensation threshold (RCT), maximal aerobic speed (MAS), maximal oxygen consumption ($\dot{V}O_{2max}$) and maximal sprint speed (MSS). Players match-demands were tracked using 5Hz GPS units in 22 fixtures (50 eligible match observations). The percentage of total distance covered running at high-speed (%HSR), very-high speed (%VHSR) and sprinting were determined using the following speed thresholds: 1) arbitrary; 2) individualised (IND) using RCT, $\dot{V}O_{2max}$ and MSS; 3) individualised via MAS *per se*; 4) individualised via MSS *per se*; and 5) individualised using MAS and MSS as measures of locomotor capacities (LOCO). Using MSS in isolation resulted in 61% and 39% of player's %HSR and %VHSR, respectively, being incorrectly interpreted, when compared to the IND technique. Estimating the RCT from fractional values of MAS resulted in erroneous interpretations of %HSR in 50% of cases. The present results suggest that practitioners and researchers should avoid using singular fitness characteristics to individualise the intensity distribution of time-motion analysis data. A combination of players' anaerobic threshold, MAS, and MSS characteristics are recommended to individualise player-tracking data.

Keywords: External load, fitness characteristics, GPS, match-demands, Soccer, Intensity-distribution

Introduction

Player movement tracking in training and competition has become a common feature of the sports scientists' and/or performance analysts' role description. In professional team sports, particularly at the elite performance levels, it is not uncommon for teams to employ a number of practitioners to collect and interpret data pertaining to the distances covered by players, and the distribution of running speeds or intensities. As team-sport competitions are contested on an absolute basis, player-tracking data is traditionally expressed as distances covered in arbitrary, or player-independent, speed zones to evaluate the physical output or external loading of the player. This practice permits longitudinal pattern analysis of players/teams locomotor demands, and is often considered as rich-information for periodization of training plans. However, it is also widely accepted that it is the individual players internal (physiological) response to the movement demands that underpins the nature and degree of adaptation to physical stimuli [20,29,31].

Collection of external load data is now commonplace in team sports with either semi-automated image tracking or global positioning system (GPS) technology. Internal load can be measured concurrently with the use of heart rate monitors, which are generally unobtrusive to the player and are routine in training environments. Nonetheless, heart rate monitoring is generally not permitted in competition [14]. Since 90 minutes of match-play accounts for approximately 25% of the players' weekly physical dose [20], the use of player-independent speed zones *per se* to characterize the intensity distribution of match-play does not reflect the individual's dose-response [31] and energetic demands [23]. For example, we recently observed a 40% difference in the relative high-intensity running demands of two players who served very similar tactical roles in the team, and demonstrated comparable (within 5%) absolute running demands during competition [23]. To evaluate players match-play locomotor demands, and to inform subsequent recovery and training plans, we have recommended that an individualised approach to time-motion analysis is used in conjunction with the traditional arbitrary, or player-independent, approach [1,23].

Common techniques to express player-tracking data with reference to individual fitness characteristics have used maximal sprint speed (MSS) [3,8] or the running speed corresponding to measures of the anaerobic threshold [1,21,23,30]. Used in isolation these methods do not reflect the complete locomotor profile of the player, and the subsequent classification and justification of speed zones to determine the match-play intensity distribution is problematic [31]. Alternatively, Mendez-Villanueva et al., [26] adopted an individualization technique for match-play data, which encapsulated fitness data from field-based tests to estimate the players' aerobic (maximal aerobic speed [MAS]) and anaerobic capacities (MSS). This approach likely avoids the difficulties encountered when adopting one phenotype to normalise speed thresholds, and is convenient for practitioners who may not have access to the economic and expertise requirements of laboratory-based assessments. However, estimated maximal aerobic speed does not reflect the transition from the moderate- to the high-intensity exercise domain, and the accuracy of using field-based fitness assessments versus laboratory determined physiological

thresholds to calibrate individualised speed zones is unknown. Furthermore, the most appropriate physical/physiological test to individualise speed zones has not yet been established [9,23,31]. In this study, we therefore sought to compare the intensity distribution of soccer match-play when speed zones were determined by discreet, and a combination of, locomotor capacities (MAS and MSS), laboratory-determined physiological thresholds, and the traditional arbitrary zones. We considered that information of this nature would be a useful resource for practitioners who interpret player-tracking data of elite team-sports players on a daily basis.

Materials & Methods

Twelve elite-youth (U18) soccer players (stature: 1.80 ± 0.05 m; body mass: 71.8 ± 6.7 kg; $\dot{V}O_{2\max}$: 62.9 ± 4.9 ml·kg⁻¹·min⁻¹) representing an English Championship team were eligible for this study, which was approved by an institutional ethics committee and meets the ethical standards of the journal [17]. The players routinely trained on a daily basis and played 1-2 competitive fixtures per week. This was a convenience sample because the research design necessitated four repeated laboratory and field assessments, together with analyses of match demands during the competitive phase of the 2010/11 and 2011/12 seasons.

