

Research article

Minimal Agreement between Internal and External Training Load Metrics across a 2-wk Training Microcycle in Elite Squash

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Abstract

This study investigated the relationships between internal and external training load metrics across a 2-week 'in-season' microcycle in squash. 134 on-court and 32 off-court 'conditioning' sessions were completed by fifteen elite squash players with an average (\pm SD) of 11 ± 3 per player. During every session, external load was captured using a tri-axial accelerometer to calculate *Playerload*; i.e., the instantaneous rate of change of acceleration across 3-dimensional planes. Internal load was measured using heart rate (HR), global (sRPE) and differential RPE (dRPE-Legs, dRPE-Breathing). Additionally, HR was used to calculate Banister's, Edward's and TEAM TRIMPs. Across 166 training sessions, *Playerload* was moderately correlated with TRIMP-Banister ($r = 0.43$ [95% CI: 0.29-0.55], $p < 0.001$) and TRIMP-Edwards ($r = 0.50$ [0.37-0.61], $p < 0.001$). Association of *Playerload* with TRIMP-TEAM ($r = 0.24$ [0.09-0.38], $p = 0.001$) was small. There was a moderate correlation between sRPE and *Playerload* ($r = 0.46$ [0.33-0.57], $p < 0.001$). Association of sRPE was large with TRIMP-Banister ($r = 0.68$ [0.59-0.76], $p = 0.001$), very large with TRIMP-Edwards ($r = 0.79$ [0.72-0.84], $p < 0.001$) and moderate with TRIMP-TEAM ($r = 0.44$ [0.31-0.56], $p < 0.001$). Both dRPE-Legs ($r = 0.95$ [0.93-0.96], $p < 0.001$) and dRPE-Breathing ($r = 0.92$ [0.89-0.94], $p < 0.001$) demonstrated nearly perfect correlations with sRPE and with each other ($r = 0.91$ [0.88-0.93], $p < 0.001$). Collection of both internal and external training load data is recommended to fully appreciate the physical demands of squash training. During a training microcycle containing a variety of training sessions, interpreting internal or external metrics in isolation may underestimate or overestimate the training stress a player is experiencing.

Key words: Squash, training load, accelerometry, RPE, heart rate.

Introduction

Monitoring training load is a priority for coaches and sport science/medicine practitioners who balance a quest for optimal physical adaptation with the potential for overtraining and/or injury risk. Training load monitoring is well established in team sports, including football (Impellizzeri et al., 2005; Akubat et al., 2012), rugby (McLaren et al., 2018) and Australian Rules Football (Boyd et al., 2013). Although highlighted as a research priority within tennis (Vescovi, 2017), limited literature has monitored load experienced by racquet sports' players. As with many racquet sports, squash elicits considerable metabolic and muscular demands (James et al., 2021). Indeed, players undertake

repeated high-intensity changes of direction within a small area (Jones et al., 2018), with additional contributions from upper body activity during shot playing (Fernandez-Fernandez et al., 2010). These characteristics, allied with an intermittent activity profile, present a challenge for support staff in identifying the most appropriate method of monitoring training load in squash.

Squash elicits the greatest physical demands of all racquet sports (Girard and Millet, 2009), with the longest rallies (~15-20 s) and smallest work:rest ratios (1:1) (Girard and Millet, 2009; Jones et al., 2018), which results in a mean match intensity of 86% of $\dot{V}O_{2max}$ at elite level (Girard et al., 2007). Consequently, elite squash players undertake a high volume of physical training, encompassing specific on-court training such as 'group' or 'feeding'/ 'pressure' sessions, that simulate match-play scenarios, whilst allowing greater control of the physical stimulus (James et al., 2021; Gibson et al., 2019). Within a typical training microcycle, players may also undertake 'ghosting' sessions, involving repeated simulated shots and movement patterns, in addition to off-court strength and conditioning training (Bennie and Hrysomallis, 2005). However, the most appropriate methods of monitoring cardiovascular and musculoskeletal demands across this variety of training methods remains unknown, hindering practitioner's ability to interpret and adjust physical loads across a microcycle.

Across many sports, including squash, heart rate (HR) monitoring is the ubiquitous approach to quantifying internal load (Gibson et al., 2019). HR data may be aggregated into a training impulse (TRIMP) metric, whereby a weighting is applied in accordance with physiological strain, derived from a prior HR: blood lactate curve (Banister, 1991; Edwards, 1993; Stagno et al., 2007; Akubat et al., 2012). Recent TRIMP calculations advocate assigning weightings from population-specific HR: blood lactate relationships, and these approaches demonstrate dose-response relationships with fitness improvements over a training period (Stagno et al., 2007; Akubat et al., 2012). Indeed, methods of training load monitoring should reveal such a dose-response relationship to demonstrate convergent construct validity (Manzi et al., 2009). However, the agreement between exercising HR and oxygen consumption is reduced by fluctuations in exercise intensity, especially above the second ventilatory threshold, which squash players regularly exceed (Girard et al., 2007). This weakens confidence in utilising HR to fully

represent the demands of training within intermittent activities such as squash or other racquet sports (Fernandez et al., 2006).

External training load represents the physical training completed during a session and is typically expressed as running distance (total or differentiated by velocity) and may include total accumulated high-intensity movements (Impellizzeri et al., 2005). Consequently, the instantaneous nature of external load measurement through wearable accelerometers becomes advantageous for quantifying short duration, high-intensity accelerations or decelerations. Many wearable technology companies now offer a metric that represents the global stresses placed upon the musculoskeletal system outside the scope of velocity/distance, by aggregating 3-dimensional (3D) accelerometer data. These algorithm-derived metrics may therefore capture multidirectional squash-specific demands, such as repeated accelerations, decelerations, lunges and potentially the upper body work associated with shot playing. Whilst upper body actions from shot playing elicits additional physiological strain to that from locomotive movement demands (Fernandez-Fernandez et al., 2010), the sensitivity of a vest-worn accelerometer to detect these actions has yet to be ascertained. Nevertheless, whilst global metrics such as *Playerload* (Catapult Sports, Melbourne, Australia) have been used to quantify external load in tennis (Gescheit et al., 2015) and badminton (Abdullahi et al., 2019; Wylde et al., 2019), they have yet to be used in squash. It is therefore unknown if external metrics demonstrate agreement with internal load measurements in squash.

Compared with HR monitoring and wearable technology, multiplying the session rating of perceived exertion (sRPE) by the training duration offers an affordable, time-efficient and holistic measure of training load (sRPE-TL), which has been used in tennis (Murphy et al., 2015; Vescovi, 2017). Internal training load encompasses an individual's psychophysiological responses to exercise and thus includes perceptual responses such as RPE (Impellizzeri et al., 2005). The sRPE represents an integration of a range of inputs including, but not limited to, working muscles, cardiovascular and pulmonary systems, joints, sweating, possible pain and dizziness (Borg et al., 2010). Whilst sRPE-TL is a valid measure of training load across a variety of training modalities (Scott et al., 2013b), sRPE lacks sensitivity in differentiating the specific demands players experience during training (McLaren et al., 2016). Differential RPE (dRPE) helps overcome this issue, taking specific exertion responses for the active muscles and breathing, to provide more actionable information into the source from which the subjective perception of exertion is determined (Arcos et al., 2014; Weston et al., 2015; McLaren et al., 2016). Previous research advocates utilising dRPE during exercise aligned with endurance (Borg et al., 2010; McLaren et al., 2016) and team sports (Arcos et al., 2014; Weston et al., 2015). However, whether dRPE-TL demonstrates agreement and therefore serves as a suitable proxy for internal or external load in squash is unknown.

Therefore, the primary aim of this study was to investigate the relationships between training load monitoring approaches in international squash players, during a 2-

week 'in-season' microcycle. It was hypothesized that internal and external training load approaches would demonstrate little agreement when analysed across a training block however, there would be agreement within internal metrics. A secondary aim was the novel reporting of high-intensity movements in squash measured using wearable technology. We hypothesised a comparable number of accelerations and decelerations, as well as changes of direction to the left as to the right, across the training block.

Methods

Subjects

Fifteen professional Malaysian squash players (11 males, 4 females) volunteered for this study (age: 19.1 ± 2.5 years, playing side: 14 right-handed and 1 left-handed). All players typically completed ten training sessions per week (~11 hours). They had been taking part in the national program for at least 2 years and regularly competed internationally in Professional Squash Association (PSA) events. A typical training week may comprise three 'group' on-court training sessions, one/two match-play sessions, one/two individual coaching 'feeding' sessions, two strength sessions and two/three conditioning sessions (outdoor running or on-court, audio-based 'ghosting'). Players provided written, informed consent and the study received institutional ethical approval, conforming to the Declaration of Helsinki.

Design

Across a 2-week (in-season) microcycle, training data were collected from players at the National Squash Centre of Malaysia. During every training session, data were obtained using a tri-axial accelerometer embedded within a GPS unit, HR monitor and RPE, pertaining to global (sRPE) and differential RPE (dRPE). Strength training sessions were not included in the study. All players had completed an incremental squash-specific aerobic fitness test (James et al., 2019), within three months of the training block, to derive blood lactate and HR relationships for the calculation of TRIMP metrics.

Training load measures

External load - *Playerload*

Players wore a 100 Hz accelerometer/GPS unit (G5, Catapult Sports, Melbourne, Australia) harnessed between the scapulae in a customised sports vest, with a paired, chest-worn HR monitor (Polar T31-coded, Kempele, Finland). All players had worn the vest previously and used the same devices throughout every session, starting before the warm-up until completion of the warm-down. Accelerometer data were downloaded with associated software (Openfield, Catapult Sports, Melbourne, Australia). Activities were cropped to include training data and rest periods but exclude warm-ups and cool-downs. Session duration was derived from *Openfield* software, with this duration used across all external and internal metrics where duration contributed to the calculation.