Laboratory Assessments

Players attended the laboratory at least 48 h after their last competitive fixture, in an appropriately rested and hydrated state. Players then performed a graded exercise test to exhaustion on a motorised treadmill (Woodway ELG55, Woodway, Weil an Rhein, Germany). The starting treadmill speed was 7 km·h⁻¹ for 3 min to accustom the players to the experimental configuration, thereafter the speed was increased by 0.2 km·h⁻¹ every 12 s until volitional test termination. We adopted a ramped incremental protocol to facilitate the precise assessment of both the respiratory compensation threshold (RCT) and maximal aerobic speed. Maximal aerobic speed was taken as the treadmill speed at the time of test termination, and we assumed that this would derive similar results to those obtained in field based tests, such as the VAM-EVAL [26]. During the test, players were fitted with a heart rate monitor (Polar FS1, Polar Electro, OY, Finland) together with a face-mask to collect standard cardio-respiratory data using a breath-by-breath metabolic cart (Oxycon Pro, Jaeger, Hoechberg, Germany). The respiratory compensation threshold was identified as the running speed that corresponded to the inflection in the ventilatory equivalents for both oxygen and carbon dioxide, and a corresponding decrease in the end-tidal partial pressure of carbon dioxide [12,24]. Data were discarded if the oxygen cost associated with the inflection points in these three parameters differed by more than $\pm 5\%$. The inter- and intra-observer typical error for the running speed corresponding to the respiratory compensation threshold in our laboratory is 0.5 km·h⁻¹ (90% confidence intervals [CI]: 0.4 to 0.7 km·h⁻¹) and 0.5-0.7 km·h⁻¹, respectively. Maximal oxygen consumption ($\dot{V}O_{2\max}$) was taken as the peak value recorded from 12-sec time-averaging, with the velocity at \dot{V}

O_{2max} ($v\dot{V}O_{2max}$) recorded as the running speed that first elicited an oxygen consumption corresponding to $\geq 95\%$ of $\dot{V}O_{2max}$.

Field-Based Assessments

24-48 h after the laboratory assessment, players performed maximal sprint speed assessments at the teams' training facility. After a standardized warm-up players performed three maximal 40 m sprints, with 3 mins recovery between efforts. Split times at 10, 20, 30 and 40 m were recorded (SmartSpeed Timing Gates, Fusion Sport, HaB International Ltd, Warwickshire, UK), and the players' peak speed was determined from their fastest 10 m split in accordance with previous literature [3,26].

Match Analyses

Player movement tracking data were recorded via 5 Hz GPS units (MinimaxX, Catapult Innovations, Canberra, Australia; firmware 6.75) during 22 competitive league fixtures. GPS units were positioned between the scapulae in neoprene undergarments that were supplied by the manufacturer. We excluded match observations from goalkeepers, and those players who did not complete the full match. In accordance with manufacturers instructions we also discarded match observations in which the number of satellites tracking the units position was less than 6, and/or the horizontal dilution of precision was greater than 1.5. Match analysis data was included if the fixture was scheduled within 6 weeks of the players' laboratory and field based assessments. However, we excluded match data if a player missed more than 20% of the squad's total training time in the preceding week, or if they presented with illness or injury. 50 match observations for the 12 players met our eligibility criteria (2-4 observations per player). For the purposes of this study we treated players with multiple fitness assessment data and corresponding match observations as separate cases. This resulted in 18 match clusters, defined as cases where a player had completed the necessary laboratory and field based fitness assessments, and had corresponding and eligible GPS data from match-play within 6 weeks of testing. We deemed this an appropriate procedure as players' fitness characteristics often change within the competitive playing season [4,10] and may impact upon the intensity distribution of match-play [25]. Adopting match-clusters also provided an opportunity to examine the interpretation of GPS data using a variety of analytical methods, when players' fitness characteristics altered during the season.

Match Intensity Distribution Methods

For each analysis method, we categorised the data into the following locomotor categories: low-speed running (LSR); high-speed running (HSR); very-high speed running (VHSR) and sprinting (SPR). The distance covered in each of these categories was accumulated if the Doppler-derived instantaneous velocity was within the speed zone for 1 s (5 consecutive GPS samples). The classification of locomotor categories according to the different methods is shown in Table 1. Arbitrary (player-independent) speed zones are not

standardised in the research literature, which makes between study contrasts difficult. We adopted a hybrid approach for our arbitrary (ARB) thresholds, using $15 \text{ km}\cdot\text{h}^{-1}$ as the entry point for high-speed running because players often transition into the high-intensity exercise domain at this speed [1]. The lower threshold for sprinting was set at $25 \text{ km}\cdot\text{h}^{-1}$ to facilitate comparisons with other studies [13]. Running speeds corresponding to maximal aerobic speed and maximal sprint speed were used independently to examine the impact of anchoring speed zones on a solitary fitness attribute. Whilst analogous approaches have been used in the literature [1,3,16,23], should a practitioner wish to further sub-categorise data into different locomotor categories, it is difficult to justify the criteria for multiple speed zones determined by a single fitness characteristic [31]. We concede that the criteria adopted in this study are equally subjective, but considered this a necessary exercise to examine the impact of such approaches on interpretation of match demands.

Table 1: Classification of speed zones for different techniques to determine the match-play intensity distribution.