External load – High-intensity movements

Accelerations, decelerations and left/right changes of direction were detected using Inertial Movement Analysis

(IMA version 2, Catapult Sports) (Catapult sports, 2019). Movements that exceeded 2.5 m.s^{-2} and 3.5 m.s^{-2} were recorded as high-intensity (HI) and very high-intensity (VHI) events, respectively (Harper et al., 2019). Movements $<2.5 \text{ m.s}^{-2}$ were excluded. The sum of all VHI movements was combined into a single measure of multidirectional high-intensity load (Total VHI) (Luteberget et al., 2018).

Internal load - TRIMP

HR data were processed as per *PlayerLoad*. The following TRIMP calculations were made in custom-made spreadsheets: 'Banister's TRIMP' (TRIMP-B) (Banister, 1991), 'Edward's TRIMP' (TRIMP-E) (Edwards, 1993) and 'Team TRIMP' (TRIMP-TEAM) (Akubat et al., 2012). TRIMP-B utilises the mean exercising HR through the following formula:

$$\text{TRIMP} = D(\Delta\text{HR ratio})e^{b(\Delta\text{HR ratio})}$$

where D is the duration of training session is 1.67 for females and 1.92 for males and $\Delta\text{HR ratio}$ equals $\text{HR}_{\text{exercise}} - \text{HR}_{\text{rest}} / \text{HR}_{\text{max}} - \text{HR}_{\text{rest}}$.

TRIMP-E was calculated by multiplying the duration spent in each HR zone (50-60%, 60-70%, 70-80%, 80-90%, and 90-100% HR_{max}) by the weighing factor allocated to each zone (1 = 50-60%, 2 = 60-70%, 3 = 70-80%, 4 = 80-90%, and 5 = 90-100%) and summing the results (Edwards, 1993).

TRIMP-TEAM was calculated in accordance with Akubat et al. (2012), using pooled incremental test data to generate a group exponential curve and formula of the HR: blood lactate relationship. To utilise all training data, a TRIMP value was calculated for every HR reading. Due to differences in physiological responses to squash-specific exercise and continuous treadmill running (Girard et al., 2005), the HR: blood lactate relationship was derived from an incremental squash-specific aerobic fitness test (James et al., 2019), in accordance with the recommendation for test specificity within intermittent sports (Akubat and Abt, 2011). HR_{max} was the highest value observed during any fitness test, training or match in the past 12 months.

Internal load - RPE

Fifteen minutes after each session, sRPE, as well as differentiated ratings of exertion for active muscles (dRPE-legs) and the chest/breathing (dRPE-breathing) were recorded on a printed, training diary sheet. Following familiarisation, sRPE data were collected using the CR100 *Centimax* scale (Borg and Borg, 2002), which provides increased precision for monitoring training intensity over the CR10 scale (Scott et al., 2013b). Players were instructed to use the descriptive terms on the CR100 scale to indicate the intensity of the session (with regard to their 'whole-body' [sRPE], 'legs' [dRPE-legs] and 'breathing' [dRPE-breathing]) and write down the corresponding number. Players selected numbers between descriptors, where they felt the answer lay between two descriptive terms (Borg and Borg, 2002). All RPE responses (sRPE, dRPE-legs and dRPE-breathing) were multiplied by the session duration, to provide three separate measures of training load.

Statistical analyses

Data are presented as mean \pm SD. Data were assessed for

normality of distribution using histograms, boxplots and measures of skewness and kurtosis, prior to analysis. Relationships between training load metrics were analysed using Pearson product-moment correlations, with 95% confidence intervals calculated around the correlation coefficient (r), using a custom Microsoft Excel (Microsoft Inc., Washington, USA) spreadsheet (Hopkins, 2006). Interpretation of the correlation coefficients was evaluated qualitatively as: 0-0.09, *trivial*; 0.1-0.29, *small*; 0.3-0.49, *moderate*; 0.50-0.69, *large*; 0.70-0.89, *very large*; 0.90-0.99, *nearly perfect*; 1.00, *perfect* (Hopkins et al., 2009). Due to the absence of a normal distribution of data, differences between high-intensity movements were investigated using Friedman's ANOVA, with Wilcoxon Signed Rank test post hoc (Bonferroni correction). The effect size (ES) R , was calculated in accordance with Rosenthal (1991) and these data were analysed using SPSS (Version 25, IBM Inc, USA).

Results

A total of 166 training sessions were recorded (mean 11.1 ± 3.1 per player), with a mean duration of 54.7 ± 21.8 minutes. The microcycle comprised a total of 21 Feeding, 16 Ghosting, 53 Group, 44 Match-play and 32 Running Conditioning sessions. Five sessions revealed erroneous HR data containing only zero values and were excluded from final analysis.

The mean HR of training sessions was $78 \pm 6\%$ of individual HR_{max} . Mean internal training load values were 87 ± 38 , 178 ± 70 and 1011 ± 677 a.u. for TRIMP-B, TRIMP-E and TRIMP-TEAM, respectively. The mean sRPE score was 71 ± 18 (or '*very strong*'). The mean sRPE-TL was 3903 ± 1848 a.u. The mean *Playerload* was 388 ± 143 a.u.

The relationships between internal and external training load metrics are shown in Table 1 and Figure 1. *Playerload* was *moderately* correlated with internal load metrics TRIMP-B and TRIMP-E, whilst revealing a *small* correlation with TRIMP-TEAM. *Playerload* also demonstrated *moderate* relationships with sRPE-TL and dRPE-TL derivatives. Total VHI revealed *moderate-large* correlations with all metrics, apart from *Playerload*, which was *small*. There were *large-to-very large* correlations between both TRIMP-E and TRIMP-B and all sRPE-TL and dRPE-TL derivatives. However, sRPE-TL and dRPE-TL only revealed *moderate* correlations with TRIMP-TEAM. The mean TRIMP-TEAM, *Playerload* and sRPE-TL training loads across the microcycle are shown in Figure 2.

Training loads derived from dRPE-legs and dRPE-breathing demonstrated *nearly perfect* correlations with sRPE-TL (Figure 3) but dRPE-breathing revealed a range of correlations with HR-based internal metrics (Table 1). There was a *moderate* correlation between the training load from dRPE-breathing with TRIMP-TEAM, a *large* correlation with TRIMP-B and a *very large* correlation with TRIMP-E. Training load from dRPE-legs demonstrated a *moderate* correlation with *Playerload*. Within dRPE-TL metrics, dRPE-legs and dRPE-breathing demonstrated a *nearly perfect* correlation (Figure 3).

There were more HI ($>2.5 \text{ m}\cdot\text{s}^{-2}$) accelerations (831 ± 383 per player) than decelerations (609 ± 350 per player) across the training microcycle ($p < 0.001$, ES R = 0.31). Similarly, VHI ($>3.5 \text{ m}\cdot\text{s}^{-2}$) accelerations (479 ± 262 per player) were more frequent than VHI decelerations (193 ± 130 per player, $p < 0.001$, ES R = 0.50). There were more changes of direction to the left than right for both HI (left: 1451 ± 523 , right: 414 ± 452 , $p < 0.001$, ES R = 0.60) and VHI (left: 573 ± 255 , right: 129 ± 230 , $p < 0.001$, ES R = 0.57).

Discussion

This study investigated the relationships between internal and external training load approaches during a 2 week ‘in-season’ training microcycle. For our primary aim, we observed *small-to-moderate* agreement ($r = 0.23\text{-}0.50$) between internal (HR-based) and external (accelerometer-derived, *Playerload*) loads. Comparatively, sRPE-TL revealed stronger relationships with TRIMP calculations ($r = 0.41\text{-}0.79$), but similarly weak agreement with *Playerload* ($r = 0.41$). We also observed that relationships derived from legs/breathing dRPE-TL were highly agreeable with sRPE-TL ($r = 0.92\text{-}0.95$). This indicates these measures may not reveal additional, actionable information, compared with utilising sRPE-TL alone within a squash training period. In accordance with our hypothesis, the poor agreement between *Playerload* and TRIMP calculations indicate these measurements capture different demands of training in squash. For our secondary aim, we report a larger number of VHI accelerations than decelerations, as well as more frequent changes of direction to the left, rather than the right, across the microcycle.

Playerload

Some divergence between HR derived metrics and *Player-*

load was expected, given the delay in HR response to short, intermittent, high-intensity movements occurring in racket sports (Fernandez et al., 2006). These data support the overall *trivial* relationships that have been identified in badminton matches, between HR and *Playerload* (Abdullahi et al., 2019). However, in badminton, improved agreement ($r = 0.44$) has been found when only HR and *Playerload* data from predefined high-intensity zones were used, as opposed to all training data. The authors concluded the strength of the relationships were dependent on the duration of activities performed in low and high-intensity zones. In the current study, data are not drawn solely from matches, nor differentiated by intensity zones, but represent all on- and off-court training during the microcycle. We have previously shown different sessions within a squash microcycle to elicit specific physical demands (James et al., 2021). However, for our current analysis, we combined all sessions, to provide a ‘weekly’ view of training load, as required by a practitioner. Due to the variety of sessions and activity profiles within our dataset, this *real-world* perspective may exacerbate differences between internal and external metrics. In particular, measurements derived from a given training session may be influenced by different intended technical or physiological objectives, such as high duration, low intensity conditioning sessions (‘run’) producing high *Playerload* values, with low corresponding TRIMP scores (Figure 1A). Similarly, some high-intensity, but short duration matches and group sessions, resulted in high TRIMP values, again with low *Playerloads* (Figure 1A). Session structure has previously been highlighted as a factor influencing the relationship between training load metrics (Scott et al., 2013a), as the duration of rest periods will partly determine internal stress for a given external load. Therefore, practitioners should be aware of the potential for under- or over-estimating training load if utilising only TRIMP or *Playerload* metrics across a training week which contains a variety of sessions.

Table 1. Relationships (Pearson’s correlation coefficient [r] and 95% confidence intervals) between internal and external training load metrics.