	Match Intensity Distribution				
	ARB	IND	MAS	MSS	LOCO
Low-Speed Running	<14.99	<RCT	<79% MAS	<49% MSS	<79 MAS
High-Speed Running	15.0 – 17.99	RCT - $\dot{v}O_{2\max}$	80 - 99% MAS	50 - 59% MSS	80% - 99% MAS
Very-High Speed Running	18.0 – 24.99	$\dot{v}O_{2\max} - 29\%$ ASR	100 - 139% MAS	60 - 79% MSS	100% MAS - 29% ASR
Sprinting	25.0 – 35.0	30% ASR - MSS	140% MAS - 35km/h	80 - 100% MSS	30% ASR - MSS

RCT: speed corresponding to a players respiratory compensation threshold; $\dot{v}O_{2\max}$: Speed corresponding to the players velocity at 95% maximal oxygen consumption; ASR: anaerobic speed reserve; MAS: maximal aerobic speed; MSS: maximum sprint speed; ARB: arbitrary speed zones; IND: Individualised speed zones incorporating RCT, $\dot{v}O_{2\max}$, and MSS; LOCO: locomotor speed zones incorporating MAS and MSS.

We also employed the method of Medez-Villanueva and colleagues [26] who were the first to use a combination of maximal aerobic speed and maximal sprint speed (hereafter termed the locomotor method [LOCO]) to represent the functional limits of the endurance and sprint locomotor capacities [7] in match analysis research. This technique permits an estimation of the players' anaerobic speed reserve (ASR) and has been used to demarcate the individuals' transition ($\geq 30\%$ ASR) to sprint work in match-analysis research [26]. Whilst maximal aerobic speed is strongly correlated ($r = 0.9$ [22]) with $\dot{v}O_{2\max}$ and can be easily assessed in field-based settings, it typically overestimates $\dot{v}O_{2\max}$ by 5-10% and is influenced by the anaerobic speed reserve [5]. To examine the effect of this potential bias on match-play intensity distribution, we also determined the anaerobic speed reserve using laboratory determined $\dot{v}O_{2\max}$, together with maximal sprint speed in our individualisation

method (IND). This IND approach also used the running speed corresponding to the respiratory compensation threshold to determine the players' transition to the high-intensity exercise domain. The LOCO approach assumes this transition point as a fixed fraction of maximal aerobic speed [26], which does not account for the individualised nature of the exercise-intensity continuum, and may result in erroneous interpretation of match-play demands [23]. Therefore, for the purposes of this study we classified the IND approach as our criterion measure of match-intensity distribution, and examined the differences between speed zone methods.

Statistics

The distance covered in each speed zone was expressed as a percentage of the total distance covered, with data presented as mean \pm SD unless otherwise stated. Group based differences between the analytical methods were assessed using magnitude-based inferences with a within-subjects model. *A priori* we determined the minimum practically important difference as 0.6 between-subjects SD, which translates to a 'moderate' (≥ 0.3 ; [11]) correlation co-efficient [19]. This decision was based on the between match variability observed in the current cohort for total high speed running (Typical error [TE]: 2.4%; 90% confidence intervals [CI]: 2.0 to 3.2%), total very-high speed running (TE: 1.9%; 90% CI: 1.6 to 2.5%), and sprinting (TE: 0.9%; 90% CI: 0.7 to 1.2%) using arbitrary thresholds. Using a customized spreadsheet [18], the magnitude of the effect statistic was classified as moderate or large via standardised thresholds (0.6 and 1.2, respectively) established from the between-subject SD. Mechanistic inferences were determined from the disposition of the 90% confidence interval for the mean difference to these standardized thresholds. Where the difference in percentage distance covered was $\geq 5\%$ in both a substantially positive and negative sense, the true effect was classified as unclear. In the event that a clear interpretation was possible, the following probabilistic terms were adopted: $< 0.5\%$, *most unlikely*; 0.5–5 %, *very unlikely*; 5–25 %, *unlikely*; 25–75 %, *possibly*; 75–95 %, *likely*; 95–99.5 %, *very likely*; > 99.5 : *most likely* [19].

As the individualisation of time-motion analysis aims to determine the player-dependent demands of match-play, we also adopted a series of case-study approaches to examine the impact of different individualisation approaches upon interpretation of the intensity-distribution of match-play. For this purpose, practically important differences in match-play intensity distribution between individual match clusters were deemed when the mean difference was greater than 0.6 of the between-subjects SD determined via the IND approach. We selected the IND as our benchmark given its greater between-subjects SD for the locomotor categories.

Results

Players covered 10296 ± 683 m in matches, of which $17.2 \pm 2.6\%$ was completed at high-speed (≥ 15 km·h⁻¹) when using arbitrary speed thresholds. Figure 1 depicts the individual players' running speed corresponding to the respiratory compensation threshold, $\dot{V}O_{2max}$, 30% anaerobic speed reserve and maximal sprint speed, together with their resultant speed zones according to the IND method. The group mean percentage of total distance covered in each locomotor category of the match-analysis methods are presented in Figure 2. The maximal sprint speed method over-estimated very-high speed running (1.1%; 0.5 to 1.7%) and under-estimated sprinting (-1.3%; -1.1 to -1.6%) versus IND. The maximal aerobic speed approach also under-estimated sprinting (-1.8%; -1.4 to -2.1%) in comparison to IND. No meaningful differences were observed in low-, high-, very-high speed running, and sprinting in LOCO compared to IND.

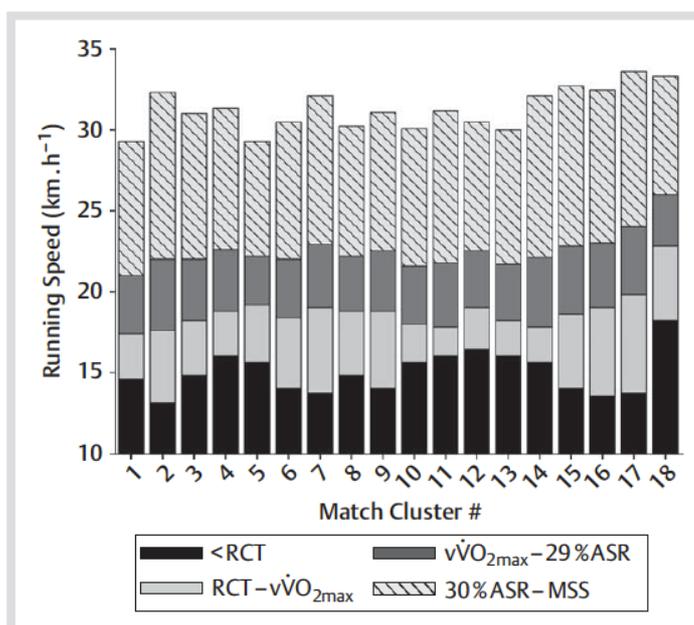


Fig. 1 Player running speed corresponding to RCT, $\dot{V}O_{2max}$, 30% ASR and MSS. MAS: Maximal Aerobic Speed; MSS: Maximal Sprint Speed; RCT: Running speed corresponding to the Respiratory Compensation Threshold; $\dot{V}O_{2max}$: running speed corresponding to maximal oxygen uptake; ASR: Anaerobic Speed Reserve.

The application of an absolute (35 km·h⁻¹) upper threshold for sprinting in ARB and MAS methods resulted in 3 ± 5 m covered above this speed, which was treated as erroneous GPS data (range: 0-16 m). When the maximal sprint speed was used for this purpose in MSS, LOCO and IND approaches to individualisation, 15 ± 13 m (range: 0-44 m) of data was recoded above players' peak speed during matches, and was discarded.

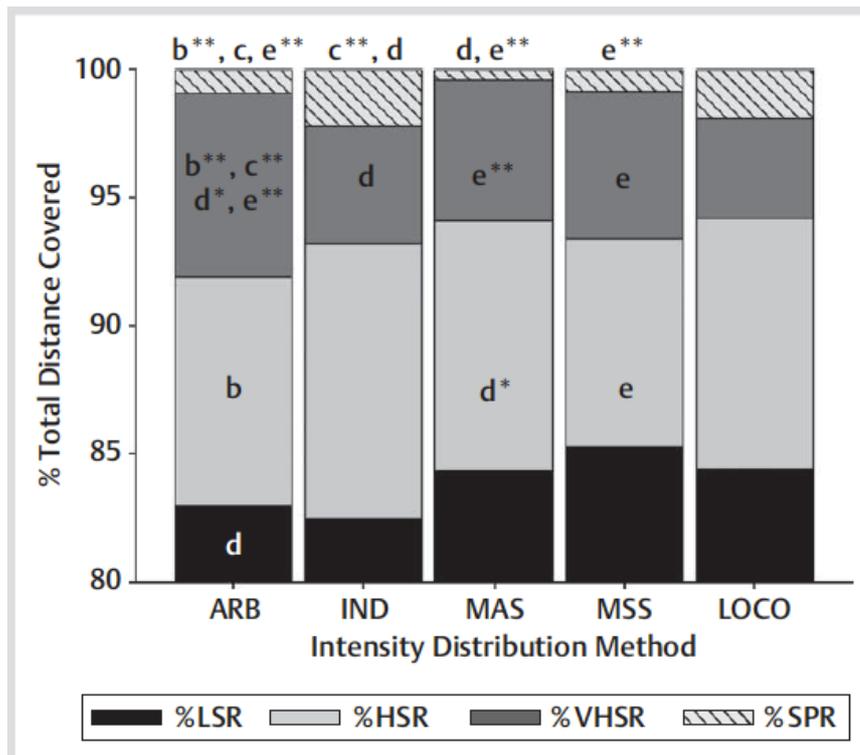


Fig. 2 Intensity distribution distances covered in match-play using arbitrary (ARB) and various individualised approaches to time-motion analysis. LSR: low-speed running; HSR: high-speed running; VHSR: very-high speed running; SPR: Sprinting. a = likely difference vs. ARB; b = likely difference vs. IND; c = likely difference vs. MAS; d = likely difference vs. MSS; e = likely difference vs. LOCO. Emboldened characters denote a large effect. * denotes very likely difference; ** denotes most likely difference.