	Session duration	TRIMP Banister	TRIMP Edwards	TRIMP-TEAM	<i>PlayerLoad</i>	sRPE	dRPE-Breathing	dRPE-Legs
TRIMP Banister	0.72* [0.64 - 0.79]	-						
TRIMP Edwards	0.86* [0.81 - 0.9]	0.95* [0.93 - 0.96]	-					
TRIMP-TEAM	0.39* [0.25 - 0.51]	0.74* [0.66 - 0.8]	0.65* [0.55 - 0.73]	-				
<i>PlayerLoad</i>	0.47* [0.34 - 0.58]	0.43* [0.29 - 0.55]	0.50* [0.37 - 0.61]	0.26* [0.11 - 0.4]	-			
sRPE	0.82* [0.76 - 0.86]	0.68* [0.59 - 0.76]	0.79* [0.72 - 0.84]	0.44* [0.31 - 0.56]	0.46* [0.33 - 0.57]	-		
dRPE-Breathing	0.77* [0.7 - 0.83]	0.60* [0.49 - 0.69]	0.71* [0.62 - 0.78]	0.35* [0.21 - 0.48]	0.46* [0.33 - 0.57]	0.92* [0.89 - 0.94]	-	
dRPE-Legs	0.83* [0.78 - 0.87]	0.69* [0.6 - 0.76]	0.78* [0.71 - 0.83]	0.44* [0.31 - 0.56]	0.48* [0.35 - 0.59]	0.95* [0.93 - 0.96]	0.91* [0.88 - 0.93]	-
Total VHI	0.66* [0.56 - 0.74]	0.58* [0.47 - 0.68]	0.64* [0.55 - 0.73]	0.35* [0.21 - 0.48]	0.11 [-0.04 - 0.26]	0.50* [0.37 - 0.6]	0.43* [0.3 - 0.55]	0.51* [0.39 - 0.62]

Data are drawn from all sessions during the training microcycle. Total VHI = combined accelerations, decelerations and left/right turns $>3.5 \text{ m}\cdot\text{s}^{-2}$ during a given session. Data derived from inertial movement analysis (IMA Version 2, Catapult Sports). * represents statistical significance ($p < 0.05$). Interpretation of the correlation coefficients; 0-0.09 *trivial*, 0.1-0.29 *small*, 0.3-0.49 *moderate*, 0.50-0.69 *large*, 0.70-0.89 *very large*, 0.90-0.99 *nearly perfect* and 1.00 *perfect* (Hopkins et al., 2009). sRPE, dRPE-Breathing and dRPE-Legs all represent the training load calculated from the respective raw RPE values, multiplied by the session duration.