The use of MSS *per se* to individualise the intensity-distribution derived interpretation errors of 61% and 39% in total high-speed running and total very-high speed running, in comparison to IND (see Figure 3). The running speed corresponding to the respiratory compensation threshold and 80% of maximal aerobic speed as used in the IND and LOCO approaches, respectively, did not differ on a group basis (RCT: 15.0 ± 1.3 ; 0.8 MAS: 15.4 ± 0.8 ; likely trivial). There were also no squad differences in the high-speed and very-high speed running categories between IND and LOCO (see Figure 2). However, using 80% of estimated maximal aerobic speed as the entry threshold for high-speed running in LOCO resulted in 50% of match clusters under- (39%) or over-estimating (11%) total high-speed running (see Figure 4A). Maximal aerobic speed was $4.0 \pm 3.4\%$ greater than $\dot{V}O_{2max}$ (range: 0.0 to 9.8%). The relationship between maximal aerobic speed and $\dot{V}O_{2max}$ was strong ($r^2=0.90$), but there was no association between the $\dot{V}O_{2max}$ – maximal aerobic speed difference and the change in total very-high speed running when these parameters were used to determine its entry-threshold in the IND and LOCO approaches. Using maximal aerobic speed as the entry point to the very-high speed running category had a meaningful effect on the interpretation of its data (see Figure 4B), together with the percentage of distance covered sprinting in 5 of the 18 match clusters (28%).

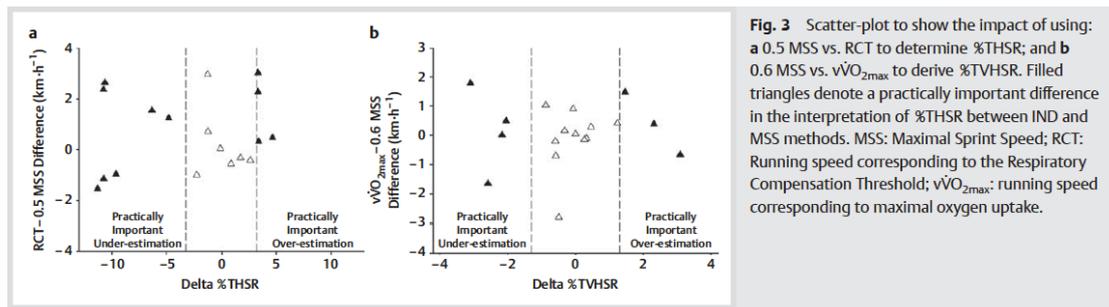


Fig. 3 Scatter-plot to show the impact of using: **a** 0.5 MSS vs. RCT to determine %THSR; and **b** 0.6 MSS vs. $\dot{v}O_{2max}$ to derive %TVHSR. Filled triangles denote a practically important difference in the interpretation of %THSR between IND and MSS methods. MSS: Maximal Sprint Speed; RCT: Running speed corresponding to the Respiratory Compensation Threshold; $\dot{v}O_{2max}$: running speed corresponding to maximal oxygen uptake.

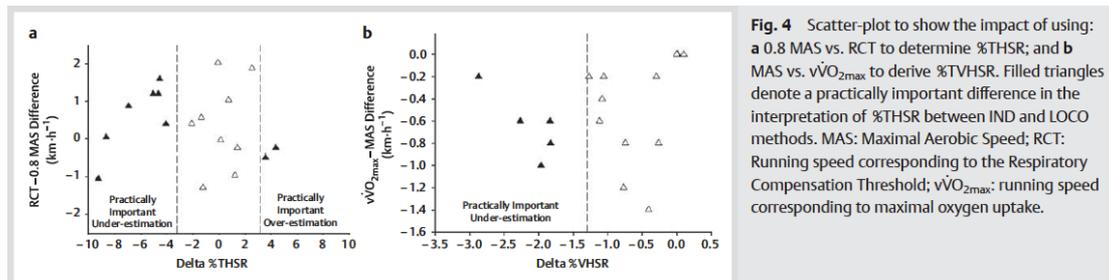


Fig. 4 Scatter-plot to show the impact of using: **a** 0.8 MAS vs. RCT to determine %THSR; and **b** MAS vs. $\dot{v}O_{2max}$ to derive %VHSR. Filled triangles denote a practically important difference in the interpretation of %THSR between IND and LOCO methods. MAS: Maximal Aerobic Speed; RCT: Running speed corresponding to the Respiratory Compensation Threshold; $\dot{v}O_{2max}$: running speed corresponding to maximal oxygen uptake.

Case Contrast 1: Role of the respiratory compensation threshold (# 8 vs. #12)

Both of these players performed in the central midfield position and covered similar total distances covered (#8: 10927 ± 521 vs. #12: 11285 ± 892 m) in their respective match cluster. These players were selected for a case-contrast due to their similar maximal sprint speed (#8: 30.3 vs. #12: 30.5 $\text{km}\cdot\text{h}^{-1}$), maximal aerobic speed (#8: 19.2 vs. #12: 19.2 $\text{km}\cdot\text{h}^{-1}$), and $\dot{v}O_{2max}$ (#8: 18.8 vs. #12: 19.0 $\text{km}\cdot\text{h}^{-1}$), however their respiratory compensation threshold differed by 10.8% (#8: 14.8 vs. #12: 16.4 $\text{km}\cdot\text{h}^{-1}$; see Figure 1). There were practically meaningless differences between the players' intensity distribution with the adoption of arbitrary and LOCO thresholds (see Table 2). In contrast, the IND method observed #8 to have covered 4.1% greater relative total high-speed running distance due to his lower respiratory compensation threshold.

Table 2: Comparison of Match-Play Intensity Distribution Data from #8 and #12 using different analytical approaches. Values are % (SD).