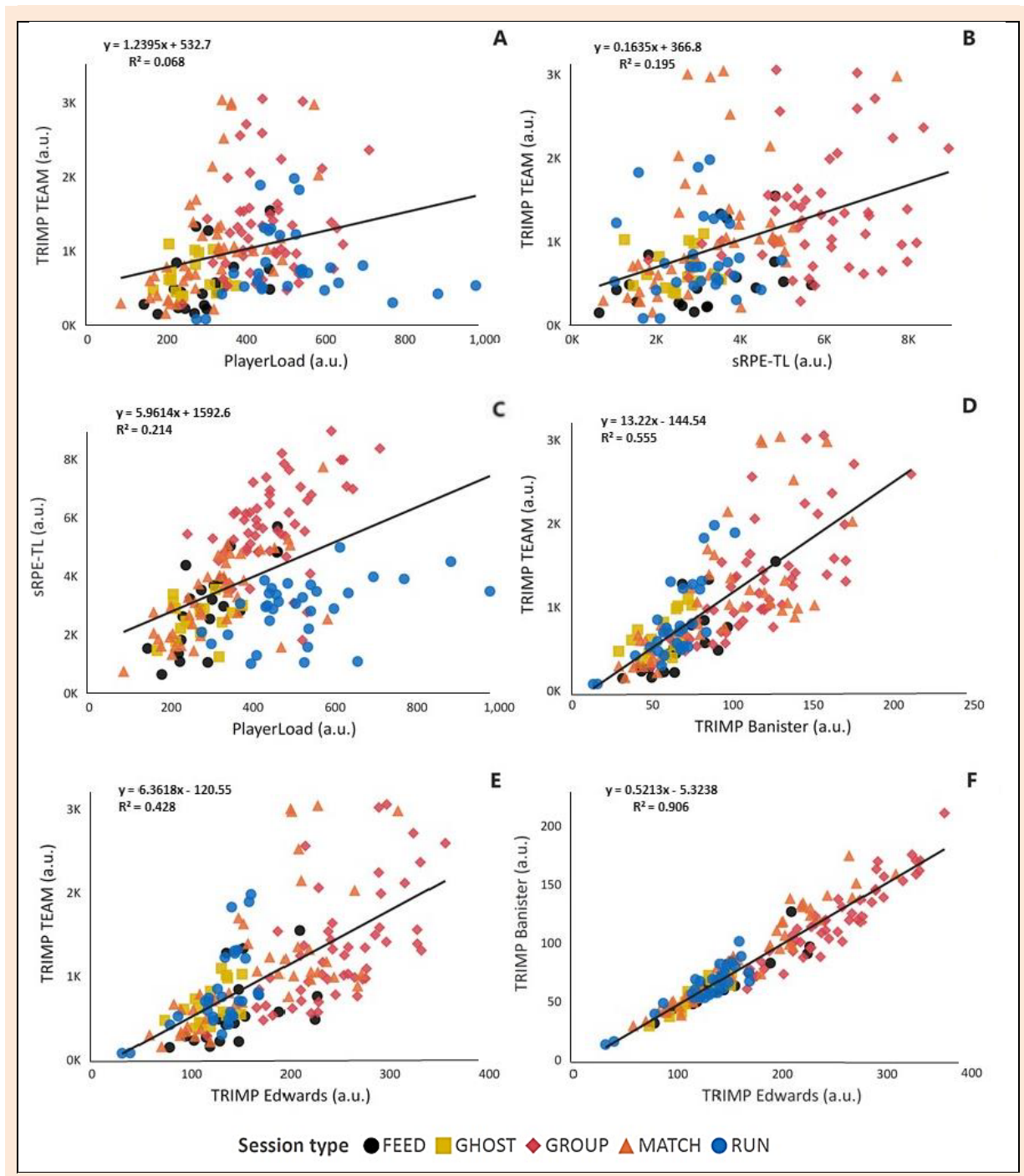


Figure 1. Agreement between primary internal and external training load metrics over the 2-week training period. All axes represent loads in arbitrary units. FEED = Coach Feeding session, GHOST = audio-based Ghosting session, CON = running Conditioning session. sRPE-TL represents the training load calculated from the sRPE multiplied by the session duration.

External load measurements such as *Playerload* benefit from independence of environmental factors such as temperature (James et al., 2017) and altitude (Turner et al., 2014) that may bias HR. However, it is unclear if the device location (between scapulae) accurately quantifies upper body work associated with shot playing, which hinders the interpretation of the poor agreement we observed between *Playerload* and internal loads. A further limitation of interpreting *Playerload* within this squash microcycle is the influence of accelerations measured from vertical

motion (z-axis) within the algorithm. *Playerload* displays a *nearly perfect* correlation with total distance in team sports (Scott et al., 2013a; Boyd et al., 2013). During the squash sessions we analysed however, there were multiple changes of direction with repeated accelerations and lunges that drive up HR (Gibson et al., 2019). As a result, it is unclear if *Playerload* is sensitive in detecting these squash-specific demands across the training microcycle. Future research should therefore investigate how shot playing may influence *Playerload*.

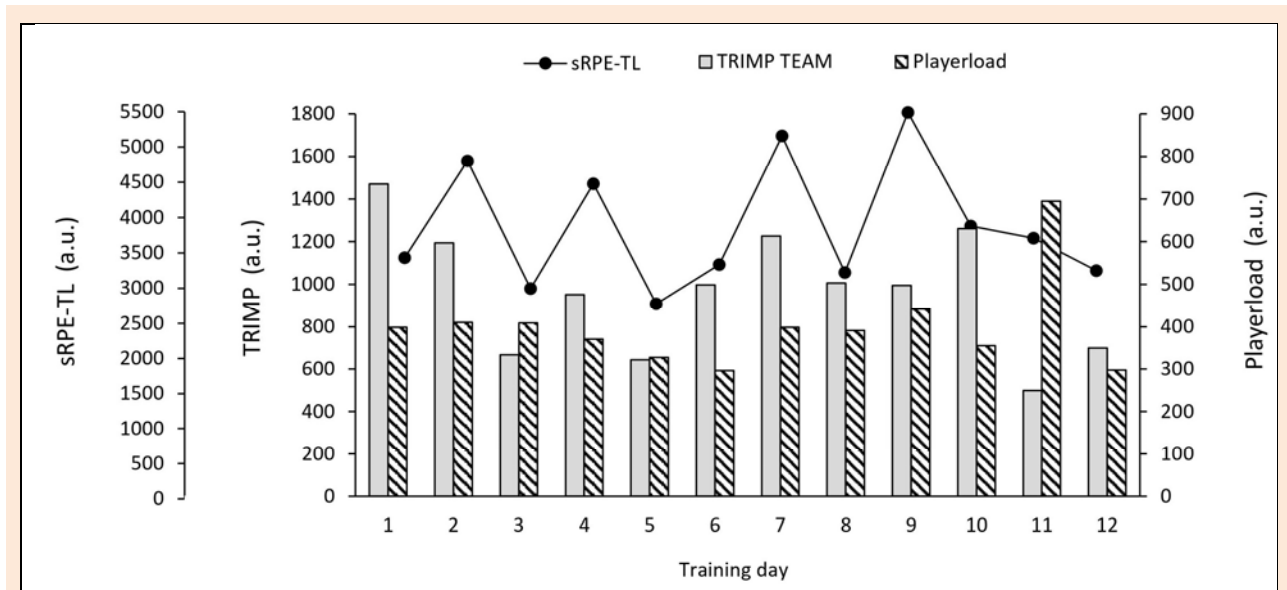


Figure 2. Longitudinal training loads across the microcycle training load derived from TRIMP TEAM, *Playerload* and sRPE-TL (sRPE multiplied by session duration).

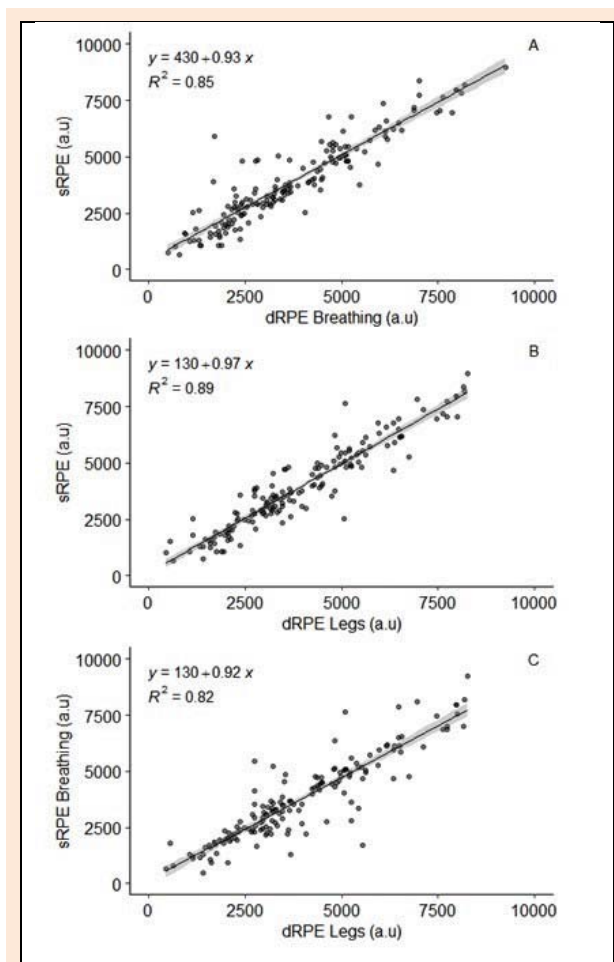


Figure 3. Agreement between session RPE (sRPE) and differentiated RPE (dRPE) for breathing (A), sRPE and dRPE for legs (B) and between dRPE-breathing and dRPE-legs (C). Data from all training sessions are plotted. Data were collected using CR100 scale. sRPE, dRPE-Breathing and dRPE-Legs all represent the training load calculated from the respective raw RPE values multiplied by the session duration. Shaded area around trendline represent 95% confidence intervals.

TRIMP

Overall, TRIMP calculations and *Playerload* demonstrated poor agreement, yet agreement with *Playerload* varied between TRIMP calculations. The weakest relationship was between *Playerload* and TRIMP-TEAM. This TRIMP calculation appears best-supported within the literature, as it demonstrates convergence validity with changes in aerobic fitness across a training block (Stagno et al., 2007; Akubat et al., 2012). Unlike TRIMP-B and TRIMP-E, TRIMP-TEAM is underpinned by the exponential HR: blood lactate relationship of these specific players, derived from a squash-specific aerobic fitness test (James et al., 2019). Therefore, the weightings ascribed to the HR data are likely to provide a more representative indication of physiological strain during squash, compared with weightings derived from a continuous treadmill test (Akubat and Abt, 2011). Furthermore, TRIMP-TEAM does not categorise HR data into training zones. This approach would have resulted in values around zone boundaries being assigned different weightings and may not be representative of the progressive nature of changes in exercise intensity (Akubat et al., 2012). Consequently, whilst TRIMP-TEAM demonstrated *large* correlations with TRIMP-B and TRIMP-E, there was divergence during sessions of higher exercise intensity (Figure 1D, 1E). This may reflect the linear, rather than exponential, weightings assigned using TRIMP-E or because TRIMP-B uses only the mean HR and thus, is less sensitive to fluctuations in exercise intensity. Whilst previous literature indicates TRIMP-TEAM to be more accurate in quantifying the training dose-response relationship than TRIMP-B and TRIMP-E (Stagno et al., 2007; Akubat et al., 2012), we caution that studies have yet to be conducted within racquet sports demonstrating convergence validity with changes in physical fitness.

Session RPE

In light of the divergent findings between HR and *Playerload*, the potential utility of a ‘global’ indicator of the psychophysiological response to training stress, such as sRPE

is apparent. Indeed, sRPE-TL is now being utilised in both tennis (Murphy et al., 2015; Vescovi, 2017) and squash (Gibson *et al.*, 2019). Session RPE-TL demonstrated strong correlations with TRIMP-B ($r = 0.68$) and TRIMP-E ($r = 0.79$) and a *moderate* correlation with TRIMP-TEAM ($r = 0.44$). Therefore, these relationships support the notion that, when measured using the CR100 scale, sRPE-TL can provide useful information as a surrogate for HR metrics during squash training (Gibson et al., 2019).

The sRPE may also be sensitive to neuromuscular fatigue arising from external demands such as repeated isometric and eccentric muscle actions during lunging and shot playing, which contribute to lower-body neuromuscular fatigue in squash (Girard et al., 2010). Such sport-specific movements have been suggested as an explanation for elevated RPE without concomitant HR load during soccer training (Impellizzeri et al., 2004). However, sRPE-TL demonstrated only modest agreement ($r = 0.46$) with *Playerload*, reaffirming that internal and external metrics are quantifying different training demands.