Analysis Method	Match Cluster	Locomotor Category			
		%LSR	%THSR	%TVHSR	%SPR
ARB	#8	81.3 (1.6)	18.7 (1.6)	9.7 (1.4)	1.1 (0.6)
	#12	78.8 (2.3)	21.2 (2.3)	10.0 (1.9)	0.8 (0.2)
LOCO	#8	82.6 (1.9)	17.3 (1.8)	7.1 (1.2)	2.7 (0.6)
	#12	80.4 (2.3)	19.6 (2.3)	7.1 (1.6)	2.4 (0.5)
IND	#8	80.6 (1.6)	19.3 (1.6)*	7.9 (1.2)	3.0 (0.5)
	#12	84.8 (2.0)*	15.2 (2.0)	7.5 (1.8)	2.5 (0.5)

* denotes practically meaningful difference (> 0.6 between-subjects SD) between match-clusters. ARB: arbitrary speed zones; IND: Individualised speed zones incorporating RCT, $\dot{v}O_{2max}$, and MSS; LOCO: locomotor speed zones incorporating MAS and MSS; LSR: low-speed running; THSR: total high-speed running; TVHSR: total very high-speed running; SPR: sprinting.

Case Contrast 2: Seasonal Variation in Fitness (#5 vs #6)

Match clusters #5 (mid-season) and #6 (end-season) are taken from the same player who played as a central defender. The total distances covered by the player in matches within a few weeks of the fitness assessments did not change (#5: 9589 ± 402 vs. #6: 9588 ± 530). Over the course of the second half of the competitive phase of the season, we observed a decline in his respiratory compensation threshold (#5: 15.6 vs. #6: 14.0 $\text{km}\cdot\text{h}^{-1}$), and $\dot{V}\text{O}_{2\text{max}}$ (#5: 19.2 vs. #6: 18.4 $\text{km}\cdot\text{h}^{-1}$), whereas maximal aerobic speed was unchanged (#5: 22.2 vs. #6: 22.0 $\text{km}\cdot\text{h}^{-1}$). Although the players' fitness was reduced, his total very-high speed running was marginally increased in #6 as determined via arbitrary thresholds (see Table 3). Alternatively, when LOCO and IND methods were applied to the same data, an increase in the intensity distribution of match-play was shown in #6.

Table 3: Comparison of Match-Play Intensity Distribution Data from #5 and #6 using different analytical approaches. Values are % (SD).

TMA Method	Match Cluster	Locomotor Category			
		%LSR	%THSR	%TVHSR	%SPR
ARB	#5	84.4 (2.1)	15.6 (2.1)	7.2 (1.3)	0.5 (0.4)
	#6	82.6 (2.5)	17.4 (2.5)	8.9 (1.4)*	0.6 (0.2)
LOCO	#5	87.7 (1.8)*	12.2 (1.8)	3.9 (1.2)	1.4 (0.7)
	#6	83.4 (2.5)	16.6 (2.5)*	6.0 (1.0)*	2.1 (0.5)*
IND	#5	86.4 (2.0)*	13.6 (2.0)	4.9 (1.3)	1.8 (0.8)
	#6	78.8 (3.1)	21.2 (3.1)*	7.8 (1.2)*	2.5 (0.6)*

* denotes practically meaningful difference (> 0.6 between-subjects SD) between match-clusters. ARB: arbitrary speed zones; IND: Individualised speed zones incorporating RCT, $\dot{V}\text{O}_{2\text{max}}$, and MSS; LOCO: locomotor speed zones incorporating MAS and MSS; LSR: low-speed running; THSR: total high-speed running; TVHSR: total very high-speed running; SPR: sprinting.

Case Contrast 3: Impact of the Anaerobic Speed Reserve

In this case-contrast we selected players #8 and #16 because their $\dot{V}\text{O}_{2\text{max}}$ (#8: 18.8 vs. #16: 19.0 $\text{km}\cdot\text{h}^{-1}$), and maximal aerobic speed (#8: 19.2 vs. #16: 19.0 $\text{km}\cdot\text{h}^{-1}$) were similar, yet #16 had a greater maximum sprint speed (#8: 30.3 vs. #16: 32.5 $\text{km}\cdot\text{h}^{-1}$). Although the total distance covered was greater in #8 (10927 ± 521) versus #16 (10037 ± 746), according to the arbitrary thresholds method, the relative intensity distribution was not markedly different between these players (see Table 4). When anchoring speed thresholds to the maximal sprint speed *per se*, the total high- and very-high speed running of #16 were underestimated in comparison to #8. When locomotor categories were derived from measures of both aerobic and anaerobic phenotypes in the LOCO and IND approaches, this under-estimation in very-high speed running was not apparent.

Table 4: Comparison of Match-Play Intensity Distribution Data from #8 and #16 using different analytical approaches. Values are % (SD).

TMA Method	Match Cluster	Locomotor Category			
		%LSR	%THSR	%TVHSR	%SPR
ARB	#8	81.3 (1.6)	18.7 (1.6)	9.7 (1.4)	1.1 (0.6)
	#16	80.5 (3.0)	19.5 (3.0)	9.7 (3.5)	1.4 (0.9)
MSS	#8	81.8 (1.7)	18.1 (1.7)*	9.1 (1.2)*	1.3 (0.7)
	#16	85.1 (3.2)*	14.8 (3.2)	6.6 (2.5)	0.9 (0.6)
LOCO	#8	82.6 (1.9)	17.3 (1.8)	7.1 (1.2)	2.7 (0.6)
	#16	81.3 (3.0)	18.6 (3.1)	7.5 (2.7)	2.5 (1.4)
IND	#8	80.6 (1.6)*	19.3 (1.6)	7.9 (0.6)	3.0 (1.2)*
	#16	74.4 (2.9)	25.6 (3.0)*	7.5 (1.4)	2.4 (2.7)

* denotes practically meaningful difference (> 0.6 between-subjects SD) between match-clusters. ARB: arbitrary speed zones; MSS: maximum sprint speed; IND: Individualised speed zones incorporating RCT, $\dot{V}O_{2max}$, and MSS; LOCO: locomotor speed zones incorporating MAS and MSS; LSR: low-speed running; THSR: total high-speed running; TVHSR: total very high-speed running; SPR: sprinting.

Discussion

In this study we compared the intensity-distribution of elite-youth soccer match-play, when a range of different techniques were used to determine the speed thresholds for locomotor categories. Although we applied empirical analysis on a cohort-basis to explore the differences between analytical approaches on the interpretation of time-motion analysis data, the premise of the individualisation approach is to better understand the individual players' dose-response and energetic demands of training and match-play. Accordingly, in this study we focused on how interpretations of individual players external loading changed as a consequence of the different analytical approaches used. Our main observations were as follows: 1) the use of maximum sprint speed *per se* to individualise player tracking data resulted in erroneous interpretation of relative high- and very high-speed running data in 61% and 39% of match clusters, respectively; 2) fractional values of maximal aerobic speed do not characterise the individualised nature of the transition speed to the high-intensity exercise domain, and resulted in 50% erroneous interpretations of relative match-demands; 3) $\dot{V}O_{2max}$ -maximal aerobic speed differences were not systematic and resulted in a mis-interpretation of total high-speed running in 28% of match clusters.

Arbitrary speed thresholds have a number of advantages for the practitioner. They enable both within and between player and team contrasts, which is necessary as team-sports are contested on an absolute level [1]. Where the same motion analysis system is employed, longitudinal monitoring of match-demands using arbitrary thresholds may derive content-rich information, perhaps regarding a tactical strategy or the effects of a training regime. However, if fixed speed thresholds are adopted, transitions between locomotor categories are set at differing points relative to the individual players' performance capacity. If the purpose of external load monitoring is to provide

an individualised approach to training prescription and evaluation, player-independent speed thresholds may mask important information [23]. Moreover, as the internal load of the player determines the adaptive response to the exercise-dose [20,29,31], it would be desirable to quantify the individuals exercise stimulus, which is often not permitted in team-sports competition [14]. Therefore we have previously recommended that an individualised approach to time-motion analysis be undertaken in synchrony with the traditional fixed arbitrary speed thresholds [1,23].

The few studies that have incorporated fitness characteristics to individualise time-motion analysis data have mostly used single attributes to anchor the locomotor categories. Players individual [3,8] or squad-mean [16] maximum sprint speed is a convenient technique as the measure is simple to ascertain during routine field assessments, providing that the sprint bout is of an appropriate length for the player to reach their maximum running speed. Because players tend to reach a high percentage of their maximum sprint speed during match-play [27], normalising speed thresholds to the players sprinting capacity might reflect an ecologically valid approach to time-motion analysis data interpretation and between player-comparisons. However, the use of maximal sprint speed in isolation to individualise time-motion analysis data erroneously assumes that players attain their peak speed in each match, irrespective of positional role [27]. Moreover, the use of maximal sprint speed to determine speed zones other than sprinting is difficult to rationalise [31]. The intensity distribution of players with lower peak speeds would be increased for the same absolute workload. This was demonstrated in case-contrast 3, where #16 had a greater sprinting capacity versus #8, which resulted in higher speed thresholds to demarcate entries into the high-speed, very-high speed and sprinting categories. Therefore, less high-speed running was performed by the faster player (#16) with the MSS approach, even through the players' aerobic locomotor capacity was equivalent. Adjusting speed zones to sprinting capacity *per se* therefore resulted in 61 and 39% meaningful interpretation errors, for high-speed and very-high speed running respectively, and suggests that this technique is inappropriate for use in both applied and research settings.

Another approach has been to determine the running speed that corresponds to the transition into the high-intensity exercise domain, via either ventilatory thresholds [1,23] or the heart rate deflection point [30]. Whilst these approaches better characterise the individuals relative high-speed running, used in isolation they do not demarcate other locomotor categories, such as very-high speed running and sprinting, which are commonly used in research and applied practice to examine external loading patterns in players [13]. To our knowledge there are only two studies that have used multiple fitness characteristics to individualise time-motion analysis data [21,26]. Lacombe and colleagues [21] used laboratory-derived measures of the anaerobic threshold and maximal aerobic speed in Rugby Union players, whereas Mendez-Villanueva *et al.* [26] estimated maximal aerobic- and sprinting speeds from field-based assessments. The latter method is convenient for practitioners and avoids costly, invasive, and time-consuming laboratory tests. In case-contrast one, we identified that the application of LOCO masked the greater relative match intensity of a player who had a lower respiratory compensation threshold

(#8). This can be explained by the assumption that players enter the high-intensity (or high-speed running) exercise domain at 80% of maximal aerobic speed. Whilst on a squad-average basis this assumption may be considered appropriate [23], the LOCO method does not represent individual player differences, and in this example provided erroneous data. In case-contrast 2 we examined a player with whose respiratory compensation threshold had decreased over the course of the season, however because their maximal aerobic speed had not changed, the magnitude of the relative increase in the players match-intensity was underestimated in LOCO. When the LOCO method was compared with IND in each player, we identified incidences in 50% of the match clusters where a meaningful change in the interpretation of total high-speed running data was observed.