Differential RPE

Theoretically, dRPE provides more specific information than sRPE, and may be associated with internal (dRPE-Breathing) and external (dRPE-Legs) loads (Arcos et al., 2014; Weston et al., 2015; McLaren et al., 2016). However, training load calculated from dRPE-Legs revealed a *moderate* ($r = 0.48$) correlation with *Playerload*, similar to that of sRPE-TL. In badminton, splitting *Playerload* into constituent parts (*i.e.* vertical, horizontal, frontal planes) does not reveal stronger relationships with dRPE-Legs (Wyld et al., 2019). Thus, within squash, it appears dRPE-Legs does not provide additional information to sRPE.

We observed strong relationships between the training load calculated from dRPE-Breathing with TRIMP-E ($r = 0.71$) and TRIMP-B ($r = 0.60$), alongside a *moderate* relationship with TRIMP-TEAM ($r = 0.35$). These relationships were consistently weaker than sRPE-TL revealed with the same TRIMP metrics, indicating a dissociation between an elevated HR and a sensation of breathlessness during squash training. This may indicate a limitation of utilising dRPE-Breathing in sports containing considerable fatiguing upper body work (*i.e.* shot playing).

High-intensity movements

Total VHI is a high-intensity external load metric that demonstrated *moderate-large* relationships with internal metrics, but only a *small* correlation with *Playerload*. The total number of high-intensity movements undertaken during a squash training period therefore represents a separate training demand to that quantified by *Playerload*. This relationship appears weakest during ‘conditioning’ sessions (Figure 1), which are characterised by a high *Playerload* and low number of VHI movements (James et al., 2021). Nevertheless, the monitoring of VHI movements appears pertinent, given a likely association with neuromuscular fatigue in squash (Girard et al., 2010) and predictive ability of muscle damage (Gastin et al., 2019).

For our second aim, we observed greater accelerations than decelerations, when classified both as HI (>2.5

m.s^{-2}) or VHI ($>3.5 \text{ m.s}^{-2}$) events. We also observed a disparity between left and right changes of direction, with left turns more frequent. This may reflect a preference for lunging off the stronger leg within our predominantly right-handed cohort. This finding may also be influenced by the specific drills completed during this training period (*e.g.* backhand drills). However, as trunk orientation influences the classification of changes of direction, these preliminary data should be interpreted with caution, given the variable accuracy reported for class changes of direction (2-18%) identified using IMA, without the added complexity of racquet strokes (Luteberget et al., 2018; Catapult sports, 2019). It is unclear whether racquet strokes may influence the classification of changes of direction, therefore future research should investigate the accuracy of identifying these squash-specific movements in isolation. Nevertheless, these novel observations indicate training programmes should prepare players for repeated accelerations $>3.5 \text{ m.s}^{-2}$ and for right-handed players, potentially a greater proportion of changes of direction to the left.

Practical applications

The collection of both internal and external training load data in squash appears advantageous to understand the training stress and optimise physical preparation. Interpreting internal or external loads in isolation, following a variety of training sessions, may either underestimate or overestimate training load. Some TRIMP calculations have shown dose-response relationships with fitness improvements (Stagno et al., 2007; Akubat et al., 2012). Therefore, monitoring of internal training load using approaches that are derived from HR: blood lactate relationships may improve individual training prescription. However, we caution that our data were derived from fitness tests performed within 3 months of the study and therefore may be susceptible to changes in fitness during within this period. Moreover, dose-response relationships have yet to be reported using TRIMP during squash training and subsequent changes in fitness, using squash-specific testing protocols. Whilst external metrics cannot be used to assume improvements in fitness from training loads, the measurement of external load remains pertinent for quantifying mechanical load on the musculoskeletal system, which may be considered an injury risk factor.

Session RPE is not liable to data errors from HR or and does not require processing time associated with wearable accelerometer technology. The agreement we observed between sRPE-TL and TRIMP metrics indicates sRPE-TL is an effective surrogate for HR metrics during squash training, so provides a low-cost and time-efficient monitoring strategy.

Conclusion

In elite squash, little agreement was observed between HR-based, internal load metrics and the accelerometer-derived, external metric *Playerload* during a 2-week training microcycle. Differential RPE training loads did not reveal stronger relationships with other metrics than sRPE-TL alone, which may be appropriate surrogate for HR

monitoring across a squash microcycle. Future research should investigate relationships of training load metrics with changes in squash-specific fitness to identify dose-response relationships and inform the most appropriate metrics to monitor.

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Key points

- In elite squash, little agreement was observed between HR-based, internal load metrics and the accelerometer-derived, external metric Playerload during a 2-week training microcycle.
- Across a squash training microcycle, interpreting internal or external loads in isolation, may underestimate or overestimate training load.
- Differential RPE training loads did not reveal stronger relationships with other metrics than sRPE-TL alone, which may be appropriate surrogate for HR monitoring across a squash microcycle.

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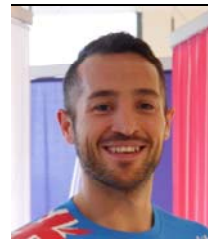
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