The LOCO method also relies on an estimate of players' maximal aerobic speed. We observed a strong positive relationship between maximal aerobic speed and $\dot{V}O_{2max}$ in support of previous research ($r = 0.9$; [22]). In our study we estimated maximal aerobic speed from the players peak treadmill speed on a ramped incremental protocol to volitional test termination. The bias between maximal aerobic speed and $\dot{V}O_{2max}$ was not systematic and ranged between 0 and 10%. We also did not observe a relationship between the maximum aerobic speed- $\dot{V}O_{2max}$ bias and the anaerobic speed reserve. An example of the impact of estimating maximal aerobic speed was provided in case-contrast 2, where the same players' $\dot{V}O_{2max}$ decreased during the season, yet he was able to somewhat maintain his maximal aerobic speed in the treadmill test. Whilst application of LOCO to the match data successfully identified the increased total very-high speed running in #6 versus #5 owing to the decline in fitness, this was underestimated in comparison to IND. When applied to each match cluster, LOCO underestimated total very-high-speed running in 5 of the 18 match clusters (28%). Nonetheless, maximal aerobic speed is associated with repeated sprint performance [2] and improvements in this attribute are related to increased repeated high-speed running ($\geq 19 \text{ km}\cdot\text{h}^{-1}$) occurrences in elite-youth soccer match-play [4]. Since locomotor factors (aerobic capacity in combination with running economy) are important in determining the ability to perform repeated high-speed actions during intense match-play periods [4], the use of maximal aerobic speed to individualise time-motion analysis data may possess more ecological validity versus $\dot{V}O_{2max}$. Furthermore, given the sophisticated laboratory requirements for $\dot{V}O_{2max}$ assessment and its sensitivity to the determination protocol [28], the LOCO method incorporating a field-based maximal aerobic speed assessment is economical and practical in squad-based sports, and characterises the match intensity distribution, particularly in the very-high speed running and sprinting categories.

The results from the current study suggest that the LOCO method could be further enhanced by an individual assessment of players' transition to the high-intensity exercise domain. This is supported by the greater sensitivity of this transition to alterations in training status in comparison to $\dot{V}O_{2max}$ [10,15], together with the strong association of the anaerobic threshold and the time engaged in high-intensity running during matches [25]. As described in case-contrast 2, when the same player reduced fitness (respiratory compensation

threshold) during the competitive season, their absolute match demands as determined by arbitrary speed thresholds were not noticeably different between match clusters, however, the relative intensity distribution of the matches in #6 were greater, as revealed when the respiratory compensation threshold was incorporated into the individualisation method. As anaerobic threshold determination in laboratory settings is expensive and time-consuming, field-based methods of assessment would seem necessary, particularly in team-sports. One potential avenue is the determination of the heart rate deflection point, which may be ascertained during a maximum aerobic speed assessment with the use of a beat-to-beat heart rate monitor. A promising analytical method to facilitate the identification of the deflection point has been described previously [6] and in our laboratory we have observed acceptable inter- (typical error of the estimate: $0.4 \text{ km}\cdot\text{h}^{-1}$; 90% CI: 0.3 to $0.5 \text{ km}\cdot\text{h}^{-1}$) and intra-rater (typical error of the estimate: 0.3 - $0.5 \text{ km}\cdot\text{h}^{-1}$) reliability of this technique, albeit with a subtle bias when respiratory compensation threshold was used as the criterion measure (typical error of the estimate: $1.0 \text{ km}\cdot\text{h}^{-1}$; 90% CI: 0.8 to $1.3 \text{ km}\cdot\text{h}^{-1}$). Further research may be warranted to refine field-based techniques to estimate running speeds corresponding to the transition to the high-intensity exercise domain, and to examine the effect of any measurement bias upon the interpretation of the match-play intensity distribution.

In summary, this study demonstrated for the first time how different methods of individualising time-motion analysis data influences its interpretation. An individualised approach to external load monitoring may enhance the practitioners understanding of the match and competition demands, and facilitate appropriate recovery and periodization schedules to manage player work-loads and optimise the adaptation to training stimuli. However, in this study we observed that the use of single fitness attributes to anchor multiple locomotor categories across the exercise-intensity continuum resulted in erroneous interpretations of a players' intensity distribution. The use of two fitness measures that characterise the functional limits of endurance and sprint capacities better represented the players relative external load, however the lack of an anaerobic threshold measure rendered the LOCO method insensitive to changes in training status and also resulted in interpretation errors. With the application of IND, transitions between each intensity domain were represented, which may better characterise the individuals dose-response and reduce the incidence of false data interpretations. We suggest that fitness measures characterising the multiple transitions between intensity-domains should be incorporated into time-motion analysis, to facilitate interpretations of the individual players' match demands.

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